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FalconSAT-7—A Deployable Solar Telescope

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ABSTRACT

We report on the design of FalconSAT-7 (FS-7), a 3U Cubesat with a deployable solar telescope payload. The program is run by undergraduate cadets at the Air Force Academy, and graduate students at the Air Force Institute of Technology. The purpose of the mission is to demonstrate a deployable telescope with larger aperture than the spacecraft structure. The telescope deploys from one end of FS-7, and has a clear aperture of 20cm, twice the cross section of the host spacecraft structure. This novel payload is made possible by the use of a thin (28 micron) membrane optic using diffractive principles to focus H-alpha light from the sun onto an onboard camera. The membrane optic is deployed using a set of spring loaded pantographs, which tension the membrane and hold it flat. The Colony-II program office provided the 3U bus which is built by the Boeing Company. The FS-7 mission is supported by the Defense Advanced Research Projects Agency (DARPA) Tactical Technology Office. Launch of FS-7 is expected in late 2015.

INTRODUCTION

Large primary mirrors are required to collect high-resolution optical imagery. These mirrors typically drive the size, weight, and subsequent cost of imaging satellites. FalconSAT-7 (FS-7) is an innovative approach to perform space-based imaging with a deployable membrane optic as its primary mirror.

This proof-of-concept program will deploy a 20cm primary optic from a 3U cubesat. The membrane optic weighs only 1.75 grams and is known as a photon sieve. It utilizes diffraction through billions of microscopic surface indentations to produce a high-quality image. The deployed size is two times the cross section of the satellite bus, allowing four times the light collection and twice the resolution of a traditional lens. To demonstrate the deployable technology, the system is designed to image the sun at the hydrogen alpha, H_α, line, 656.4nm.

The entire payload, consisting of the optical, deployment, and control subsystems, fits within one half of the satellite, in a volume of (10cm × 10cm × 15cm). The second half of the satellite provides power, pointing, and communications with the ground control system.

The FalconSAT-7 program is targeting five key mission success criteria. First, and foremost, is education. The United States Air Force Academy and Air Force Institute of Technology use this program as a tool to teach students the technological and programmatic hurdles involved in space development. Through active hands-on learning our students understand the benefits and limitations of space technology and are better prepared to enter a highly technical workforce.

The second mission goal is to demonstrate the ability to deploy the photon sieve. The deployment mechanism consists of three spring-loaded pantograph arms that are folded around the photon sieve. The pantograph arms extend 43cm from the satellite body, placing the photon sieve at a precise point above the optical platform.

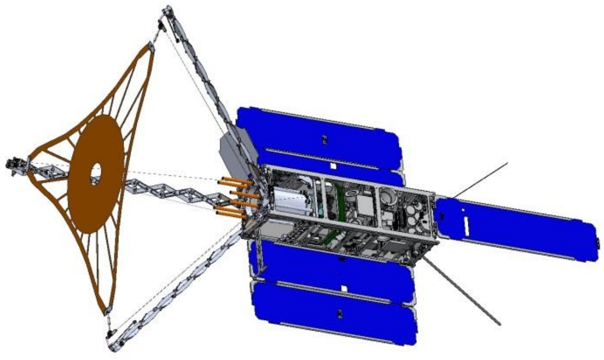


Figure 1: FalconSAT-7 Deployed Configuration

The successful deployment of the photon sieve enables the next mission objective, imaging the sun. This goal tests the end-to-end system including the operation of the photon sieve, bus control, and payload pointing.

The fourth goal is to characterize image performance. This includes controlling camera integration time, focus, and gain. Performance at each setting will be compared to theoretical photon sieve performance.

The final mission goal is to demonstrate flight heritage of the polyimide photon sieve material. To accomplish this, we will collect solar imagery and analyze the long-term degradation of the membrane optic. The objective is to demonstrate minimal degradation after 30-days of operation.

PAYLOAD

The FS-7 payload consists of two main components: the optical subsystem and the deployment subsystem. Each of these is described in detail below.

Optical subsystem

The optical system of FalconSAT-7 peregrine payload consists of eight elements. A flexible membrane primary focuses light at 40 cm. A 12 mm achromatic doublet with 15 mm focal length is used to collimate the light coming from the primary followed by a Fabry Perot bandpass filter with a 0.1 nm bandwidth centered at 656.45 nm to eliminate unwanted wavelengths. A second achromatic doublet with a 100 mm focal length focuses the image on the camera (Figure 2 and Figure 3). Three fold mirrors are used to direct this beam to an 8-bit monochrome CMOS camera.

