WV Rocketeers

Spaceflight through Earth’s Atmosphere and Ionosphere

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1.0 Mission Statement

The goals of the 2014 RockSat project are for West Virginia University (WVU) and West Virginia Wesleyan College (WVWC) students to build experiments to operate in and measure properties of the Earth’s space environment. The experiments are launched on a two-stage sounding rocket from NASA’s Wallops Flight Facility.

The first goal was to measure several different plasma and atmospheric variables as a function of altitude, between 60 km to 120 km of the rocket’s flight (Fig. 1). In the Earth’s upper atmosphere, solar UV radiation ionizes the gas and produces plasma. This layer, or the ionosphere, is important for radio communications, navigation, and other applications (Fig. 2).

A. The most important physical variables of the ionosphere are related to charged particles. The ionosphere is composed of electron and ion plasma so one such variable is the electron density (or plasma density) which we can measure using charged-particle detectors such as Langmuir probes (LP). The electron density is expected to vary throughout the ionosphere from $10^4$ to $10^6$ electrons per cm$^3$. As the layers of ionization vary greatly from day to night, we should measure more ionization during the day throughout the D, E, and F layers. As the rocket reaches an altitude of greater than 90 kilometers, the E layer of the ionosphere will begin to reach its peak close to the Terrier-Orion apogee, which should be around 120 kilometers. The temperature of the plasma is anticipated to be between 200 and 500 Kelvin.

In the plasma, the Langmuir probe will create a perturbation of the positively charged ions and negatively charged electrons. This effect will be observed at a particular length (radius), known as the Debye length.

The Debye length for a plasma is represented here:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_e}{n_e e^2}}$$

(1)

where $\varepsilon_0$ represents the permittivity of free space, $k_B$ represents the Boltzmann constant, $T_e$ is the temperature of the electrons, $n_e$ represents the number density of electrons, and $e$ represents the electric charge.

When tests of the plasma are taken, a current-voltage (I-V) trace should be acquired, showing ion saturation as well as electron saturation. An ideal example of this is given in Fig.3 [Merlino, 2007]. The dotted line illustrates the rounding due to plasma noise or averaging effects. From the ion and electron saturation currents we can calculate the ion and electron density. The change of slope of the I-V trace should give us the temperature of the electrons as well.

Any perturbation to the plasma will move more electrons to the probe and we may observe plasma oscillations, known as the characteristic plasma frequency.

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}$$

(2)

Equation (2) is the characteristic plasma frequency in which the ionospheric electrons oscillate around the heavier ions. Here, $m_e$ represents the effective mass of the electron.

A different group of particles, energetic electrons coming into the ionosphere from higher atmospheric layers, can be measured using Geiger counters and similar
detectors. Compared to plasma electrons with energies of several electron-volts, energetic electrons have energies of several kilo-electron-volts or higher. A schematic of very high energy particles entering the atmosphere is shown in Fig. 4.

B. A second important physical property is the Earth’s magnetic field. The magnitude of the B-field decreases approximately as a power law with distance from the Earth’s center. The magnetic field is important in shaping the trajectories of charged particles such as ions and electrons.

Models of the magnetic field are available from the National Oceanic and Atmospheric Administration (NOAA) and other sources. The WVWC experiment will measure the Earth’s field as a function of height and compare with the current NOAA model.

C. In addition to charged and neutral atoms and molecules, the atmosphere contains large solid particles called “dust.” They come from the planet’s surface and from meteor debris that slowly descends to Earth. The meteor dust changes the optical properties of the highest atmospheric layers. When energized by sunlight they emit an electromagnetic radiation called airglow (or dayglow). Sodium is an important element present in meteor dust and its emission lines (Fig. 5) are a major part of the airglow intensity. The sodium layer is a bright yellow layer at about 90 km and can be measured by measuring the intensity of the sodium emission lines (Fig. 6).

Measuring the properties of the atmosphere and ionosphere is the goal of several experiments by the WVU and WVWC teams.

A second major goal is related to flight dynamics. To understand any science data taken during the rocket flight, it is important to know the rocket’s altitude as well as its flight path and orientation. Our second major goal is to continuously record the flight dynamics of the rocket, such as its acceleration and rotation rate.

Finally the third major goal concerns radio communications which are key for space missions. We want to understand how communication works from a Mach-4 space vehicle such as the Terrier-Orion rocket. The data from the WVWC magnetic-field experiment will be broadcast from an on-board transmitter to a ground station.

