Airglow-CubeSat with Orientation Control by Aerospike Puff-jets

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Abstract: Observations of upper atmospheric emissions further the understanding of the effects of the chemiluminescent energetics of the Earth's atmosphere. The Airglow-CubeSat will scan the desired altitudes of the mesosphere and the upper thermosphere. The resulting data is intended to help validate results collected from measurements taken from rocket profiles as well as the SABER/TIMED satellite. The Airglow-CubeSat will be monitoring the atomic oxygen green line at a wavelength of 557 nm. Research is also being conducted into the feasibility of using aerospike technology for altitude maintenance and satellite orientation control.

Objectives & Approach

The Airglow-CubeSat is based upon the SABER sensor that was engineered and flown by the USU Space Dynamics Laboratory and the NASA Langley Research Center. The atomic oxygen airglow in the atmosphere is a bright emitting light source in the mesosphere of the Earth which has been readily observed by astronauts (see Figure 1) [1]. The Airglow-CubeSat is to scan the atmospheric limb by spinning along its long axis oriented at right angles to its orbital motion.

Figure 1: Airglow Viewed from the International Space Station

Payload Subsystem

Photometer/Optics

The payload of the cube satellite includes a sensor that measures the airglow emission layer. The airglow is at a wavelength of 557 nm in the green. The purpose is to see the distribution of the airglow as a function of altitude. As the satellite spins, the sensor scans the Earth limb and collects the data. A narrow field of view (FOV) is needed to be able to spatially resolve emissions.

For precise readings from the sensor, a large lens was desired to take in light and a small detector to reduce noise. An optical filter is used to isolate the 557-nm line.

Approach

- Focal length must fit in Cube Satellite 10×10×15 cm
- Black silicon detector
- 0.03 degrees FOV to distinguish airglow altitude profile
- Long axis rotation

To gather adequate light to the sensor, a 25-mm diameter lens is used with a 0.0157-mm^2 black silicon sensor. A double convex lens would be used to obtain the desired focal point. In order to achieve a FOV of 0.03 degree full angle

$$\boldsymbol{FOV = 180 * \frac{diameter\ of\ sensor}{\pi * Focal\ Length}} \qquad \textbf{Equation 1}$$

was used to design the focal length for the lens of about 30 mm. The focal length of the lens had to be able to fit within the cube satellite. The lens curvature radii for the lens was designed from the conventional lens-makers equation [3].

$$\boldsymbol{\frac{1}{Focal\ Length} = (\frac{1}{R1} - \frac{1}{R2} + (n-1) * \frac{Thickness\ of\ lens}{n * R1 * R2}))}$$

Equation 2

The light rays require a specified distance to come to a focal point dependent on the radii of the lens and what FOV is desired. This is illustrated in Figure 2 showing the light rays passing through the lens and converging to a focal point on the photodiode detector.

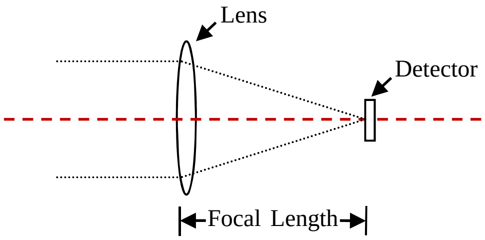

Figure 2: Lens/Photodiode Diagram

A double convex lens with a diameter of 25 mm was used with a focal length of 30 mm to meet the specifications for the optical system. In order to filter out unwanted wavelengths, a 557-nm optical filter with a bandwidth of 80 nm was employed.

All mounting hardware was based on the size of individual components, focal length, and FOV to provide housing for the optical system.

The complete optical system integrated into the cube satellite is shown in Figure 3 to illustrate the orientation of the optical system in relation to the cube satellite.

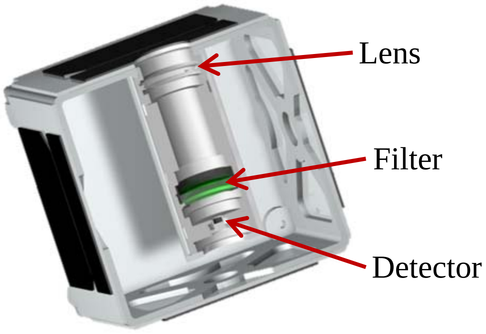

Figure 3: Cutaway of CubeSat with Optics

The individual lens, filter, and mounting assembly in Figure 3 are attached to the extension tube.

