FalconSAT-7: A Photon Sieve Solar Telescope

Geoff Andersen, Michael Dearborn and Geoff McHarg
USAF Academy

ABSTRACT

In the event of a sudden loss of space-based surveillance assets, a limited, rapidly deployed replacement system is desirable until more capable satellites can be built and launched. Cadets and staff at the USAF Academy are currently building FalconSat-7, a 0.2m diameter solar observatory to be deployed from a 3U Colony II CubeSat (10x10x30cm). While not optimized for ground observation, such a telescope would have a 1.8m resolution at an orbital altitude of 450km.

1. INTRODUCTION

The nation relies heavily on operations in space to include intelligence, surveillance, and reconnaissance satellites. This dependence on space operations is a vulnerability to the ability to execute missions. For example, in the event of a sudden, catastrophic loss of space-based surveillance assets, a simple, rapidly deployed replacement system would be desirable for rapid reconstitution. Here we present our design for a large aperture membrane telescope deployable from a small, inexpensive satellite. Beyond the obvious fabrication and launch cost savings there is the increased flexibility such instruments offer. We could potentially rapidly "re-seed" any critical gaps in space-based surveillance with ready-made satellites. These would provide a modest capability until larger, more complex assets can be launch under their longer lead-time.

Cadets and staff at the Air Force Academy in collaboration with others at NASA, AFIT and AFRL and with support from the NRO and DARPA, are constructing FalconSat-7: a 3U CubeSat solar observatory in low Earth orbit. The science payload is Peregrine: an innovative 0.2m diameter membrane primary occupying a mere 1.5U volume (Fig. 1). The modest project goals are to demonstrate the ability to:

1. Deploy a rigid boom structure that can support a membrane photon sieve flat to precise requirements
2. Capture images of the Sun with the photon sieve telescope and transmit them to the ground

The primary membrane is a photon sieve (PS) – a flat diffractive element that consists of billions of holes. The sizes and positions of each hole are configured such that transmitted light is diffracted to a focal plane where a CCD camera is located. The CubeSat platform will be a standard Colony II bus built by the Boeing Corporation and provided to the USAF Academy (USAFA) by the NRO. Peregrine will be investigated in two stages: The first is a laboratory prototype of the PS integrated with a deployed structure. The second is a flight model that will demonstrate full deployment and operation of a space-based photon sieve telescope from a CubeSat platform.

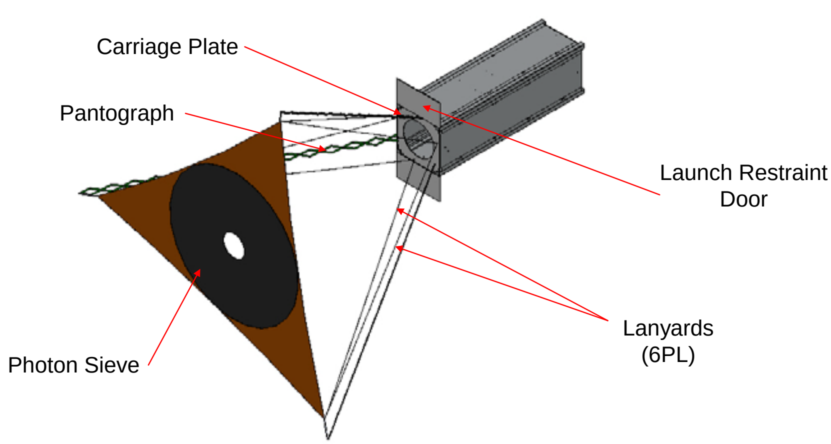

Fig. 1: Solid Works picture of Peregrine, a 0.2m photon sieve deployed from a 3U CubeSat.

Telescope technology has only incrementally improved in areal mass since the beginning of space-based imagery. For example, the Hubble Space Telescope has a mirror with 180 kg/m^2 while the James Webb Space Telescope has reduced this to just 25 kg/m^2 over a quarter of a century later. Not only is size an issue but the cost of fabricating surfaces to the high degree of precision results in telescope costs scaling roughly as the diameter to the power of 1.75. Added to this there is still the issue of packing large monolithic structures into limited launch vehicle volumes.

The membrane photon sieve has several advantages over that of a primary mirror or lens used in traditional imaging systems. First, the material is made on a flexible membrane that can be folded. This allows for deployed apertures with a diameter larger than the satellite bus. Second, the PS surface requirement is around two orders of magnitude less stringent than that of traditional optical surfaces. Third, the PS is extremely lightweight. With the use of polyimide membranes we are aiming at areal densities of 0.25 kg/m^2 – a game-changing 3 orders of magnitude improvement above current state-of-the-art. This comes along with similar savings in fabrication a materials cost.

2. PHOTON SIEVES

A photon sieve (PS) is essentially a Fresnel zone plate (FZP) in which the rings have been broken up into isolated circular holes. For an infinite conjugate, binary FZP of focal length at a wavelength λ, radial distance to the center of the nth bright zone is given by $r_n = 2nf\lambda + f^2\lambda^2$. In its simplest version, the PS consists of holes of diameter r_n located at the corresponding radial distance r_n. The holes can be distributed regularly or randomly in angle about the zone. It has since been found that the diameter of the holes can be increased to an optimum value of 1.514 times the underlying zone width, greatly relaxing the fabrication constraints.