In summary, the mission of the RockSat 2014 project is to understand several properties of the space environment by building experiments. Specifically, we expect to learn about the physical environment; the rocket trajectory, and about ground-to-space communications.

2.0 Mission Requirements and Description

In order to reach the mission goals presented in Section 1, the rocket and payload must meet several requirements for the rocket and the payload.

**Mission requirements.**

First we present the requirements for the overall mission.

a. The mission trajectory should cover a part of the upper atmosphere above 60 km. The mission should spend at least 2 minutes above 60 km.

b. The payload should fit in the provided volume. We have chosen to use half a canister so 9” in diameter and approximately 4.5” height.
Power is not provided by the rocket so we must use batteries to power the payload. In accordance with the RockSat-C User’s Guide, no rechargeable lithium-ion cells may be used at Wallops so the power is supplied by disposable lithium batteries. Also, no high-voltage sources is used in this payload.

d. The payload must be electrically isolated from the canister.

e. There is no direct access to space from the payload so a special port is needed for plasma measurements.

f. An optical port is required for the cameras.

**Description and subsystems**

The mission is built on 7 subsystems. Five of these are experiments:

1. Flight Dynamics (FD). This WVU experiment measures flight dynamics variables such as acceleration, angular speed, and Earth’s magnetic field. Its measurements are important for understanding the rest of the data and images.

2. Plasma Dynamics (PD). This WVU experiment measures the density of electrons. If the signal to noise ratio is low it can also yield electron temperature and ion density. In addition, we use a particle detector to record the number of high-energy electrons as part of the PD experiment.

3. Spaceflight (SPACE). This WVWC experiment measures flight dynamics variables. It is conceptually very similar to FD experiment, but is implemented differently.

4. Amateur Radio Communication (ARC). This WVU/NASA IV&V project tests a transmitter that is planned to be placed on a cubesat.

5. Camera, or airglow, experiment (CAM). This WVU project takes images of the atmosphere, land, and ocean during the mission. It focuses on the optical properties of the upper atmosphere.

Two additional subsystems are:

6. Power distribution. The power supply is controlled and regulated at the main (FD) board and related components.

7. Flight software. A number of programs were written and revised for the microcontrollers operating during the mission.

**Payload and experiment requirements**

The following are requirements specifically for the payload and individual experiments:

a. All data-recording experiments: the acquisition rate should be 15 Hz or higher.

b. Plasma: the electric current resolution should be at least 0.5 μA. Based on the dimensions of the probe this should give a density of 2.5 \(10^4\) cm\(^{-3}\).

c. The Langmuir probe should be mounted on the outer skin of the rocket in a special port requested from Wallops. The probe will extend beyond a certain length from the rocket, larger than several Debye lengths, reducing any chances of interference from the charge on the rocket, while ensuring accurate data of the ionosphere will be collected.
d. Magnetic field: the field should be measured at an accuracy of 100 nanoTesla.
e. Flight dynamics: acceleration resolution should be 0.1 g, and the angular speed resolution should be 10°/s or lower.
f. Communications experiment: the power will not exceed 1 W. The frequency needs to be within the MHz frequency spectrum allowed by WFF.
g. Imaging experiment: The rocket is spinning fast (5.6 Hz after Orion burnout) so the video frame rate should be several times the highest spin rate. The rate will be 30 Hz or higher.
h. Imaging experiment: the cameras need to be small enough to fit in the required canister and access to a 1.5”-diameter optical port on the rocket’s body.
i. Imaging: one of the filters should be centered at a characteristic airglow wavelength. A second filter should be centered at a reference (background) wavelength. All filters should have a bandwidth of at most 10 nm.
j. Plasma and communications experiments: a pocket needs to be designed and built for the special port.
k. Redundancy should be built into the payload. Some experiments or sensors are duplicated (flight dynamics by WVU and WVWC; magnetic field measurements by inertial measurement unit (IMU) and micromagnetometer; cameras with near-identical fields of view)

These requirements were important in developing and revising the payload design and following them is necessary for minimum success.

3.0 Payload Design

This section discusses how the experiments and other subsystems were designed.