The components used to construct the optical assembly are listed in Table 1:

Table 1: Photometer and Lens Cost

Lens	Double-Convex Lens, 25 mm Dia. x 30 mm FL, VIS-NIR Coated	NT63-683	$39
Filter	557nm CWL, 80 nm Bandwidth, 25.4 mm Mounted Diameter	NT62-811	$50
Photodiode Mounts	C-Mount to TO-18/TO-46 Detector Mount	NT58-731	$64
Lens mount	C-Mount Thin Lens Mount	NT56-353	$73
Focus/extension tube	C-Mount Fine Focus Tube	NT03-625	$78
Filter mount	C-Mount Achromatic/Thick Lens Mount	NT56-354	$73
Detector	Black Silicon Detector 0.0157 mm^2		$TBD
		Total	**~$400**

Testing

Testing of the photodiode was performed to show functionality of the optical system. The testing was executed by using the photometer to measure the light from an incandescent light source at various distances (Figure 4) as well as voltage versus the angle (Figure 5). The results were conclusive that a regular silicon photodiode is not sensitive enough to measure the radiance expected from the airglow layer. The feasibility of using a newly developed black silicon detector with a D* that is 800 times higher than conventional silicon is being explored.

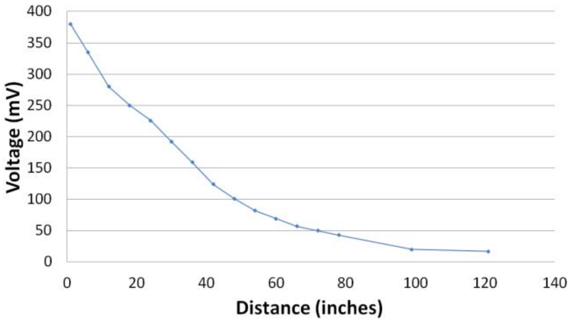

Figure 4: Voltage vs. Distance

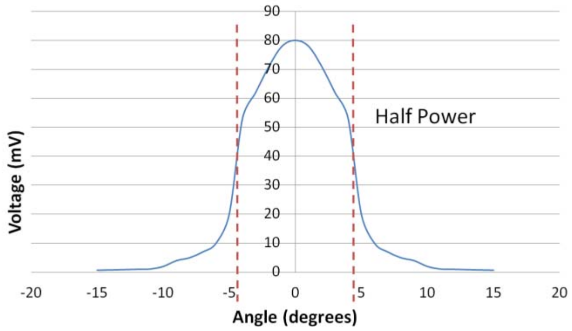

Figure 5: Angle vs. Voltage at 44 Inches

Alternative approach

The original requirements for the viewing angle of the optical system have been changed due to the remoteness at which the measurement of the airglow will take place. The distance to the airglow layer from the satellite is approximately 2000 km, which requires an angle of view of 0.03 degrees to be able to distinguish the layer profile. For this case, it is assumed that the black silicon detector is the same size as the regular silicon photodiode. The focal length for the angle of view of 0.03 degrees would be 154.7 cm, which is too long. A smaller detector would be more feasible for this project by shortening the focal length to more easily fit into a cube satellite. Another alternative to accommodate the focal length would be the use of mirrors allowing for the focal length to be longer than the CubeSat dimension.

Data Subsystem

The desired transceiver rate is 9600 baud**.** Depending on the orbit the satellite will have about 500 seconds of communication with the base station. This is approximately 586 kilobytes per pass. The period of the orbit will be around 100 minutes.

The 12-bit analog-to-digital converter (ADC) on the microcontroller will be used to record data from the black silicon detector. It is planned to spin the satellite at 5 revolutions per minute (0.083 Hz). At this frequency samples are obtained 60,600 samples per orbit. It is necessary to ascertain how much data each sample will require.

