FalconSAT-7, A Deployable Membrane Optic Telescope

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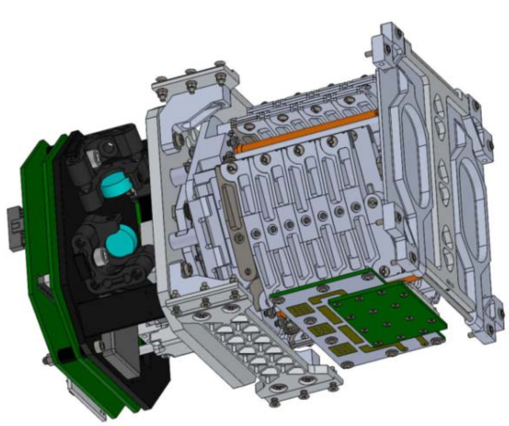
ABSTRACT

We report on the development of the flight model of FalconSAT-7 (FS-7), a 3U CubeSat with a deployable diffractive membrane solar telescope. The program is managed by undergraduate cadets at the Air Force Academy and is supported by graduate students at the Air Force Institute of Technology. The purpose of the mission is to demonstrate a deployable telescope with an aperture significantly larger than the spacecraft structure. The primary element deploys from one end of FS-7 and has a clear aperture of 20 cm, twice the cross-section of the host spacecraft structure. This novel payload is made possible by use of a thin (28 µm) membrane optic using diffractive principles to focus H-alpha light from the Sun onto an onboard camera. The diffractive optic is deployed using a set of spring-loaded pantographs that tension the membrane and hold it flat. The Colony-II program office provided the 3U bus that is built by the Boeing Company. The FS-7 mission is supported by the Defense Advanced Research Projects Agency (DARPA)'s Tactical Technology Office. The Air Force Academy plans to deliver FS-7 to the Space Test Program for launch integration in late 2015 and expects FS-7 to launch on STP-2 in the spring of 2016.

INTRODUCTION

Conventional high-resolution optical imagery typically requires large diameter primary optics. These optics drive the size, weight, and subsequent cost of imaging satellites. As we previously discussed at the Small Satellite



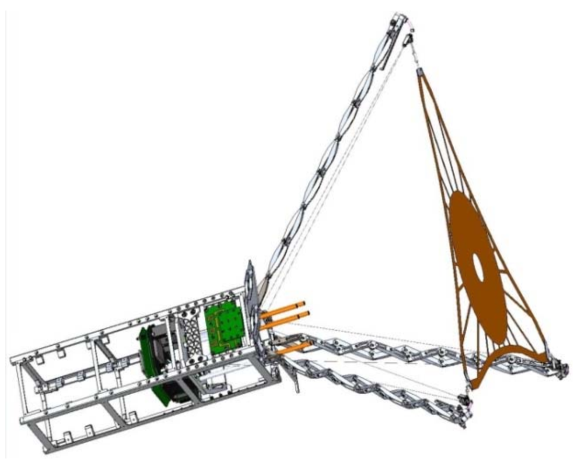


Exhibit 1: Stowed (1.5U) and deployed Peregrine payload schematics.

Conference in August 2014[i], FalconSAT-7 (FS-7) is an innovative approach to perform space-based imaging with a deployable membrane optic as its primary optic. FS-7 seeks to be the first-ever on-orbit demonstration of a deployable telescope on a CubeSat platform. The entire FS-7 payload, which we refer to as Peregrine (Exhibit 1), consists of optical, deployment, and control subsystems, and fits within one half of the satellite volume (10 cm × 10 cm × 15 cm). The remaining half of the satellite provides power, pointing, and communications with the ground control system.

Use of a diffractive optic membrane as a primary optic for a space-based telescope offers several distinct advantages, as summarized in this paper. Other papers may be referenced for further detailed discussion and analysis of photon sieves[ii,iii,iv]. First, diffraction limited performance can be achieved with extremely lightweight polyimide sheets that can be gently rolled and folded into compact volumes and then unfurled on orbit. On FS-7, the membrane itself has a mass of less than 1.75 g and can be stowed into a volume of less than 160 cm^3. Since the volume in which the membrane is stowed becomes part of the optical path for the fully deployed telescope, there is very little wasted space. Second, because the primary optic is deployed on orbit, the telescope's collection aperture can be much greater than the cross-sectional area of the spacecraft. On FS-7, the primary optic is 20 cm in diameter, twice the 10-cm cross-section diameter that could be achieved with a traditional reflective primary placed on a CubeSat. This results in four times the in-band light collection and twice the resolution of a traditional optic. Larger satellites could conceivably achieve even larger disparity between primary optic diameter and spacecraft size. Finally, diffractive optic membranes have much less stringent surface requirements. Traditional mirrors have to be polished with incredible precision, requiring roughly $\lambda/10$ accuracy across their surface, while diffractive optics can achieve diffraction limited imaging performance with a flatness requirement of 10 times the design wavelength. Additionally, a diffractive optic membrane is an optical flat, rather than the curved surface of a traditional optic.