1. FD experiment.
The subsystem records time, acceleration, attitude, and magnetic-field information. This is necessary both for understanding the flight and for calibrating and interpreting data collected by other experiments. It is a legacy experiment flown on WVU payloads for a number of years. It combines an inertial measurement unit (IMU, ADIS16405 by Analog Devices) with several other sensors. The IMU provides vector acceleration, vector rotation rate, vector magnetic field, and the board temperature. Precision is 14-bit except for the temperature which is 12-bit. The interface is SPI and data acquisition rate can reach up to tens of kHz.

A second sensor is a micromagnetometer (HMC2003 by Honeywell) which has also been flown on all WVU RockSat missions. This is an analog sensor so it allows much higher resolution than the IMU magnetometer.

The selection of these sensors was based on trade studies. High-range sensors included an additional gyroscope. There was no large-range accelerometer on this mission.

Electrical design:
The FD circuit is shown in Fig. 7 and its printed circuit board (PCB) is shown in Fig. 8.
Data acquisition:
The microcontroller operating this subsystem is a NetBurner MOD5213 programmed in C++.

2. PD experiment.

This experiment measures properties of charged particles such as: electron and ion density and temperature, and count rates of energetic particles.

Langmuir probe. The electron density increases above 60 km and appreciably more so above 90 km (Fig. 1). The E region peak is typically between 100 and 120 km. The experiment is going to measure this density with a probe extended into the ionospheric plasma. The probe voltage is swept from -9 to +9 V and the resulting current is measured using a shunt resistor of 1 kΩ (Fig. 9).

The probe used in the lab tests was prebuilt and made from graphite. For the flight, the probe was made of tungsten, which is strong enough to withstand atmospheric effects during ascent. An insulating material, alumina, is used to electrically separate the probe from the payload canister. The tip remains the only uninsulated piece (3’’ length) and is exposed to the ionospheric plasma.

The probe is mounted on a pocket provided by Wallops and placed in a special port between the two sets of RockSat canisters (Fig. 10).

Geiger counter. In addition to thermal electrons which are responsible for the current measured by the plasma probe, higher-energy electrons are also present in the ionosphere typically coming from overlying regions of Earth’s space environment (Fig. 4). Electron energies of keV and MeV are not uncommon. A Geiger counter was built and tested (Fig. 11). Its characteristic energy for beta radiation (electrons) is 50 keV.

Electrical design:
The LP electronic circuit includes several operational amplifiers. A differential op amp is used to compare the swept voltage from the microcontroller with a reference voltage. The op amp output drives the probe as well as a shunt resistor placed in series with it. The probe current is equal to the current through the shunt. The voltage across the shunt is measured by an instrumentation amplifier (INA217) with a gain of 110. We control the probe voltage using a pulse width modulated (PWM) signal from the NetBurner in the range of (-9,+9 V). Several versions of the probe circuit were tested in the helicon device of the WVU plasma lab. An electrical enclosure (Faraday cage) was built and used to shield the circuit from plasma emissions during the lab tests. The v. 4 PCB is shown in Fig. 9.

Data acquisition:
The NetBurner of the FD subsystem is used for control and data acquisition of the PD system. It records the PWM signal, probe voltage, and probe current. Due to programming issues, the data rate is 16 Hz which is low compared to past RockSat missions (50 Hz).

3. SPACE experiment.
The experiment measures the Earth’s magnetic field which will be compared to a reference model by the National Oceanic and Atmospheric Administration. The Wesleyan College experiment is nearly identical to WVU’s FD. The IMU and
magnetometer sensors are chosen to be the same. However the electronics and flight code of the experiment are developed separately. The experiment is shown in Fig. 12.

**Data acquisition.**
The microcontroller was Arduino Mini and the effective acquisition rate was 2.2 Hz.

4. **ARC experiment.**
The radio communications experiment by the IV&V Facility is designed to transmit data from the RockSat vehicle to a ground station in packets of 190 bytes. The transceiver and antenna will be used on a cubesat currently in development by IV&V staff and students (Fig. 13). The data to be transmitted are the magnetic field and IMU data recorded by the SPACE experiment. A Radiometrix transceiver is used for this purpose and is operated within the amateur radio band (70 cm) at a frequency of 435 MHz, compatible with WFF specifications. Transmitted packets include the valid amateur radio call sign KD8-SXG. A Bell 202 modem is used to modulate the signal and the data transmitted is encoded/decoded using the AX.25 protocol.