For data compression, research has involved looking into lossless and lossy algorithms. Neither, algorithm will compress the data sufficiently. The following is a summary of data compression:

- Lossless data compression – allows the exact original data to be reconstructed from the compressed data
- Lossy data compression – only allows an approximation of the original data to be reconstructed in exchange for better compression rates.

The time sampling is summarized as follows:

- 32 bits for the processor
- 12 bits for the ADC converter
- a time stamp
    - UNIX time: 1332368408 (2012-03-21 22:20:08Z)
- 3 bits per number
- 40 bits per time stamp
- To improve bit usage, truncate the time stamp to exclude the year and month
- 52 bits of data to send down per sample.

Recorded data from the solar panels are used to verify the satellite attitude and the solar panels' power. Another concern with the satellite is that if the silicon detector looks directly into the Sun the detector would be damaged. An additional factor that has been researched is a lens/filter that could dim when too much light is experienced. This approach was abandoned due to the long response time.

Communication Subsystem

An important subsystem for the CubeSat is the communications system. Several transceivers made specifically for CubeSat systems were considered. The high prices of these transceivers prevented their use in the CubeSat system.

A transceiver module called the RFM23BP from HopeRF Electronic will be used. It is an inexpensive alternative. Its most important features are summarized below:

- Frequency range
    - 433/470/868/915 MHz ISM
- Sensitivity -120 dBm
- Output power range
    - +30 dBm Max (RFM232BP)
- Low power consumption
    - 25 mA receive
    - 550 mA @ +30 dBm transmit
- Data rates of 0.123-256 kbps
- FSK, GFSK, and OOK modulation
- Power supply of 3.3-6 V
- Ultra-low-power shutdown mode
- Digital RSSI

This module is on par with many of its CubeSat specific counterparts in terms of output power and power usage. The transceiver has a small footprint. Figure 6 shows the layout of the transceiver.

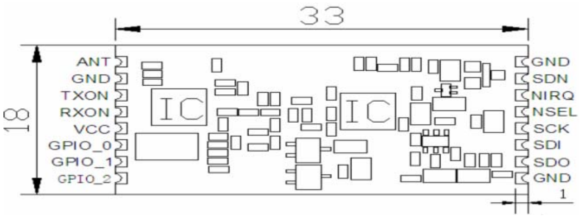

Figure 6: Physical Layout of Transceiver

Because the CubeSat will be spinning, a special dipole antenna will be used to transmit and receive data. Figure 7 shows a mock-up with antennas at 45-degree angles.

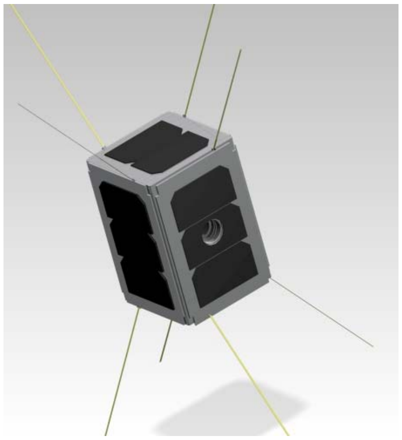

Figure 7: CubeSat with Dipole Antennas at 45°

Figure 8 and Figure 9 show the radiation pattern for this array. Although the antenna gain is not constant with direction, the pattern will facilitate transmission of data regardless of CubeSat orientation with respect to the ground station.

