



# Membrane diffractive space telescopes

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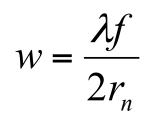
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### **Photon Sieve**

- Essentially a Fresnel Zone Plate with rings broken up into individual holes
- In simplest version holes are same diameter (d) as ring width (w)

$$r_n^2 = 2nf\lambda + n^2\lambda^2$$

- Can be randomly or regularly distributed with angle
- Can have any density (fill) in each zone as desired



# **Thermal Distortion**

- In-plane stretching or shrinkage of the substrate will move the holes locations off the zones
- Due to substrate itself or the support structure
  Not simply a matter of finding a zero CTE polymer
- For a given  $CTE(\alpha)$  there will be a shift in the position of the outer ring of  $\Delta r$ :

 $\Delta r = \alpha . r . \Delta T < w/10$ 

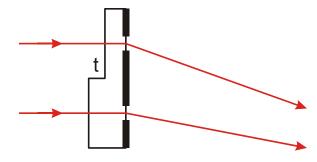
• Typically in the order of  $10^{-6} \circ C^{-1}$ 

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# **Thickness Variation**

- Sieve surface may be flat but the phase of the input wavefront is affected by substrate thickness variations
  - Problem for transmissive photon sieves
- OPD between any two zones depends on material thickness, t and refractive index, n:

OPD = t(n-1)

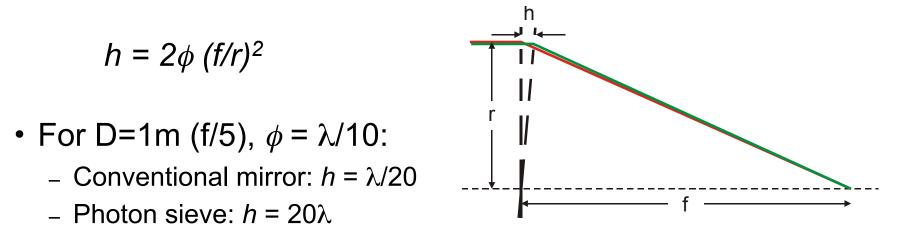


• Max thickness error for n = 1.45:  $\lambda/10$  : t < 0.22 $\lambda$  (0.11 microns)

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# **Mechanical Deformation**

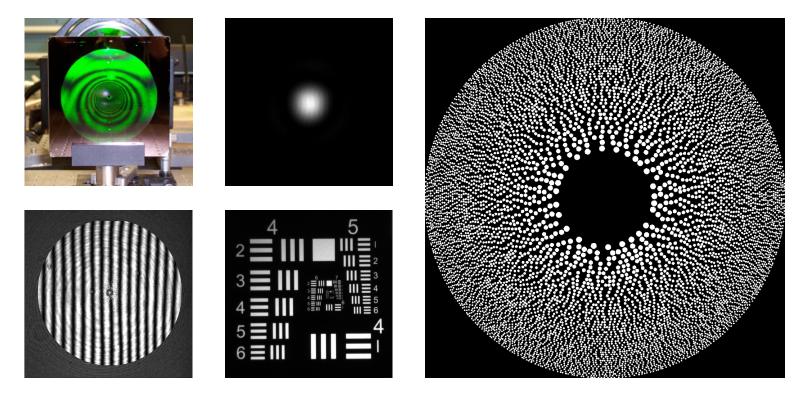
- Surface deformations mean diffracted light is no longer perfectly in phase from one hole to another
- A deviation of height *h* will change the path length of a ray from that point according to:



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# Summary of past work

- 4" tests using chrome-coated quartz sieves
  - 5 million holes, 20-330 $\mu$ m in diameter
  - 0.02λ RMS wavefront, 0.98 Strehl



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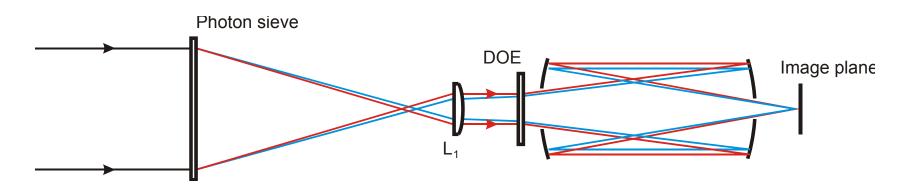
# **Broadband operation**