**Electrical design:**
The radio antenna for this experiment was mounted on the special port on the outer surface of the canister using two layers of Kapton ESD tape. A ¼ inch wide strip of spring steel measuring tape cut at 6.125 inches was used for each dipole. SMA bulkhead connectors were used to pass the signal from the transceiver through the special port insert block to the antenna. An SMA cable had to be cut and spliced to the antenna using small nuts/bolts and eye-hook crimp connectors.

**Data acquisition:**
An Arduino Mini was shared with the SPACE experiment. The ground station used to receive data packets from the ARC experiment included the same Radiometrix transceiver/antenna design and an additional handheld (HT) talkie with a whip antenna for redundancy. These were both connected to a laptop with a USB cable and a terminal program was used to access the COM ports of the respective devices. During tests and the actual flight, data packets received through the serial COM ports were then saved to text files.

5. **CAM experiment.**
The camera, or airglow, experiment was originally an imaging experiment which would record video of the flight through an optical port. However the experiment requirements focused on a specific wavelength, with a second wavelength needed for reference, and at the same time there were functional problems with the helmet camera used. The original camera for this mission was a GoPro Hero 3 HD. However, there were technical difficulties with it and in addition there was a requirement for a smaller-volume imaging system of two cameras needed to fit with the RockSat optical port. A trade study resulting in the Raspberry Pi camera by Omnivision being selected.

We used two identical cameras to measure the intensity of two narrow regions of the visible spectrum. The first camera targets the main emission wavelength which is the sodium doublet line near 589 nm (Fig. 5). The sodium emission spectrum is dominated by the 568.82-nm along with the 588.99-nm and 589.59-nm range, known as the sodium D₂ line. These lines are emitted when an atom transitions from the 3p level to the 3s level.
atomically. Therefore most of the light from excited sodium atoms comes from the D₂ lines [HyperPhysics].

A second camera measures the intensity of a baseline emission selected at a nearby wavelength at 535 nm. Each camera was equipped with a bandpass interference filter (Edmund Optics) with a bandwidth of ±5 nm.

**Mechanical design:** A Lexan bracket of several slides was manufactured. The camera height above the deck was adjusted by changing the number and thickness of the slides. The camera axes were parallel to each other and the fields of view included the optical port.

**Electrical design:** The experiment was activated by the main (FD) board using a power relay and was run continuously from before launch to recovery.

**Programming:** A Raspberry Pi microcontroller was used with each camera. The maximum rate of 90 frames per second (fps) was selected. The main code was written in Python and a few additional scripts were written in Debian Linux. Due to the slow boot time of the microcontroller, the activation time was moved up from launch to T-03:00.

In addition to the experiment subsystems, two other subsystems were used:

6. **Electrical subsystem.**

The electrical subsystem includes power supply and regulation for the FD (main) board, and a second, regulated supply from FD to the SPACE, ARC, and CAM experiments.

7. **Software subsystem.**

The majority of the flight code is written in C++ for NetBurner and Arduino. The FD and PD codes are modified from earlier versions for the NetBurner microcontroller. A flowchart is shown in Fig. 14.

The codes for the SPACE experiment were developed in Arduino C++ while the code for the CAM experiment controlled by the Raspberry Pi was written in Python with several basic boot scripts in Linux.

The data analysis code had major changes from previous RockSat missions and was rewritten in IDL. It included some time series analysis of the plasma and optical data. The first stage of the image analysis software was written in Matlab for analysis of the raw files and the second stage in IDL for time series analysis. A study of the images for feature identification used the Smithsonian Astronomical Observatory Image ds9 program.

**Mechanical design**

The payload was housed in a half-canister (Fig. 15) with the remaining canister volume taken by a project of the University of Colorado. The top deck contains the SPACE, ARC, and CAM experiments, the Geiger counter of the PD (Fig. 16). The bottom deck contains the FD (main) and PD boards. Thanks to the low-mass sensors and packaged design the payload was underweight so ballast (21 fishing sinkers) was used to satisfy the mass requirement.

4.0 **Student Involvement**
Students from WVU and WVWC worked on this payload. At WVU, Tessa Maynard with help from Chris Sommers, and then Greg Lusk and Michael Lindon worked on the flight dynamics. Amy Sardone, Greg, and Michael designed and built the plasma probe and several circuits and pieces of equipment useful in testing it in a helicon device in the WVU plasma lab. They took measurements of the current for a number of circuit designs.