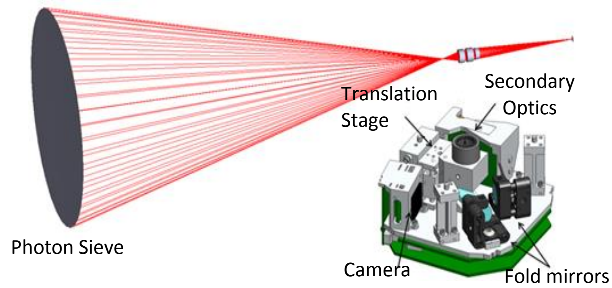


Figure 2: Zemax model of the optical system (left) and CAD model (right) of the optical platform

We used Zemax optical software to simulate images of the Sun as seen by FalconSat-7. Fig. 2a shows photo of the Sun taken on 2012/07/31 that is 0.14 degrees in angular size or 0.59 arcsec/pixel. This image was produced by the Solar Dynamic Observatory (SDO) and closely matches the FOV and resolution of the photon sieve imaging capabilities (0.139 deg, 1360 x 1024 pixels, 0.37 arcsec/pixel). This image was then used for Peregrine telescope performance analysis in Zemax software. This Zemax model included the effects of diffraction and aberrations through the photon sieve and secondary optics.

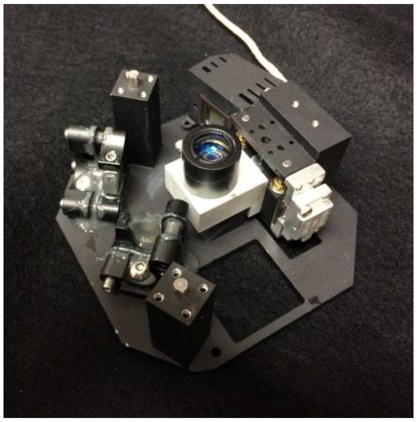
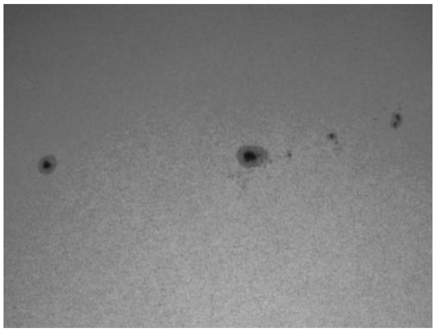
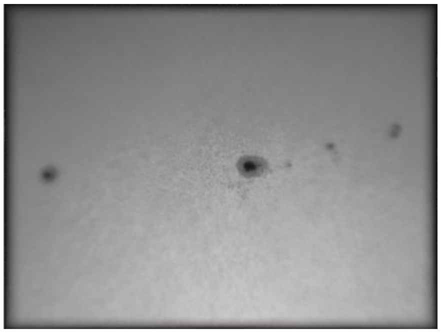


Figure 3: Satellite Optical Platform



(a)



(b)

Figure 4: (a) Image taken by SDO (b) Representative FS-7 image

The photon sieve is the heart of the optical system. The United States Air Force Academy has been working on photon sieve technology for the past 8 years. They are constructed on aluminum-coated polyimide films that are strong, rollable, and light. To create an image, 2.5 billion depressions are photolithographically etched on the surface forming images in essentially the same manner as a Fresnel lens. The pattern used for FS-7 is shown in Figure 5. To maintain diffraction-limited performance, the sieve must be flat to within about 10 times the wavelength of light. This constraint is significantly relaxed from the surface quality required for refractive or reflective optical elements, which must maintain a surface quality of about 1/10 of a wavelength. Despite this simplification to the surface quality requirement, the deployment of the photon sieve must be exceptionally precise for the optical system to produce high-quality imagery.