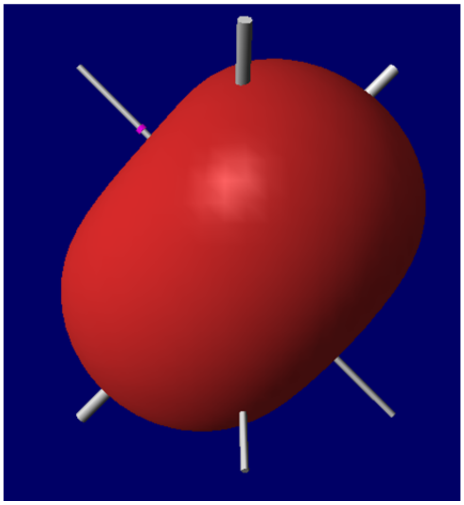

Figure 8: 3D Radiation Pattern

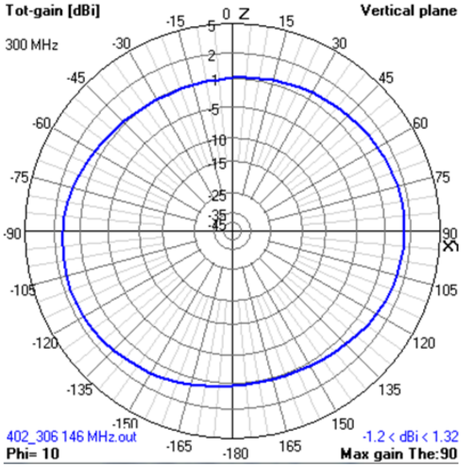

Figure 9: 2D Radiation Pattern

Control Subsystem

The satellite's intelligent control system will be used to configure the rotational position with respect to the Earth limb. The intent is to align the satellites onboard optical sensor with the airglow emission by means of aerospike puffers or magnetorquers. Another crucial aspect of control will be data management. Throughout the mission, data will be received and stored for later transmission to a ground station. The controller must meet power and size specifications. With these control system requirements in mind, the STM32F4 Discovery development kit appeared to be the best match for this CubeSat mission.

Choice of Microcontroller

Some of the considerations for a microcontroller were:

- Architecture support 8, 16, 32 bit
- Processor speed
- Power consumption
- Available communication protocols
- Availability of code examples (open source code)
- Product availability
- Cost of unit

An STM32F4 Discovery evaluation board was used. The board costs $17. It supported 32-bit architecture and has a list of available IDE's for programming, including many coding examples. The Discovery board also has access to all the pin-outs of the microcontroller for debugging and programming purposes. A benefit of this microcontroller is a built-in 12-bit ADC. The board is shown in Figure 10.

Principal Features of Microcontroller

- STM32F407VGT6 microcontroller featuring 32-bit ARM Cortex-M4F core, 1-MB Flash, 192-kB RAM in an LQFP100 package
- On-board ST-LINK/V2 with selection mode switch to use the kit as a stand-alone ST-LINK/V2 (with SWD connector for programming and debugging)

- Board power supply: through USB bus or from an external 5-V supply voltage
- External application power supply: 3 and 5 V
- LIS302DL, ST MEMS motion sensor, 3-axis digital output accelerometer
- Eight LEDs:
    - LD1 (red/green) for USB communication
    - LD2 (red) for 3.3 V power on
    - Four user LEDs, LD3 (orange), LD4 (green), LD5 (red) and LD6 (blue)
    - Two USB OTG LEDs LD7 (green) VBus and LD8 (red) over-current
- Two push buttons (user and reset)
- USB OTG FS with micro-AB connector
- Extension header for all LQFP100 I/Os for quick connection to prototyping board and easy probing
- 12-bit ADC converter with plenty of channels

Figure 10: Discovery Microcontroller

Data Inter-system Communication

The system has hardware components that require different communication protocols. The transceiver uses I^2C and the microSD card uses SPI. Other communications are through standard serial using TTL logic levels.

Position Control

Aerospikes & Magnetorquers

Aerospike cold-gas puffers will be used to control the orientation of the CubeSat with the use of a PID control algorithm. The main feedback into a PID Controller will be magnetometer or accelerometer readouts. This Controller will also be used to de-tumble the CubeSat after the satellite has ejected into low Earth orbit. As a back-up orientation control, magnetorquers will also be placed and implemented within the CubeSat structure. The puffers use the design of aerospike thrusters constructed in a simplified form (2).

Figure 11: Simple Aerospike Design

High-level System Diagram

Power Subsystem

Batteries

To meet the CubeSat power requirements while keeping within a low budget, it was decided to design a custom power system. Lithium-ion batteries were selected for energy storage because of their very high energy density. Considering CubeSat volume restraint, a 1.5U CubeSat structure with a 3-amp-hour battery pack would best meet the systems power needs. The design team also determined that the supply voltage from the batteries should be no less than five volts.