For Wesleyan College’s SPACE experiment, Josh Hiett designed, built, and tested their flight dynamics project. In the IV&V ARC experiment, Steven Hard revised an earlier design with Alex Bouvy of the RockSat-X 2013 team who returned to help with ARC. Steven and Josh then integrated ARC with SPACE so that the latter experiment’s data could be transmitted.

For WVU’s CAM (airglow) experiment, Caitlin Ahrens tested the first camera (a GoPro). Later Michael and Greg worked on the new camera specifications, designed and built a support structure, and programmed and tested the camera and microcomputer system.

A group of students (Hard, Hiett, Lindon, and Lusk) visited ATK to have the payload vibed and tested. The integration team (Lusk, Lindon, Hiett, Hard, and Sardone) worked in the week prior to launch to have the payload tested and delivered it to Wallops.

Four of the students (Ahrens, Maynard, Sardone, Sommers) were enrolled in a course and they prepared final reports which were used to compile this report.

5.0 Testing Results

We tested the payload in several different ways. Much of the testing took place in the payload development lab however the LP circuit was tested repeatedly under different conditions in a helicon device in the WVU plasma lab (Fig. 17-18). The current in the plasma device is much higher than any ionospheric current for the same voltage range, so the signal to noise ratio is much higher in the lab (Fig. 19). We built an electric enclosure and installed the LP circuit in it so it was shielded from radio-frequency effects while recording plasma data. The tests were useful for improving the probe electronics. The plasma probe, ARC antenna, and other parts were placed in a special port (Fig. 10). For the energetic-particle experiment, Geiger counters were built in the payload development lab and tested using low-radioactivity sources (Fig. 11).

The Wesleyan College team built several parts of testing equipment for their flight dynamics experiment (Fig. 20). They were able to control the rotation rate, vibration (acceleration) magnitude, and magnetic field.

In addition to on-campus tests, the payload underwent several types of testing (vibration, thermal/vacuum, and electronics inspection) in ATK’s Allegany Ballistics Laboratory facilities during a visit in June 2014. The ATK staff provided us with useful recommendations on electronics, sensors, and structural stability.

6.0 Mission Results
The Terrier-Orion launched at 07:21 am on June 26, 2014 (Fig. 21). Almost all experiments worked successfully during the flight and returned a large amount of data and images. Minimum success was achieved in all but one experiment (ARC) and comprehensive success criteria were met in three experiments (FD, PD, and CAM).

Due to the CAM experiment’s microprocessor boot time, the activation was modified from launch-time (T+00:00) to early (T-03:00). Because of microcontroller startup times, data and image acquisition started at approximately T-02:30.

1. FD: the WVU flight dynamics experiment recorded from T-02:30 to the apogee of 117.9 km or T+02:52 at an effective rate of 16 Hz. The IMU accelerometer was useful in establishing timing between this and other experiments and the radar telemetry as shown in Fig. 22. All IMU channels returned high-quality data (Fig. 23). The IMU gyroscope worked well, however it is a low-rate sensor (360 °/s) so its Z component saturated after several seconds. Its X and Y components show a good correlation with the IMU B-field data and Geiger counter. The IMU magnetometer returned low-noise data with a resolution of 1 T, useful for obtaining an approximate scaling of the magnetic-field with altitude and for guidance/navigation measurements. The on-board thermal sensor data showed a temperature increase from launch until apogee.

The analog magnetometer recorded data over the same interval as the IMU sensor, but the reference voltage was not set correctly. Segments of data have different reference levels which appeared as noisy data. After correcting for the reference level, the Bx and By components agree with the IMU Bx and By. The analog magnetometer has a higher resolution than the IMU sensor, but additional processing of the magnetometer dataset needs to be done to achieve that resolution.

At apogee, data logging by the main board stopped for this experiment as well as for PD. The cause is unknown, but, after comparison with telemetry, acquisition appears to stop exactly at the time of apogee. However, payload power remained on so the three other experiments that were independent of the main microcontroller (SPACE, ARC, and CAM) functioned through the rest of the mission and up to payload recovery.

Data from the FD experiment are shown in the Appendix. They are of very good quality and there is excellent agreement between the accelerometer and radar telemetry. We have identified the flight stages from these data.

