FalconSAT-7: Towards rapidly deployable space-based surveillance

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1. ABSTRACT

The USAF Academy Department of Physics is building FalconSAT-7, a membrane solar telescope to be deployed from a 3U CubeSat in LEO. The primary optic is a 0.2m photon sieve – a diffractive element consisting of billions of tiny holes in an otherwise opaque polymer sheet. The membrane, its support structure, secondary optics, two imaging cameras and associated control/recording electronics are all packaged within half the CubeSat volume. Once in space the supporting pantograph structure is deployed to pulling the membrane flat under tension. The telescope will then be steered towards the Sun to gather images at H-alpha for transmission to the ground. Due for launch in 2015, FalconSAT-7 will serve as a pathfinder for future mission in lightweight, high-resolution space-based surveillance. We are currently investigating two possible options optimized for Earth observing and SSA. Our preliminary designs have a 0.3m aperture deployed from a 6-12U satellite. Such a telescope would be capable of providing sub-meter resolution of ground or space-based objects depending on the orbital characteristics.

2. INTRODUCTION

Surveillance imagery can always benefit from larger primary apertures, but physical limits are now being reached on the size of monolithic (or even segmented) reflectors that can be put in orbit. Ensuring a diffraction limited surface is one issue, but more fundamentally, there are limits on the mass and volume of satellites imposed by launch vehicles. This is reflected in the plot of current and past commercial and scientific space telescopes shown in Fig. 1 (blue). In order to break this trend, we are investigating the possibility of membrane diffractive optics, where the surface requirements are greatly relaxed and the primary can be compacted into a very small volume. New missions based on this technology will make it possible to significantly reduce cost, with apertures (and hence resolutions) previously thought unobtainable (Fig. 1, red). Furthermore, with high packing ratios we can begin to construct extremely compact satellites that are simple to manufacture and launch in large numbers with short lead times.

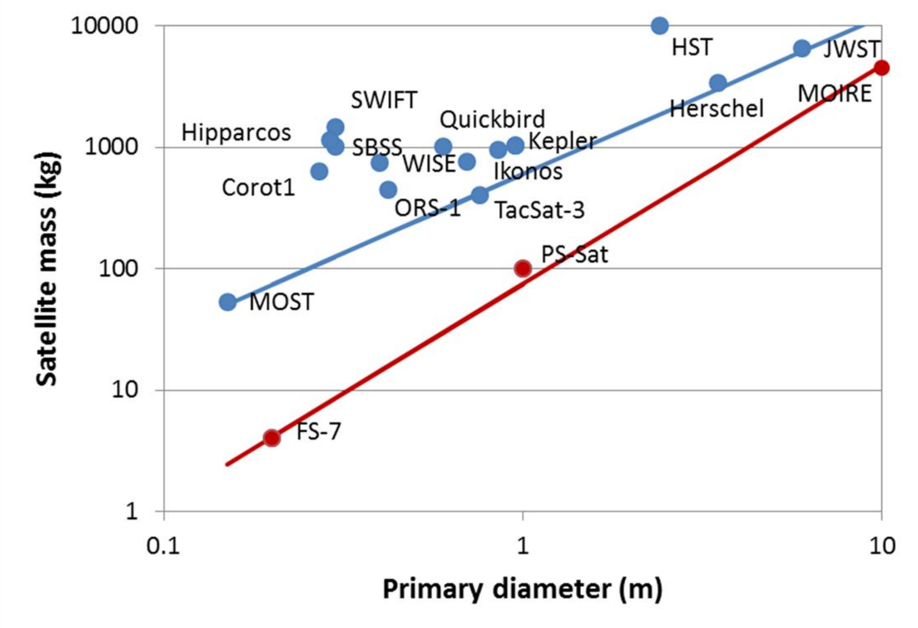

Fig. 1. A plot of current space telescopes (blue) compared to planned satellites using diffractive membrane primaries (red).

3. PHOTON SIEVES

Diffractive optical elements (DOEs) rely on extremely small features to focus light by direct modulation of the amplitude and/or phase of the incident wavefront. One such DOE is the Fresnel Zone Plate (FZP) discovered almost 200 years ago [1]. A FZP of focal length f can be constructed by locating n transparent circular zones on an otherwise opaque substrate at radial distances r_n given by:

$$r_n = 2nf\lambda + n^2\lambda^2 \tag{1}$$

A slight modification of the FZP is the photon sieve [2-9]: made by breaking the concentric rings up into individual holes of the same diameter as the underlying zones. The photon sieve has some advantages over the FZP including a simpler design and construction, apodization control and (under most circumstances) improved resolution and contrast. We have constructed and tested many types of photon sieves [5-7] at various wavelengths and F-numbers as well as experimenting with many different configurations including:

1. Amplitude/intensity and phase modulation
2. Rigid substrates (chrome coated quartz) as well as flexible membranes (Diazo, CP-1, polyimides etc)
3. Regular (equal area) and apodized fill
4. Parabolic and hyperbolic conic prescriptions
5. Anti-hole and higher-order diffraction designs

We have shown that it is possible to construct large photon sieves with millions of holes giving diffraction limited imaging suitable for large telescopes (Fig. 2). Further work included construction of such photon sieves on polyimide membranes. The key advantage here is that DOEs do not require a perfectly flat surface to give perfect imaging. In fact, the largest permissible surface error h to achieve a particular phase error ϕ is given by:

$$h < \frac{8\emptyset f^2}{D^2} \tag{2}$$

Thus where a typical mirror requires a surface good to λ/20, we can relax this to 1.6λ for even an F/2 DOE.

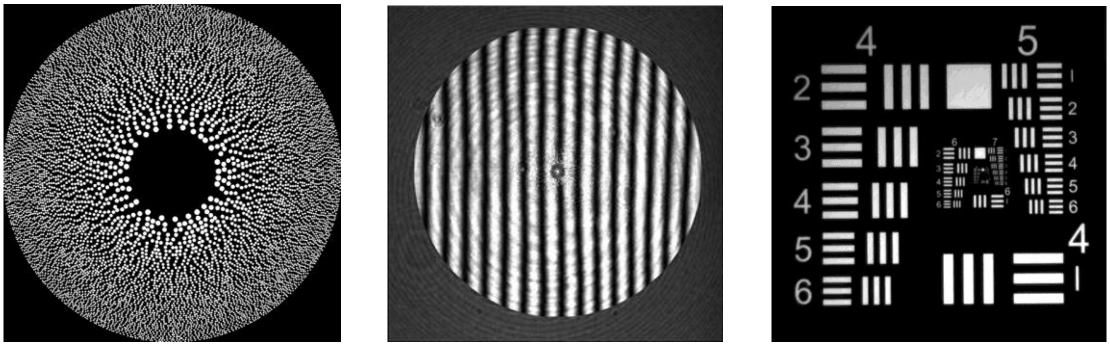

Fig. 2. Images of the central portion of the photon sieve (left), interferogram of the focused wavefront (center) and imaging performance (right).

The one significant trade-off in using DOEs is a reduced bandwidth. From Equation (1) we can see that due to dispersion, the focal length depends heavily on the wavelength of light chosen. As such, zone plates are typically limited to narrowband focusing or imaging applications. Allowing for depth of focus considerations, we can find that the bandwidth for diffraction limited imaging is given by:

$$\Delta\lambda \sim 2\lambda^2 f/D^2 \tag{3}$$

We have shown it is possible to improve the bandwidth of the overall telescope by including a secondary HOE into the design, but it is difficult to extend this beyond a few tens of nanometers to permit true multispectral imaging. As a result, the use of diffractive primaries may be restricted to high resolution, greyscale imaging only.

4. FALCONSAT-7

In the Department of Physics of the US Air Force Academy we are constructing a Solar CubeSat telescope using a membrane photon sieve. The satellite is 3U in size (30cmx10cmx10cm), with half the volume occupied by command, control, avionics etc. The scientific payload occupies the other half (Fig. 3) and consists of:

1. 20cm polyimide membrane photon sieve
2. Support structure consisting of an aluminum hexapod and polyimide lanyards
3. Secondary optics, focusing stage and CCD “science” camera
4. Imaging control electronics (storage, focusing control, image manipulation etc)
5. Secondary “inspection” camera