We have investigated many types of photon sieve designs at USAFA. Early prototypes were created in chrome-coated quartz using electron-beam photolithography (Fig. 2). For a typical 4-inch diameter sieve with a 1m focal length there were up to 10 million holes ranging in size from 8-260 μm. Many different variations have been tested including those for multiwavelength operation and others configured to arbitrary conic constants. We have also investigated phase versions to increase the efficiency towards the theoretical limit of ~40%.

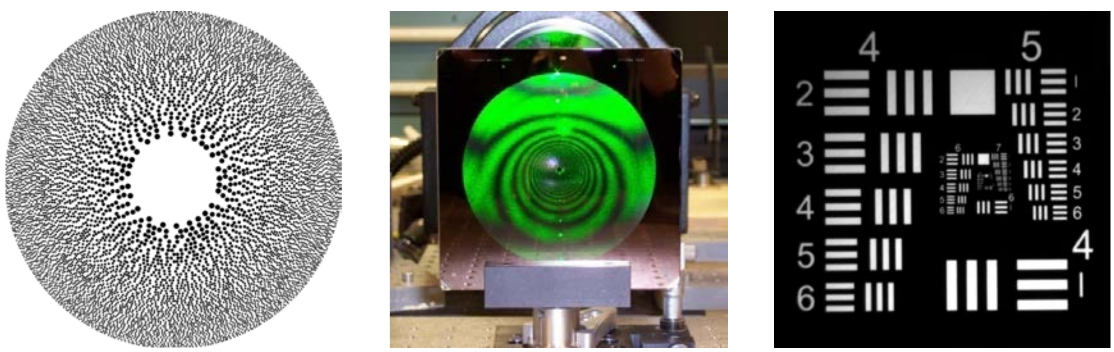

Fig. 2: Left: The central 0.01m diameter of the 0.1m sieve. Center: A photo of a quartz photon sieve under test with laser illumination. Right: High resolution imaging with the photon sieve.

Further research has led to photon sieves in flexible membrane substrates with the most recent prototypes being photolithographically patterned, aluminum-coated polyimide films that are strong, rollable and light. These membrane materials have demonstrated near-zero coefficient of thermal expansion (CTE), which is crucial for avoiding issues with pattern distortion in the changing thermal environment experienced in orbit.

Perhaps the most significant advantage for using a diffracting optic over either a refracting (lens) or reflecting (mirror) primary is that the substrate need not be pulled to an optical flatness. The height of the largest bump h can be calculated as $h < 8\phi(f/D)^2$. So for a transmitted wavefront error of λ/10, an f/2 photon sieve must have a flatness maintained to approximately 3λ. By comparison, the surface requirements for a reflector would be some 60 times more stringent. Along with the reduction in mass, this easing of engineering constraints is one of the major reasons for pursuing the photon sieve technology. The drawback, however, is the limited bandwidth.

The PS is a diffractive element and, as such, suffers from dispersion, which results in a wavelength dependent focal length. Using depth of focus considerations we find that images will remain in focus over a bandwidth given by $\Delta\lambda=2f\lambda^2/D^2$. Making the PS aperture size larger obviously provides better diffraction limited imaging. On the other hand, making the photon sieve larger decreases the optical bandwidth. For Peregrine (D = 0.2m, f = 0.4m, λ = 656.3nm) the bandwidth is only 8.6 picometers but for Solar observations there will be sufficient photon flux to permit imaging. Future missions aimed at Earth surveillance will include corrective optics to greatly improve the bandwidth.

We plan to fabricate the photon sieves in Novastrat polyimide manufactured by Nexolve. This material has been space-tested and can be chemically "tuned" to just about any desired CTE. Films of transparent polymer will be spun to a thickness of around 25 microns. While the surface deformation constraints are quite loose compared to conventional optics, we do have to ensure a high degree of thickness uniformity as the light will be transmitted through the substrate. Nexolve have demonstrated control to the thickness constraints necessary for our needs.

3. DEPLOYABLE STRUCTURE

The deployable system for Peregrine can be broken down into two major elements: the support structure and the deployment system. The support structure provides stability and stiffness to the membrane, while the deployment system releases the support structure in a controlled fashion and provides sufficient tension to keep it correctly positioned. The entire deployment must proceed in a predictable way that will not damage the PS. For Peregrine, the deployment system has a 6.8:1 expansion ratio, which is not generally difficult to achieve.