2. PD (LP and Geiger counter): the WVU plasma experiments operated normally and returned data from pre-launch to apogee so the end of the data acquisition at apogee did not impact the experiment. The E region (>90 km) which was the target of the LP experiment was identifiable by an increase in probe current (ion and electron). The voltage sweep rate was low so only 11 sweeps were made during flight (19 for the entire dataset). The electric current was much smaller than in the tests in the WVU plasma lab so the signal to noise ratio was lower for the ionospheric data. In addition to the ionospheric current, strong currents were measured at lower altitudes as discussed below.

Ionospheric plasma (E region): From the LP data we can calculate several plasma variables (Fig. 24). First, several sweeps give an ion current of 0.3 μA which is consistent with currents expected for these altitude ranges (Fig. 25). From the equation for the ion current $I_\text{i}$

$$I_\text{i} = A n_e v_{\text{th}}$$  

(3)
and the ion kinetic energy (temperature), and the cylindrical probe collecting area A we can calculate the ion density \( n_i \). Second, the electron temperature can be estimated from the change of the probe current as the voltage is increased to positive range. From the inflection point of the I-V trace we have several measurements of the electron temperature in the 1000-K range. However this is too high compared to expected values. After reexamining the circuit we found that the shunt resistor used to measure the current was too large for the low-density ionospheric plasma, although it was useful for the lab-plasma data acquisition. In the helicon plasma, the current is much higher than in the ionosphere. In a future experiment the LP shunt value will need to be lower.

The third variable is the electron density \( n_e \). Two of the sweeps, at 102 and 110 km, give an electron saturation current of 1.7 \( \mu \)A which is reasonable for these altitudes. From the current, electron temperature, and probe dimensions, the electron density can be calculated.

**Current at intermediate altitudes:** In addition to the expected strong probe currents measured for altitudes greater than 90 km, a strong current was measured in intermediate altitudes, \( h=45-65 \) km. The current is stronger than expected and may be due to a circuit problem. However this explanation is not consistent with the LP measurements taken in the E region a few seconds later, or with the lab tests. We are looking at several possible explanations.

**Energetic particles:** The Geiger counter measured energetic particle numbers during the mission shown in Fig. 26. The particles are electrons (beta radiation) with energies of 50 kiloelectron volts, which originate above the ionosphere and move downwards along magnetic field lines. The count rates depend on the altitude and also in the viewing direction. The count rates have a clear maximum at approximately 18 km and then decrease. Above 20 km they vary periodically with time since the optical port faces the nadir and zenith directions alternately (the Geiger counter has been placed close to the port to maximize the number of particles measured). These results are in very good agreement with measurements from earlier flights and the literature.

A second maximum in the electron count rate is found at 104 km, but it is narrow and it may be due to counting statistics during the slower motion through apogee.

3. **SPACE:** The Wesleyan College flight dynamics experiment took measurements from pre-launch to recovery for a total of 3 hours and 20 minutes. Its boards were in the upper deck unlike the FD and PD experiments so it was not interrupted at apogee. Its magnetometers (IMU and analog sensor) agree well with each other.

However most measurements were affected by a programming error. It seems that the flight code saved some of the data in an incorrect format that was not detected in the lab tests. Two of the IMU datasets not affected by this error are the gyroscope Z component and the internal temperature sensor.

In work done to correct the error, it is noted that since the WVU and WVWC sensors are identical and their datasets overlap in time it may be possible to correct the error by processing the flight dynamics data carefully.

4. **ARC:** There are indications that the Radiometrix transceiver operated during the flight. However the ground station did not receive any data. Prior to the flight, a number of tests were successful in the lab and a small number of field exercises. However we did not test for the rotation speed of the rocket which may have been too
high for the receiver to maintain line-of-sight radio contact with the ground station long enough to receive complete packets. We expected that some data would be recorded on the ground after the payload reentered at lower altitudes and slow rotation. However, we discovered that the Kapton tape did not withstand the heat of reentry and allowed the antenna to detach from the outer surface of the special port and eventually burn away from the fixed fasteners.

5. CAM: the two cameras of the WVU airglow experiment recorded video from T+00:43 for 3 hours and 20 min (up to and including the ocean impact shown in Fig. 27, and later recovery phase). The two cameras had nearly identical fields of view and returned similar images as shown in Fig. 28. However they were not synchronized. Due to programming error the sodium-line camera recorded at the default rate of 30 fps while the reference camera recorded at the high-speed rate of 90 fps. This error was corrected after the flight thanks to the high-time resolution of the dataset so it did not impact the time series analysis.