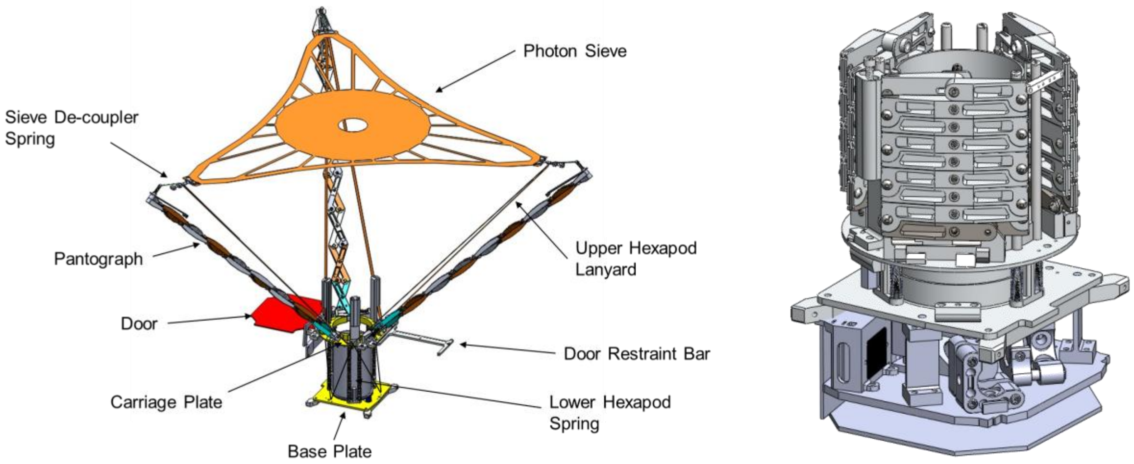

Fig. 3. A schematic of the support structure with membrane (left). The stowed configuration (right) has the photon sieve packed in the central tube (not shown) with the secondary optics and camera located on the lower platform.

When in orbit, a current is activated to melt a retaining wire allowing a spring-loaded door to open. This permits the pantograph structure to extend, deploying the photon sieve membrane under tension. The photon sieve is configured to focus light down the center of the satellite to secondary optics (lenses, filters and fold mirrors) and onto a CCD camera. Some focusing is made possible by the inclusion of an electronically controlled stage holding the secondary lenses. The photon sieve and telescope has the following design characteristics:

Photon sieve	**Value**
Diameter	0.2m
Focal length	0.4m
Wavelength	656.45nm (H-alpha)
Thermal coefficient of expansion	$<20\times10^{-6}$
Thickness	20 microns
Number of holes	2.5 billion
Hole size range	2-277 microns
Telescope	
Angular resolution	4 μrad
Exposure time	2.3 msec
Diffraction limited field of view	0.01 degrees
Diffraction limited bandwidth	0.01 nm
Primary tip/tilt allowance	1.2 mrad
Primary decenter allowance	0.5 mm
Solar resolution	600 km

We have constructed an optical model of the system and generated the expected images of the Sun and Moon as shown in Fig. 4. Photometric calculations show that there is sufficient photon budget for imaging the Sun and Moon but it is unlikely the signal to noise will be high enough for terrestrial imaging given the orbital constraints. We are planning a follow-on 6U CubeSat mission that should make it possible to achieve sub-meter resolution of the Earth.

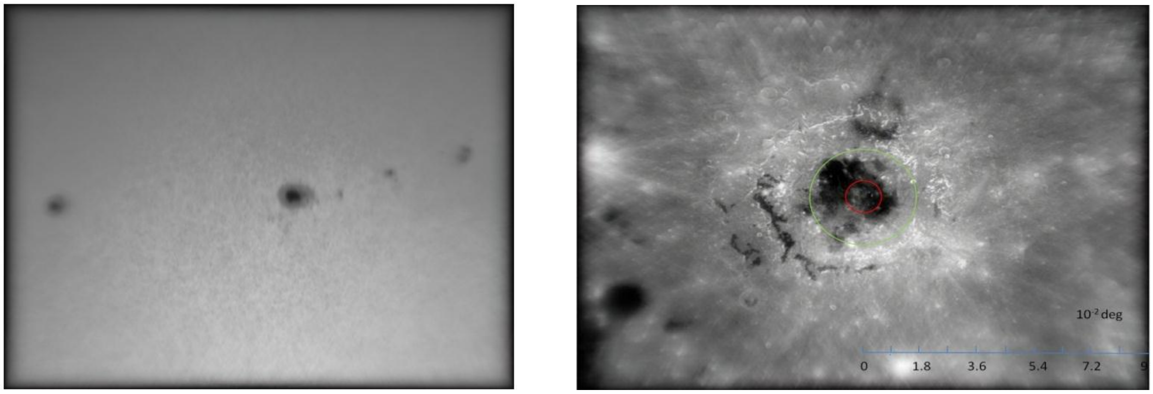

Fig. 4. Predicted images of the Sun and Moon with FalconSAT-7 generated by computer modeling of the optical system.

As well as the optical design, we have created static and dynamic models of the deployment structure and membrane to predict on-orbit performance. For example, our thermal modeling has shown that the membrane will experience thermal cycling in the range of 250-350K. This will result in dimensional changes in the membrane that cause changes in the imaging characteristics. We had initially planned on using Novastrat, a near-zero CTE polyimide, as the substrate material, but mechanical tests have shown this to be too brittle to survive our deployment process. Instead we are now looking into Kapton that has greater elastic strength but with an increased CTE which will restrict imaging to a 10 minute window in each orbit. Many such studies and trade-offs are being finalized in order to have a flight model constructed in early 2014 for launch in 2015.

5. CONCLUSION

The USAF Academy Department of Physics is constructing a FalconSAT-7: a world's first CubeSat solar membrane telescope. The payload consists of a deployable structure, pulling taut a photon sieve patterned on polyimide material. We are currently finishing the construction of the flight model for launch sometime in 2015.

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