Notably, one must contend with certain disadvantages that must be understood and mitigated when using a diffractive optic membrane. To begin with, diffractive focusing comes with significant wavelength dispersion. As a result, a telescope must be designed with dispersion correction or one must accept a telescope with a narrow useful wavelength. Since FS-7 is a proof-of-concept demonstration with significant volume constraints, FS-7 is designed to image the Sun at the hydrogen alpha (H_α) line, 656.4 nm, and includes no dispersion correction[v]. Additionally, the optical efficiency of a diffractive optic is less than that of a traditional optic, with a theoretical limit of ~40 percent. With the addition of a narrowband filter to reject the unfocused wavelengths, the overall system efficiency can drop to less than 10 percent.

MISSION SUCCESS CRITERIA

The FS-7 program is targeting five key mission success criteria. First and foremost the goal of FS-7 is education. The United States Air Force Academy (USAFA) and Air Force Institute of Technology (AFIT) use this program as a tool to teach students the technological and programmatic hurdles involved in space system development and research using space platforms. 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. A successful deployment will place the photon sieve at the expected location with no significant snags or tears. The next mission objective is to collect and transmit to the ground at least one image of 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 optimize and characterize image performance. This includes controlling camera integration time, focus, and gain. The final mission goal is to demonstrate flight heritage of the polyimide photon sieve material. To accomplish this goal, solar imagery collected immediately after deployment on orbit would be compared to imagery collected 30 days later to analyze the long-term degradation of the membrane optic.

OPTICAL SUBSYSTEM

The Peregrine membrane primary is an *f*/2, 20-cm diameter photon sieve[vi]. A photon sieve is essentially a Fresnel zone plate in which the diffraction rings are broken up into a multitude of individual holes or cylindrical bumps. The Peregrine photon sieve consists of more than 2.5 billion cylindrical bumps etched from a 28-micron thick Kapton sheet. The bumps vary in diameter from 2 to 277 µm with the largest near the center. In the case of FS-7, the diffractive optic is a phase-type with a 50-percent fill factor, having a 38-percent theoretical focusing efficiency.

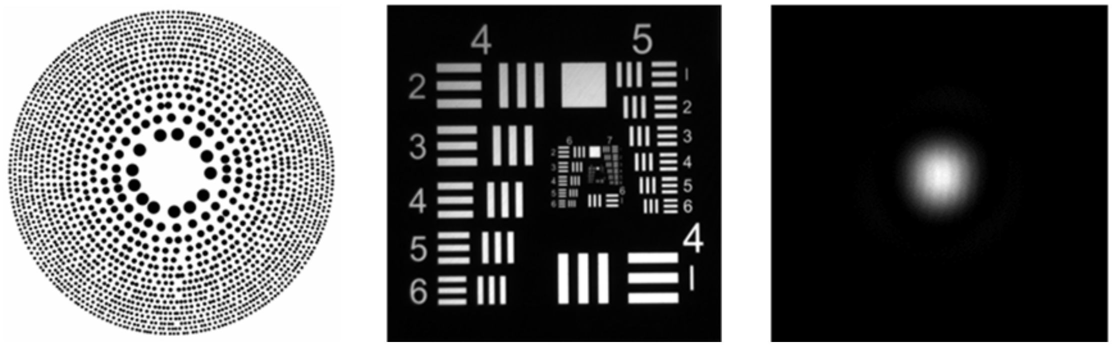


Exhibit 2: Magnified image of photon sieve (left) to produce diffracted images (center) and focal spots (right).

The secondary optics of the photon sieve telescope (Exhibit 3) collimate the focused beam from the photon sieve for transmission through a narrowband H-alpha filter (1.5 angstroms FWHM, 35-percent peak transmission) and provide a magnification of around 6. A Zemax analysis indicated less than 1.25-percent of the total incident light energy appears as stray light at the FPA. Reflecting through three fold mirrors, the beam illuminates a 10-bit monochrome CCD camera. The secondary elements are mounted to an electronically controlled translation stage with encoder providing 8 mm of travel in increments of 1.5 nm. This variable focusing capability allows for the ability to compensate for changes in focal length of the photon sieve caused by thermal or creep effects.