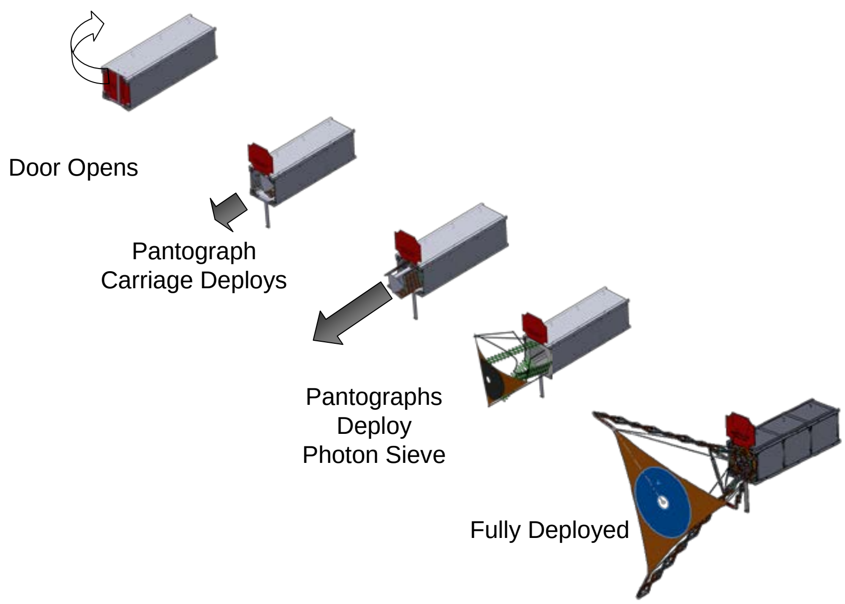

Fig. 3: The deployment sequence for Peregrine.

Peregrine has a support structure that deploys from a 1U volume and consists of the photon sieve membrane and six graphite lanyards that attach to the CubeSat bus, forming a hexapod structure that is 0.43 meters long when deployed. The deployment mechanism pulls the support structure from its stowed package to its deployed configuration with three spring-loaded pantographs. The pantographs are configured to provide loads that keep the membrane tensioned at all times. Fig. 1 shows the fully deployed Peregrine payload.

The truss and support structure are restrained for launch with two spring-loaded doors on the top surface of the CubeSat bus. To initiate the deployment sequence, a heater signal from the payload melts a release pin, freeing the doors to open. Once the doors are open a two-step deployment by strain energy occurs: *first* the support structure and deployment structure are moved in unison to the top surface of the bus, and *second* the trio of spring loaded pantographs deploys the support structure from its folded configuration to its deployed configuration. The deployment sequence for Peregrine is shown in Fig. 3.

To meet the photon sieve flatness and stability requirements the support structure must provide three support points to define the membrane plane. This limitation of the number of support interfaces can be met by selecting a determinate six-legged (graphite lanyard) tensioned truss system in a hexapod configuration. Meanwhile, the membrane must be stowed in a way that avoids forming permanent creases that are the result of small fold radii inducing deformations beyond the yield stress and can be eliminated by several possible folding arrangements. We are planning to incorporate a "coffee filter" assembly that fits loosely within two concentric containment tubes in the launch configuration and there is a hole in the center of the membrane to prevent creases at the center.

4. CAMERA AND ELECTRONICS

We will use a commercial camera for the focal plane array. Use of a commercial camera will keep costs low at the risk of flying hardware that has not been space-rated. Another advantage of using a commercial camera is that the control electronics for the camera are integrated with the camera itself and alleviates the requirement to develop new software for FPA access and control. At USAFA, we have a microprocessor payload control board that has successfully flown on orbit and we will use this to interface the payload with the bus. USAFA also has a wealth of experience with these electronics and the electronics and camera system for the payload is seen as low risk.

The payload electronics must provide command and control (C&C) of the payload subsystems, as well as data handling. These subsystems will include a minimum of two cameras, a framegrabber, opto-mechanical stages, and deployment system. One small auxiliary spy-type camera will be located within the satellite to observe the support structure and membrane. This camera will provide information on the manner in which the structure was deployed as well as providing the ability to visually diagnose the state of the membrane on a regular basis.

The second camera is the main imaging device at the focal plane of the telescope. The imaging camera will require the ability to accept changing image-capture requirements such as frame rates, exposure times, pixel binning and bin-shifting. The electronics will also require the ability to store anything from single images to multi-frame video. While on-board image processing may be beyond the scope of this first effort, we will investigate the current state-of-the-art systems to evaluate this possibility.

The other electronic systems are for control of micromechanical stages that can be used to reposition secondary optical components. While it is hoped that all the optics will be correctly aligned at launch and remain so throughout the mission lifetime, there are many factors which may cause misalignments including vibrations, thermal distortions and an incorrect positioning of the membrane on deployment. To correct for this we anticipate the need to adjust all the optical components in tip/tilt, decenter and defocus to optimize image performance. Mostly this is seen as a set-and-forget procedure but the electronics will have to have this flexibility.

CONCLUSION

The Air Force Academy is constructing FalconSAT-7, a solar telescope deployed from a 3U CubeSat. The telescope incorporates a 0.2m diameter membrane photon sieve deployed from a compact folded package. This satellite serves as a valuable teaching tool as AF cadets work on every facet of the design, build, launch and operation. Launch is scheduled for sometime in 2014 and we see this technology as a potential game-changer in space surveillance for both ultra-small and ultra-large applications.

ACKNOWLEDGEMENTS

We wish to acknowledge the support and contributions from the National Reconnaissance Office, the Defense Advanced Research Program Agency and the AF Office of Scientific Research.