• Photon sieve is narrowband due to dispersion:

$$\Delta \lambda = \frac{2\lambda f^2}{D^2}$$

• Correct with secondary DOE (hologram)

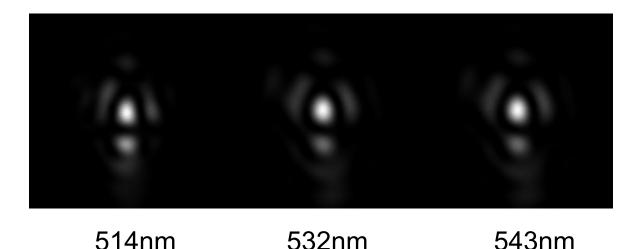




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### **Broadband telescope**

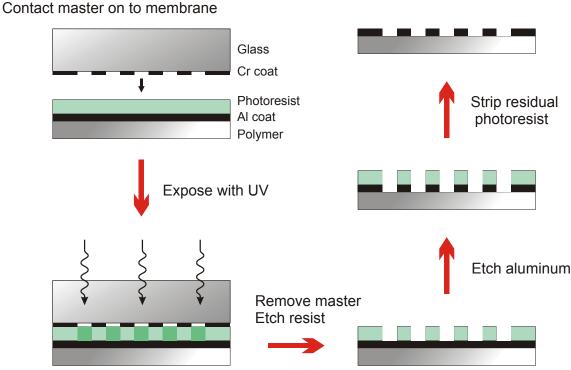
- HOE created in lab: D = 40mm, f = -158mm
- Demonstrated perfect imaging over 40nm bandwidth



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# Polyimide film

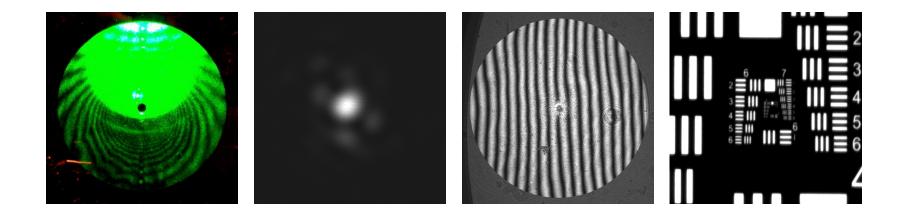
- 25µm thick polyimide with high thickness uniformity
- Coated with AI and photoresist for contact printing:



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# **Polyimide film**

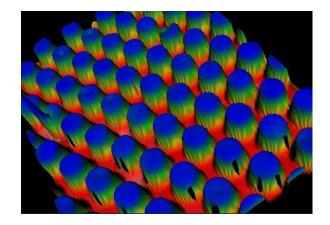
- D = 0.1m, f = 1m,  $\lambda = 532$ nm, N = 5 million
- 0.056λ RMS wavefront error, 0.88 Strehl
  - Even with less than perfect surface flatness evident
- Efficiency of this antihole design was just 0.35%



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# **Intensity vs Phase**

- Transmission photon sieves are binary intensity DOEs with limited diffraction efficiency
- Created photon sieve with optimum 50% fill
  - 3.8 million holes ranging in size from 8-395 $\mu$ m
- Al-coat CP1 films to convert to binary phase DOE
  - Al coating had to be  $\lambda/4$  thick
  - 133nm for 532nm light

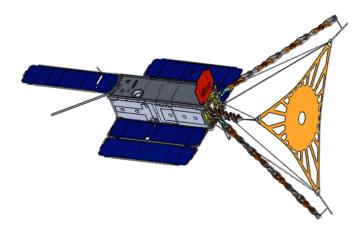


• Efficiency improved from 3.5% to 10%

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# FalconSAT-7

- FalconSAT program: cadets design, build, launch and operate small satellite
- FalconSAT-7: Deploy membrane photon sieve to observe the Sun
  - 3U CubeSat (30cm x 10cm x 10cm)
  - 0.2m membrane photon sieve





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# FalconSAT-7 Team

- USAFA Management, system design, science, optics, and electronics design and testing
  - NRO Colony II CubeSAT, launch & ground stations
- NASA / Goddard Solar science, thermal analysis