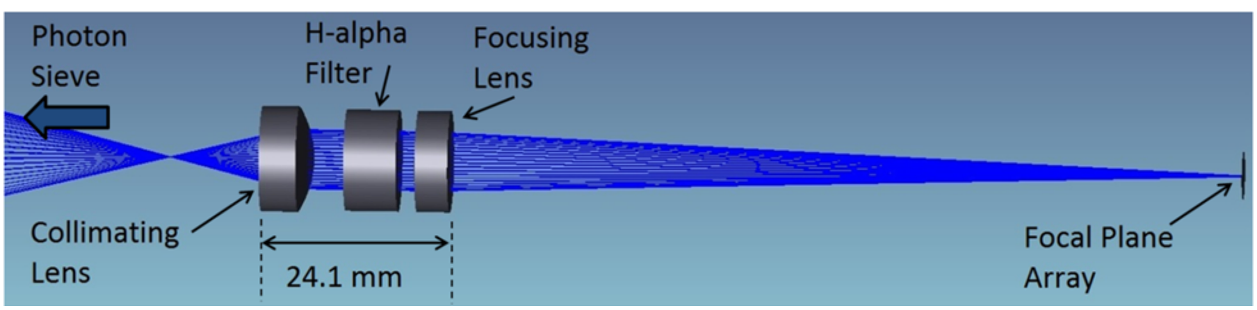
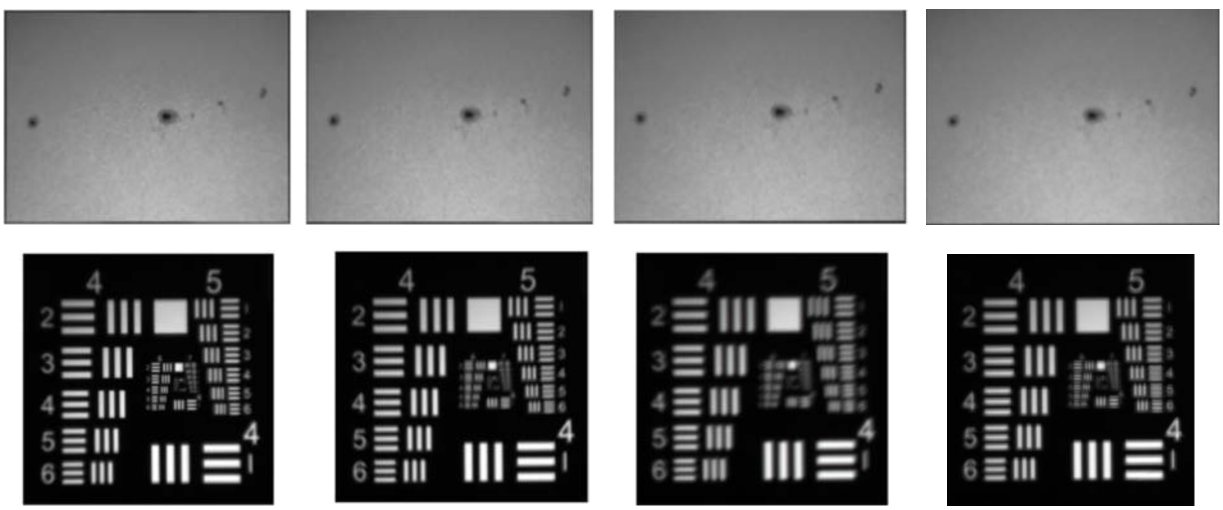


Exhibit 3: Peregrine telescope schematic. Focused light from the photon sieve (at left, not shown) passes through two lenses and filter. The collimated beam is approximately 10 mm in diameter, and the final focal distance from the second lens to the camera focal plane is about 100 mm. The three fold mirrors after the final lens are not shown.

In July 2014, we completed environmental testing on our qualification model according to the General Environmental Verification Specification (GEVS). After environmental testing, we demonstrated successful imaging with the qualification model optical system. We have some concern regarding high temperature (> 55^o C) and the functioning of our payload camera. High temperature did not cause our camera to fail, but poor imaging performance is expected while the optical platform has a temperature above 55° C. Therefore, we plan additional thermal testing using a solar simulator at AFIT to determine whether the optical platform temperature can be expected to rise to an unacceptable level while imaging the sun. If so, we will adjust our concept of operations to limit the amount of time FS-7 remains pointed at the sun.