Image processing was used to extract images, features, as well as intensity time series for each of the two wavelengths. Since the microcontroller lost power for several seconds during launch the exact timing of the beginning of the video was not available. Instead timing was obtained from other characteristic events such as apogee (approximate) and ocean impact (precise). After the timing of the two cameras had been aligned with each other and with radar telemetry as shown in Figures 29-30, we worked first on video (image) analysis and feature and time-series extraction, and then on time series analysis.

Figure 31 shows that the line-of-sight sodium intensity was correlated with altitude and was used to estimate the sodium layer’s range at 81-115 km. This measurement is comparable to the bibliography figure for the sodium layer of 80-105. The brightness of the sodium line exceeded 3 times the reference line intensity. Variance from the reference altitude range is probably due to the trajectory and rotation of the payload which are two of the parameters determining the camera viewing angle. Fig. 32 gives a synoptic view of all intensity data as functions of altitude from which we can identify the sodium layer signature, water/cloud signatures and other effects.

7.0 Benefits to the Scientific Community

Much of the new information obtained from this mission centers on the team’s work to measure plasma density and other charged-particle properties, and airglow intensity and related neutral-atmosphere features during summer daytime conditions while working with modern sensors and other technologies. The science results from the PD experiment are consistent with altitude profiles, ion current and electron temperatures for the E-region, while the optical intensity time series from the CAM experiment’s images are consistent with the altitude profile for the sodium layer. Flight dynamics and other measurements were useful for understanding the data. The results will be reported in a poster presentation in an education-themed session at the American Geophysical Union fall meeting in December 2014.
8.0 Lessons Learned

Several lessons were learned during preparation for this mission. Software revisions were made early in the spring semester and then only a few times afterwards up to integration, but it is important to test all software frequently, similar to the electronics and sensors. Clear communication between all team members are important to avoid misunderstandings and delays. Communications tools such as online drives, group-editing software (GoogleDocs) and others are useful, however frequent, direct communications, and group work in the lab are equally important. Frequent practice of presentations is recommended. It is really useful to have logistics such as parts ordering streamlined and spares of all components must be available in the lab to avoid unnecessary delays.

9.0 Potential Follow-on Work

Most of the flight data and images have been processed at this point. However several datasets need additional processing such as the WVWC SPACE data (IMU and magnetometer) which need to be compared with the WVU sensor data. The timestamp information for the CAM experiment may also need additional refinement to reduce the current uncertainty of 0.5-s timescale.

The main plasma experiment (LP) has produced good data in spite of the noise produced by the large shunt resistor. We plan to refly it in a future mission with a different circuit design and shunt value. The flight dynamics package has been a reliable component of the rocket flight missions. In the future we plan to upgrade it in collaboration with the Mechanical and Aerospace Engineering department. The airglow experiment produced a sodium profile of the entire neutral atmosphere up to approximately 118 km. We plan to revise it for a future mission. We have worked out the time-keeping between different sensors and the radar telemetry in the data analysis, and revisions in the C++ flight code have improved it. Also the data analysis program has been heavily modified and can be used in a future mission.

10.0 Conclusions

The WVU and WVWC teams flew a number of experiments that focused on space science of the ionosphere, atmosphere, and magnetic field, and on radio communications with a ground station. Members of the student team traveled to Wallops for the final integration and to attend the launch, run a ground station, and work on data analysis (Fig. 33). The majority of the experiments were successful and the problems in the flight code were in most cases overcome in the data analysis stage.

Data from the flight dynamics experiments (FD and SPACE), as well as the ground telemetry provided by Wallops, were very useful in the data analysis. The plasma probe was based on a design that was flown in 2012, and also tested in the plasma lab and in the ionosphere. The airglow experiment was an elegant application of atomic physics theory in the upper atmosphere of the Earth. The space-to-ground communications
experiment was not successful so a future team may plan to test it more carefully and improve its design. Students involved in the mission focused on one or more experiments and worked several sensors, electronics, and/or software programs. The learning curve was steep, but we managed to stay on top of it. This was a demanding payload for both the science and the organizational goals, and most of the comprehensive-success criteria were met.