• AFIT – CubeSAT integration and mission modeling



Desián LLC

• AFRL/RVSV – Membrane design

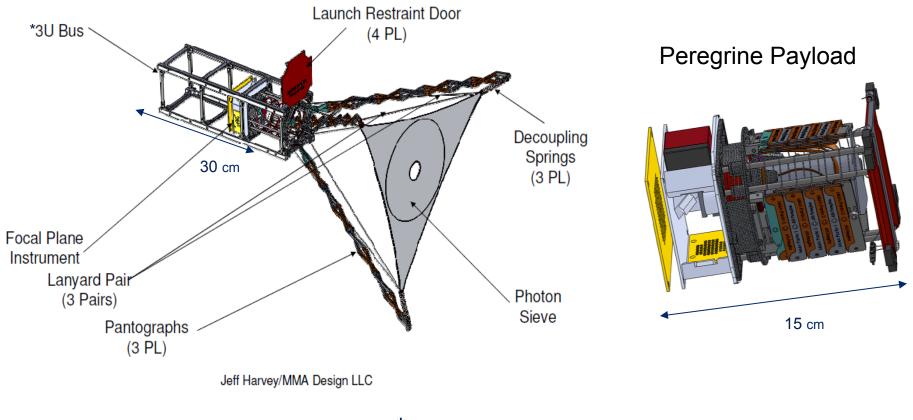








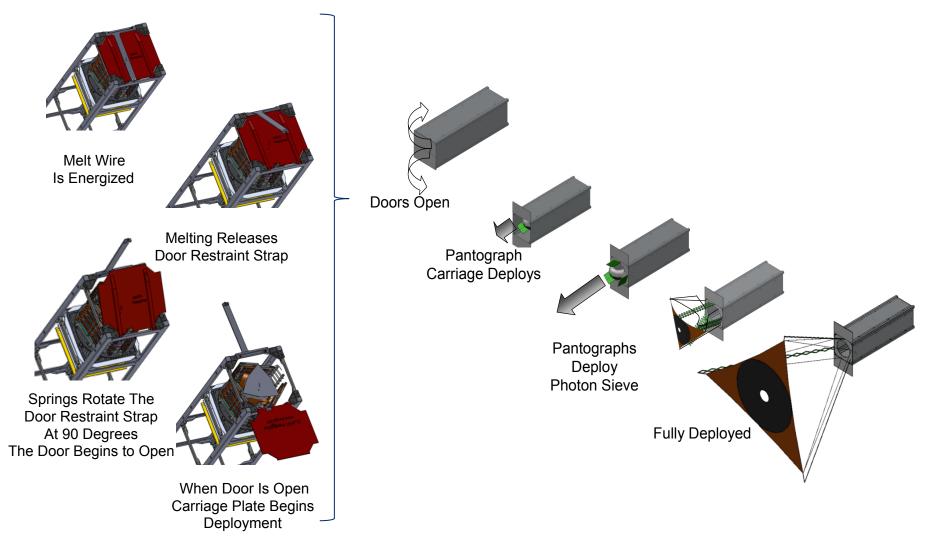
### FalconSAT-7 System



\* Avionics not shown

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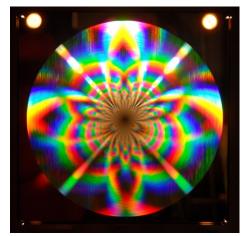
### **Peregrine Deployment Sequence**

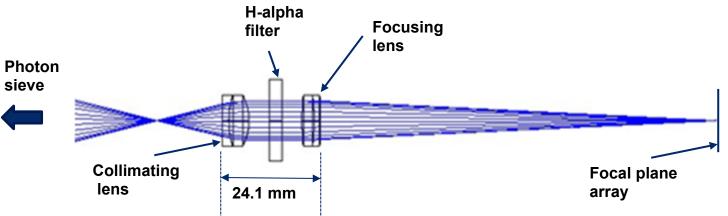


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### **Photon Sieve**

- Binary phase photon sieve
  - Master/contact process or direct-write
- 2.5 billion pinholes (2-277μm diam.)
- D = 200 mm, f = 400 mm,  $\lambda = 656.45$  nm
- 50% fill factor,  $\eta$ ~30%

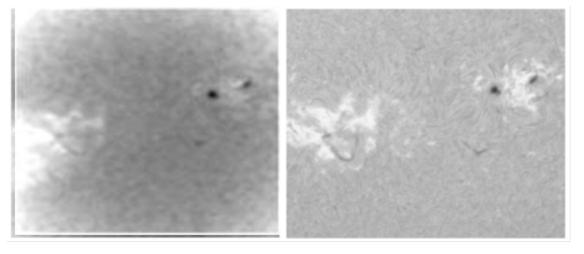




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### **Peregrine Optical System**

- 2 secondary lenses & H-alpha filter
  - Kinematic adjustment for focus/decenter
- 4 μrad resolution (600 km at Sun)
- ~0.1° FOV, 1Å spectral bandwidth
  - Depends on final choice of camera



10cm photon sieve

Big Bear Solar Observatory

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Distribution A: Approved for public release; distribution is unlimited.