We conducted a theoretical analysis to predict imaging performance under various deployment scenarios. In Exhibit 4, simulated images of sunspots and of a resolution target are shown for several cases. Left-most is a diffraction limited image. Based on repeated deployment testing, minor mechanical variations in the deployment system are expected. The 2nd set of images models a small amount of tilt in the photon sieve due to expected variability in the deployment mechanism. While we have greatly mitigated any chance of snagging or tearing of the photon sieve during deployment, tearing is still possible during deployment. Based on our modeling, minor tears would have almost no effect on imaging, but the 3rd set of images models a large tear, where a full gore has been separated. The gores are the thin ribs in the membrane that hold tension on the central diffractive surface and keep the optic flat. The last set of images shows a significant 1.8 degree tilt in the photon sieve, the maximum tilt for which our optical system will focus the far field on the focal plane array without clipping. Even under extreme cases, we expect sufficient image quality to be able to complete our mission goal to optimize and characterize imaging performance.



Diffraction limited RMS 0.002 | 0.19° tilt of PS RMS 5.3 | Missing gore | 1.8° tilt of PS

Exhibit 4: Simulated images of the Sun based on FS-7 expected performance: a) Diffraction limited performance; b) Based on deployment repeatability testing, 0.19° tilt in the primary optic; c) Based on worst-case-scenario deployment testing, tearing of a gore of the membrane is possible during deployment; d) 1.8° of tilt in the photon sieve is the maximum tilt error before clipping will occur.

The photon sieve that was patterned by NeXolve for FS-7 has bumps of 0.13-0.31 µm height, with dimpled depressions in the center of each bump, rather than the 0.47 µm-high cylindrical plateau-shaped bumps that were expected by design. As a result, the actual focusing efficiency of the primary optic on FS-7 has been measured in the laboratory to be ~1.5 percent. This is not a "show-stopper," as radiometric analysis indicates that an image SNR of greater than 10 can be achieved with a 160 ms exposure of the sun. The pointing control of C2B is expected to be sufficient to allow 160 ms exposures without motion blur. After completing our mission to image the sun, we had hoped to use FS-7 to image the surface of the moon, but due to the extremely long exposures that would be required, we no longer anticipate being able to complete that ambitious goal.

The photon sieve on FS-7 is expected to degrade once deployed in low Earth orbit and exposed to atomic oxygen. Previous experiments by Shimomura and Nakamura have measured the degradation of Kapton, the material used for the FS-7 photon sieve, as a result of atomic oxygen erosion in low Earth orbit[vii]. As the bumps in the diffraction pattern of the photon sieve are etched away, the diffraction efficiency of the optic is expected to decrease. We estimate that once we have 10-percent degradation of the photon sieve due to atomic oxygen (either 2 μm from the flat surface or .05 μm of the height of the bumps on the diffraction patterned surface), diffraction efficiency may be too degraded to continue imaging. FS-7 is expected to launch into an elliptical orbit with 300 km perigee and 720 km apogee. At apogee, atomic oxygen density is low, but at perigee atomic oxygen degradation may be significant. Based on the expected orbit for FS-7, atomic oxygen density as a function of orbit altitude, and previous experiments measuring Kapton degradation by atomic oxygen in low Earth orbit, we analyzed the maximum life expectancy of the FS-7 mission after atomic oxygen degradation. The photon sieve was assumed to always have its flat side ram facing. Using the Satellite Tool Kit (STK) we estimated that the ram flux of atomic oxygen on the photon sieve would be $8.79 * 10^{21}\ \mathrm{atoms/m^2}$ per day. According to Shimomura and Nakamura, we can expect $3.2 * 10^{-21}\ \mathrm{mg/atom}$ of Kapton loss due to atomic oxygen. Given Kapton's density of $\rho = 1.413 * 10^{9}\ \mathrm{mg/m^3}$, we expect approximately 20 nm per day would be etched from the flat side of the photon sieve, potentially limiting the lifetime of FS-7 to 100 days after deployment. Only thermal flux is expected on the patterned side of the sieve. With thermal flux calculated to be $3.50 * 10^{19}\ \mathrm{atoms/m^2}$ per day, we expect .08 nm per day of Kapton loss on the patterned side, potentially limiting the lifetime of FS-7 to 625 days. We are therefore confident that the photon sieve will survive atomic oxygen exposure long enough to complete all mission success criteria.