This would allow the addition of a DC/DC converter to provide a clean 5-volt power source for the optical photometer and the microcontroller.

With these requirements, the Ultra Fire 18650 batteries (Figure 12) were selected. They are relatively inexpensive and two of them in series provide the voltage and amp-hour storage capacity that the system requires. The form factor of the Ultra Fire batteries will also fit into the CubeSat structure adjacent to the optical assembly.

Figure 12: Lithium-ion Batteries

Charge Controller

To meet the power required by the various subsystems in the CubeSat, these high capacity batteries were required. An issue that arises with lithium-ion batteries is that the batteries are very sensitive to being overcharged and undercharged. The charge controller (Figure 13) was adopted to provide battery maintenance. This controller protects the 7.2-volt lithium-ion batteries from being over charged or over discharged. This approach was an economical solution at a cost of less than $5.

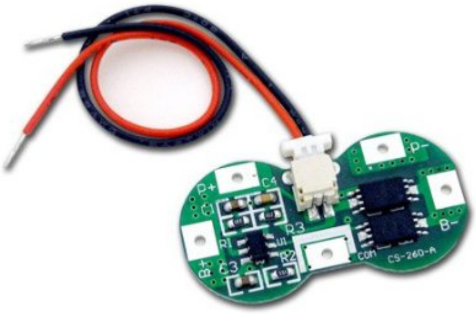

Figure 13: Charge Controller

Solar panels

In order to keep the various systems of the CubeSat powered in space, it was decided to use solar panels to continually re-charge the batteries. Several solar panel options were found that would supply the CubeSat with the needed voltage and current. An example is Clyde-Space who offer solar panels with built-in magnetorquers.

Two different types of solar panels have been acquired and tested. One panel was from allelectronics.com (Figure 14). When testing this solar panel, the panel was illuminated with a 100-watt incandescent light bulb. This particular panel generated 20 mA at 4.5 V. Two panels could be placed on each side of the CubeSat.

A cell donated by Northrop Grumman was tested. Under the same illumination as the previous test, an output of 150 mA at 0.8 V was generated.

Figure 14: Solar Panel

Another possibility are 1/8 inch-square cells from solarbotics.com, shown in Figure 15.

Figure 15: Solarbotics Cells

These cells are rated to produce a current of 80 µA at a forward voltage of 1.3 V. Each cell is $1.35, and there would be space for several cells on the CubeSat sides.

DC/DC converter

A DC/DC converter and regulator are included in the design in order to provide regulated power to the control board and sensors. The converter selected is the OKI-78SR Series depicted in Figure 16, chosen because it provides a wide range of selectable input voltages and provides a fixed output at 5 V.

Figure 16: DC/DC converter

Structure Subsystem

In the initial stages of the design, a 1U chassis was desired for this application because it was believed that all the components would fit into its 10×10×10 cm frame. However, it was subsequently decided that the 1.5U structure would better meet the required systems. The CubeSat structure design accommodates the photometer sensor on one of the sides of the CubeSat with solar panels covering the other sides. A skeleton structure is preferred because of its ease of access to sub-components. A 3D printing process was used to construct the 1.5U CubeSat mock-up from plastic material as seen in Figure 17.

Figure 17: Mock-up 3D Print with Lens and Solar Cell

The CubeSat was to tumble end-for-end in order to scan the Earth limb. However, the CubeSat would eventually spin around its long axis since that is the lowest energy dynamic state.

Conclusion

The CubeSat structure design accommodates the photometer sensor viewing from one side of the nano-satellite. The other sides are covered with solar panels to provide the power for the subsystems. The science payload of viewing the Earth limb airglow in the visible wavelength region is a viable experiment. The complete system design was comprised of: (1) photometer, (2) data subsystem, (3) communication subsystem, (4) control subsystem, (5) power subsystem, and (6) structural subsystem. Other possible emissions to scan in the same mesospheric region as atomic oxygen near 100 km are hydroxyl and nitric oxide.

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