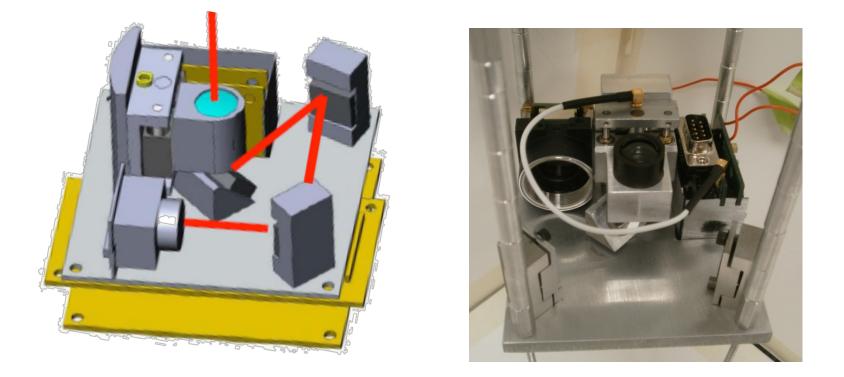
0.115 degrees

0.1925 degrees

0.5 degrees

# Optics

- Collimation optics, filter, fold mirrors and camera
- Kinematic stage to move lenses for focusing

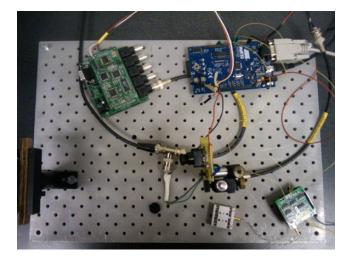


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### Cameras

Two CCDs:

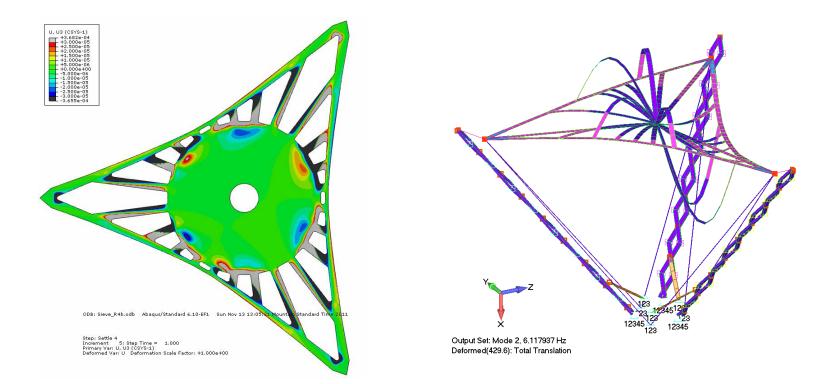
- Science camera at image plane of telescope
  - Monochrome, 4 micron pixel pitch, 720x240
  - Currently analog running @ 1/30Hz
  - Upgrading to digital camera running @ 30Hz
- Deployment camera
  - Miniaturized CCD to observe deployment



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### **Membrane analysis**

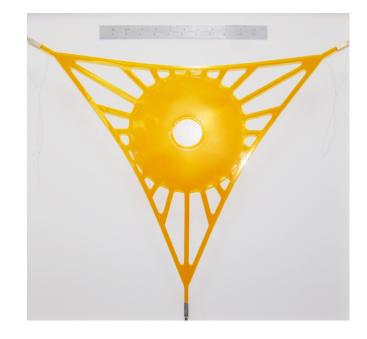
- Currently refining membrane design and tensioning scheme for optimum static/dynamic performance
  - Have already met flatness and stability specs



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# **Other considerations**

- Mechanical issues
  - Packing/folding mechanisms
  - Attachment points/tensioning
  - Zero-g test in August
- Material properties
  - Atomic oxygen
  - Thermal cycling & CTE
  - Substrate charging
  - Creep
- Environmental
  - Micrometeorites



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# **Radiometric analysis**

Solar imaging:

- 10 microsec exposure (set by pointing stability)
- SNR of 17

Earth imaging (1.8m resolution):