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, three 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 FS-7 program relies on significant experimental validation and tests of the system. The deployment system was designed and built by MMA Design LLC in Boulder, Colo., in early 2012. During the summer of 2012, an engineering model was subjected to dozens of deployments in a 1-G environment to optimize the mechanical design and stowing procedure to achieve the most reliable and repeatable deployments possible. In August 2012, the engineering model was further tested on NASA's G-Force One aircraft, more commonly known as the "Vomit Comet." On this flight, the FS-7 team demonstrated six successful micro-gravity deployments (Exhibit 5), giving us confidence that the deployment system would work on orbit as well as in 1-G. A qualification model was further subjected to over 50 deployments. Throughout testing, additional improvements to the deployment system were made to mitigate the risk of tearing and snagging of the membrane during deployment. Testing culminated with 13 successful upright deployments in a row of the final qualification model design, including two deployments conducted during environmental testing in July 2014. In October 2014, MMA completed the flight model deployment system and, with the FS-7 team, conducted two deployment tests of the flight model system, both of which were fully successful.

Exhibit 5: FS-7 Deployment tests in zero-G environment

CONTROL SUBSYSTEM

The Peregrine payload electronics provide command and control (C&C) of the payload and data handling between the payload and bus. C&C requirements include activation of the payload deployment system, operation of the main CCD camera and inspection camera, temperature sensor monitoring, and control of the translation (focusing) stage. Payload command and control electronics have been developed in-house at the US Air Force Academy and packaged onto two printed circuit boards, each less than 82 mm x 82 mm and less than 1.5 cm high. The remainder has been purchased as commercial-off-the-shelf components with some repackaging to fit the restrictive form factors of a CubeSat. Payload electronics on the qualification model successfully passed all functional testing conducted after environmental testing in July 2014.

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 FS-7 program is using Neptune/CGA extensively in the payload integration phase. The Air Force Institute of Technology, Dayton, Ohio, conducted integrated satellite testing to verify control of the satellite via the MC3 Network to include successful download of images from the payload camera. Naval Postgraduate School in Monterey, Calif., plans to execute on-orbit operations of FS-7 using Neptune/CGA running on the University MC3 ground station network. The University MC3 is a network of fully autonomous ground stations located around the globe across the United States from Hawaii to Florida.

FUTURE RESEARCH

A successful flight of FS-7 would open the door to many areas of future technology and development. The next step in deployable optics would be to scale the FS-7 concept to a more operationally useful aperture size, such as a 1-meter diameter diffractive optic on satellite designed for the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adaptor (ESPA) ring (maximum mass: 180 kg). As with FS-7, the photon sieve of an ESPA class satellite would be expected to have a primary optic diameter of roughly twice the spacecraft's cross section, though a point design for such a satellite has not yet been completed. With an optic of that size, from low Earth orbit (300km), the resolution of images of the ground would be ~0.25 meters. For comparison, TacSat-3 had a mass of 400 kg, a primary optic diameter of .76 meters and ground resolution of 0.3 meters.

While the narrowband design of FS-7 can actually be an advantage for certain missions such as laser remote sensing and laser communications, where out-of-band rejection increases SNR, for most remote sensing missions, larger bandwidth collection would be highly desirable. With the inclusion of a secondary diffractive element in the optical system, as shown in Exhibit 6, it is possible to increase the bandwidth by orders of magnitude. An initial analysis suggests that a broadband version (~10 nm bandwidth) of the FS-7 telescope would require a 6U CubeSat bus to provide sufficient space for additional optical elements. Future research is needed to establish the trade space by which designers can balance bandwidth with optical system size, weight, and cost.

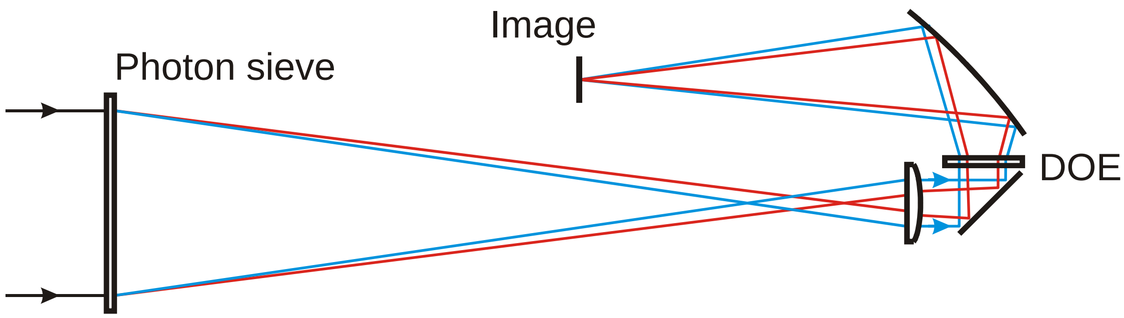


Exhibit 6: Broadband diffractive optic telescope concept using a secondary diffractive optic element (DOE) for chromatic aberration correction.