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11.0 References

12.0 Figures Including Selected Results
Fig. 1. Atmospheric (left) and ionospheric (right) layers shown schematically with rockets and other ground and space instruments (middle).

Fig. 2. The ionosphere as seen from space (auroral lights above Canada).
Fig. 3. An idealized plasma current-voltage trace [Merlino, 2007].

Fig. 4. Energetic particles coming through Earth’s atmosphere.
Fig. 5. Atomic energy levels and transitions for sodium. The D₂ doublet is the 3p-3s transition marked in yellow [Hyperphysics].

Fig. 6. The sodium layer seen from the International Space Station. The Nile Delta is in the foreground.
Fig. 7. The FD circuit was based on a legacy design. Its schematic is shown here.

Fig. 8. Printed circuit board for the FD experiment.
Fig. 9. Version 4 of the LP PCB is ready for testing.

Fig. 10. The Langmuir probe, ARC antenna, and radio sounder antenna are mounted at a special port on the rocket fuselage during integration week.
Fig. 11. Testing the Geiger counter in the lab with a calibrated low-intensity radioactive source.

Fig. 12. The SPACE experiment includes an IMU and a high-precision magnetometer.
Fig. 13. The ARC experiment and antenna shown here as part of a cubesat system in development.

Fig. 14. Flowchart of the flight code for the FD and PD experiments.
Fig. 15. Solidworks CAD for the payload plan and canister.

Fig. 16. Top view of the payload in mid-June 2014 before traveling to Wallops. The ARC, SPACE, and CAM experiments are indicated on the top plate. The bottom plate with FD and PD boards is not visible.
Fig. 17. Testing the LP circuit with a helicon plasma in the WVU plasma lab.

Fig. 18. I-V trace from the lab-plasma tests of the LP circuit. The ion saturation current and inflection point for plasma temperature are seen. The electron current has not saturated for this voltage range.
Fig. 19. I-V trace from the plasma-lab’s own data acquisition system for the same plasma as in Fig. 11. These data were useful in revising the circuit and estimating signal-to-noise.

Fig. 20. Equipment for spin and vibration tests built by Josh Hiett for the Wesleyan College’s SPACE experiment.
Fig. 21. Terrier-Orion launch at 07:21 am on June 26, 2014 from Wallops Island.

Fig. 22. FD experiment: Acceleration during the two rocket stages from the IMU accelerometer is compared to Wallops radar telemetry (heavier line).
Fig. 23. FD: Acceleration, rotation rate, magnetic field, and temperature are shown from pre-launch activation to apogee. Launch is $t=0$ s. The two burn stages are indicated by arrows. Several datasets have been very useful for interpreting most other mission measurements.
Fig. 24. PD: I-V traces from 11 sweeps taken during the flight. Left: raw data. Middle: noise-reduced data. Right: bias current removed.
Fig. 25. PD: Preliminary I-V traces during the flight in the D and E layers. The average altitude is indicated in each graph. The electron and ion saturation currents are indicated for the middle two graphs. Additional noise reduction and calibration is needed for these data.
Fig. 26. Geiger counter: energetic (50-keV) electron count rates are shown as a function of altitude. A maximum is found at approximately 18 km. Above that altitude, a slow modulation is due to the rocket spin. High fluxes correspond to zenith viewing, low to nadir.

Fig. 27. CAM experiment: Ocean impact as seen from the 535-nm camera.
Fig. 28. CAM: frames from the two cameras at approximately T+650 s. The altitude is indicated in the lower graph.
Fig. 29. CAM: time series of intensity from the 535-nm (green line) and 589-nm (orange-yellow) images. Time-alignment has not been corrected here.

Fig. 30. CAM: Intensity time series after time alignment is corrected. The moment of impact is marked with a vertical dashed line.
Fig. 31. CAM: Airglow intensity as a function of altitude. Left: background (535 nm); right: sodium line (589 nm). The nominal range for the sodium layer (80-105 km) is indicated with horizontal dashed lines. The wavy line of the 589-nm intensity is due to rocket precession.

Fig. 32. CAM: Combined view of all intensity time series data as a function of altitude. Left: 535-nm (baseline) intensity. Right: 589-nm (sodium) intensity. Ranges for the thermosphere, mesosphere, stratosphere, and troposphere are shown.
Fig. 33. ARC: A ground station for the project was set up close to the launch pad.

Fig. 34. Several members of the WV Rocketeers team attended the launch.