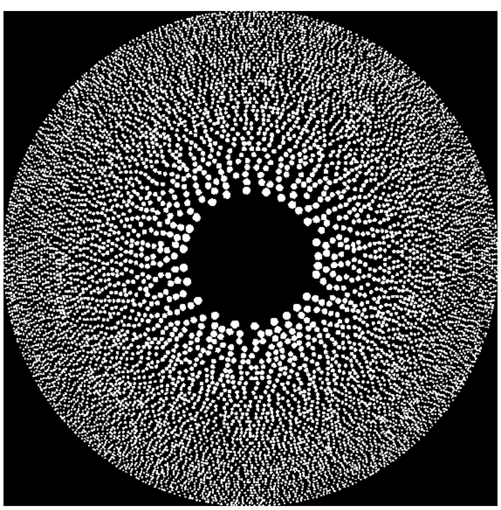


Figure 5: Photon Sieve Hole Pattern

Deployment subsystem

The FS-7 deployment system is based on a two-stage, spring-loaded deployment mechanism. This mechanism was designed to accommodate the volume and size constraints of the payload. In the first stage of the deployment system, the assembly moves linearly out of the bus. The second stage is held in place using three sequencing bars. Once the bottom of the assembly clears the top of the bus, the sequencing bars all disengage and allow the second stage of the deployment. During the second stage of the deployment 3 precision pantograph arms extend to their final position, putting tension on the photon sieve and ensuring high-quality imagery.

Because the deployment of the photon sieve is critical for meeting all of our operational objectives, the FalconSat 7 program relies on significant experimental validation of the system. This testing process has allowed the team to do hundreds of deployments to ensure that the characteristics of the deployment are known, and the program will be successful on orbit. The first of these tests started with the engineering model of the deployment system. This system was designed and built by MMA Design LLC in Boulder, CO in early 2012. During the summer of 2012, the system experienced dozens of deployments to understand the stowing process of the system, and how to repeatedly deploy the system to compare results. These deployments led up to a NASA Zero-G flight in August of 2012, more favorably known as the "Vomit Comet", Figure 6. This flight produced successful Zero-G deployments, proving to the team that the system works in a low gravity environment.

Figure 6: FS-7 Deployment tests in zero-G environment

After analyzing high-speed footage, the team was able to calculate the accelerations produced by each pantograph on each deployment. This demonstrated that the dynamics of the deployment system were very repeatable. Subsequently, the engineering model was tested in a vacuum demonstrating that aero-braking did not cause significant drag during deployments.

GROUND SEGMENT

The FalconSAT-7 ground segment uses the University Mobile CubeSat Command and Control (MC3) network running Neptune Common Ground Architecture (Neptune/CGA). This is Government Off-The-Shelf software developed by the Naval Research Laboratory (NRL) to provide a command and control software suite capable of supporting satellite development throughout the life cycle of integration and test, launch and early orbit commissioning, and nominal operations. Currently the FalconSAT-7 program is using Neptune/CGA extensively in the payload integration phase, but progress is underway in developing test suites for integrated satellite testing at the Air Force Institute of Technology, Dayton, OH. On-orbit operations of FalconSAT-7 using Neptune/CGA running on the University MC3 ground station network will be executed by the Naval Postgraduate School in Monterey, CA. The University MC3 is a network of fully autonomous ground stations located around the globe across the United States from Hawaii to Florida.

ENVIRONMENTAL TESTING

Before the flight version of FalconSAT-7 is launched, a lengthy environmental test campaign will be completed that is focused on first qualifying the payload and later the complete spacecraft. First, a qualification version of the payload will undergo a sequence of sine-sweep/random/sine-sweep vibration tests in a Cal-Poly Test-POD on AFIT’s MB Dynamics slip table shaker. These vibration tests are performed to determine if all of components in the payload can survive the harsh vibration environment expected during launch. Next, the payload will undergo thermal-vacuum (TVac) tests in which the payload will be exposed to high vacuum (1E-5 Torr) and a wide range of temperatures (-45C to +45C). The payload will be operated from the bus to ensure full functionality at all stages of the TVac tests to tests its performance in a space-like environment.

CONCLUSIONS

FS-7 is a novel approach to reduce the cost of imaging satellites while maintaining high-quality optical performance. It eliminates the need for solid glass primary optics enabling diffraction-limited imagery from a thin membrane. This proof-of-concept mission will demonstrate the potential of lightweight optical systems and open the door for inexpensive, novel applications in intelligence, astronomy, weather forecasting, and environmental monitoring.