The US Air Force Academy also intends to pursue research into phase or intensity apodization using modified photon sieve patterns. Potential alternate patterns are shown in Exhibit 7. A simple variation in the fill factor with radius, as shown in the center image of a Gaussian density profile, would allow for improved resolution (albeit with a trade-off in contrast). Alternatively, by changing the intrinsic geometry of the pattern to a spiral, it is possible to invert the point spread function to a “donut” mode. Light from an object in the center of the field of view would not be focused on the camera by this diffraction pattern, while light from objects off-center would be efficiently imaged. This type of pupil engineering may enable observation of faint companions to bright objects. Already, such approaches are gaining support for exoplanet imagery, but it may be equally applicable to detecting small, faint companion satellites near large, bright satellites in Earth orbit.

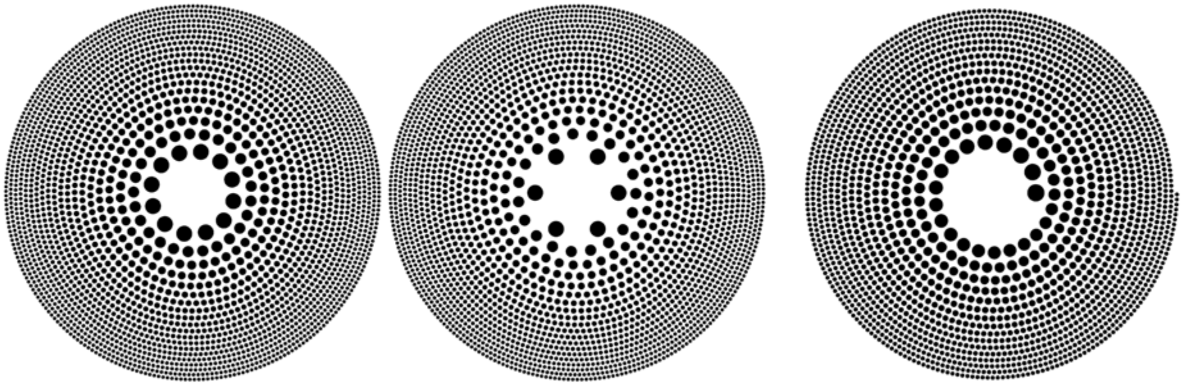


Exhibit 7: For intensity apodization, a standard photon sieve (left) can be modified to a Gaussian density profile (center) or spiral configuration (right) for different imaging properties.

Although FS-7 is designed to work in the visible portion of the spectrum, photon sieves can be easily designed to work in the infrared and ultraviolet, as well. With appropriate choice of substrate for the membrane, the diffractive optic pattern of a photon sieve can be modified for virtually any wavelength. In particular, USAFA intends to explore the utility of photon sieves for infrared sensing applications, including photon sieve designs to simultaneously focus two infrared wavelength bands separated by up to 1-2 µm.

The last area of future research USAFA intends to pursue regards contamination or degradation of photon sieves by spacecraft thrusters. FS-7 includes no on-board thrusters, but future space-based remote sensing satellites would benefit greatly by having propulsion systems for orbit adjustment. Analysis and testing will need to be conducted to explore the effects that spacecraft thrusters, including chemical, cold-gas and electric propulsion systems, would have on deployed photon sieve lenses. Because a photon sieve is deployed externally from the spacecraft body, contamination by spacecraft thruster exhaust may be significant and could increase degradation of photon sieves, either by etching or coating the sieve material.

CONCLUSION

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 by enabling diffraction-limited imagery from a thin membrane. This proof-of-concept mission seeks to demonstrate the potential of lightweight membrane optical systems and open the door for inexpensive, novel applications in intelligence, space situational awareness, astronomy, heliophysics, weather forecasting, and environmental monitoring. Flight model assembly has begun and is on track to be integrated for launch on STP-2. Analysis and testing to date gives the FS-7 team confidence that we have everything in place for a successful mission. Several avenues for follow-on research have been suggested to continue development beyond the FS-7 proof-of-concept mission toward larger, highly capable photon sieve satellites.

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