- 2.3 millisec max. exposure (set by LEO motion blur)
- SNR ~ 6
- Can improve with binning but reduces resolution

### **Project Schedule**

#### Reviews

- ✓ Oct 2010
- ✓ Dec 2010
- ✓ Dec 2011
- May 2012
- Micro\_G Payload
  - Jul 2012
  - Aug 2012
- Payload Complete
  Flight Test
- Engineering Model
  - ✓ Dec 2011
  - Mar 2012
- Qual Model
  - May 2012
- Flight Model
  - Dec 2012 Flight
  - Feb 2013
  - Aug 2013

- Payload Qual
- Flight Bus Arrives
  - Payload Flight Model Finished
- Aug 2013 FS-7
- FS-7 Integration and Testing Complete
- Ready for Launch Nov 2013

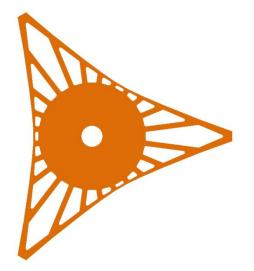
#### - System Requirements Review

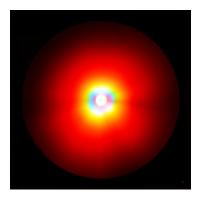
- Conceptual Design Review
- Preliminary Design Review

- Engineering Bus Arrives

- Payload Lab Prototype

- Critical Design Review

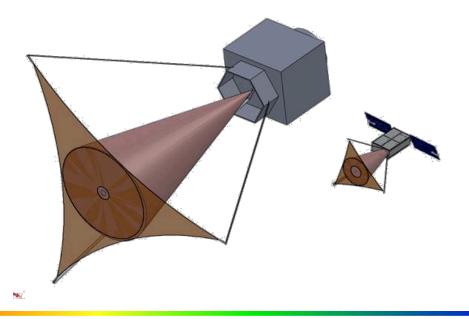




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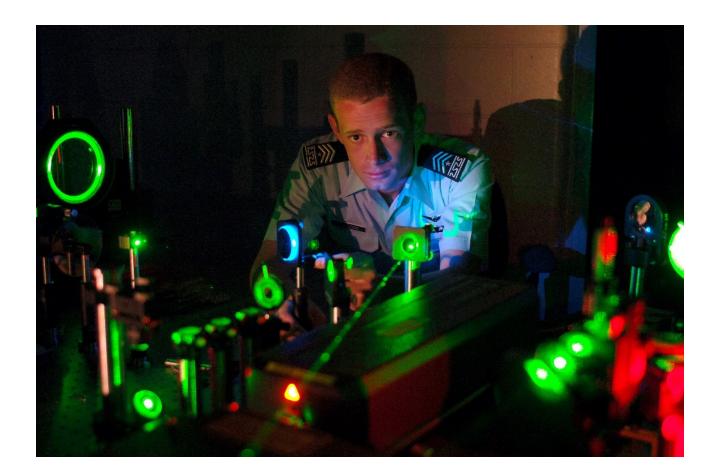
# Next generation

- Follow-on mission optimized for surveillance imagery
- Sub-meter Imaging from a Compact Low-Orbit Photon Sieve (SICLOPS)
  - ESPA-class or 6U CubeSat with broadband correction



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### **Questions?**



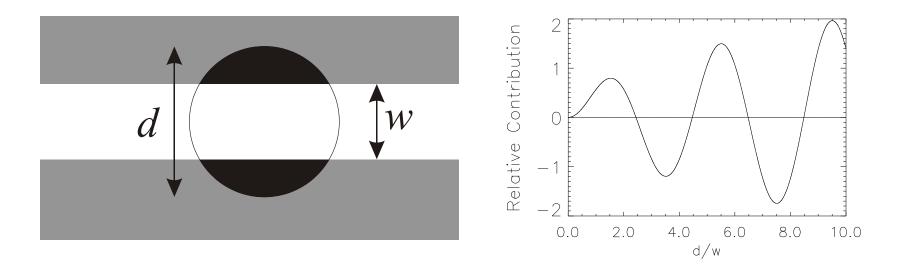
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### Hole size

• Can make hole size (*d*) > underlying zone (*w*):

$$F \propto \frac{d}{w} J_1 \left( \frac{\pi d}{2w} \right)$$

• Still get positive contribution so long as overlap with bright zone is greater than overlap with dark zone



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