Membrane diffractive space telescopes

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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 ($w$)

- Can be randomly or regularly distributed with angle

- Can have any density (fill) in each zone as desired

\[
\begin{align*}
r^2_n &= 2nf\lambda + n^2\lambda^2 \\
\omega &= \frac{\lambda f}{2r_n}
\end{align*}
\]
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 $\text{CTE}(\alpha)$ 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 $10^{-6} \, ^\circ\text{C}^{-1}$
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, $n$:

\[ \text{OPD} = t(n-1) \]

• Max thickness error for $n = 1.45$:
  \[ \frac{\lambda}{10} : t < 0.22\lambda \text{ (0.11 microns)} \]
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:

  $$ h = 2\phi (f/r)^{2} $$

- For $D=1m$ ($f/5$), $\phi = \lambda/10$:
  - Conventional mirror: $h = \lambda/20$
  - Photon sieve: $h = 20\lambda$
Summary of past work

- 4” tests using chrome-coated quartz sieves
  - 5 million holes, 20-330µm in diameter
  - 0.02λ RMS wavefront, 0.98 Strehl
Broadband operation

- Photon sieve is narrowband due to dispersion:

\[
\Delta \lambda = \frac{2\lambda f^2}{D^2}
\]

- Correct with secondary DOE (hologram)
Broadband telescope

- HOE created in lab: $D = 40\text{mm}$, $f = -158\text{mm}$
- Demonstrated perfect imaging over 40nm bandwidth
Polyimide film

- 25\(\mu\)m thick polyimide with high thickness uniformity
- Coated with Al and photoresist for contact printing:

1. Contact master on to membrane
2. Expose with UV
3. Remove master
4. Etch resist
5. Etch aluminum
6. Strip residual photoresist
Polyimide film

- $D = 0.1\text{m}$, $f = 1\text{m}$, $\lambda = 532\text{nm}$, $N = 5$ million

- $0.056\lambda$ RMS wavefront error, 0.88 Strehl
  - Even with less than perfect surface flatness evident

- Efficiency of this antihole design was just 0.35%
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 µm

• Al-coat CP1 films to convert to binary phase DOE
  – Al coating had to be λ/4 thick
  – 133nm for 532nm light

• Efficiency improved from 3.5% to 10%
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
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
- MMA Design LLC – Deployment system design
- AFIT – CubeSAT integration and mission modeling
- AFRL/RVSV – Membrane design

United States Air Force Academy
FalconSAT-7 System

*3U Bus
Launch Restraint Door (4 PL)
30 cm
Decoupling Springs (3 PL)
Photon Sieve

Focal Plane Instrument
Lanyard Pair (3 Pairs)
Pantographs (3 PL)

Peregrine Payload

Jeff Harvey/MMA Design LLC

* Avionics not shown

United States Air Force Academy

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

1. Melt Wire Is Energized
2. Melting Releases Door Restraint Strap
3. Springs Rotate The Door Restraint Strap At 90 Degrees
4. The Door Begins to Open
5. When Door Is Open Carriage Plate Begins Deployment
6. Pantographs Deploy Photon Sieve
7. Pantograph Carriage Deploys
8. Doors Open
9. Fully Deployed
Photon Sieve

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

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

- Currently refining membrane design and tensioning scheme for optimum static/dynamic performance
  - Have already met flatness and stability specs
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
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 - System Requirements Review
  - Dec 2010 - Conceptual Design Review
  - Dec 2011 - Preliminary Design Review
  - May 2012 - Critical Design Review

- **Micro_G Payload**
  - Jul 2012 - Payload Complete
  - Aug 2012 - Flight Test

- **Engineering Model**
  - Dec 2011 - Engineering Bus Arrives
  - Mar 2012 - Payload Lab Prototype

- **Qual Model**
  - May 2012 - Payload Qual

- **Flight Model**
  - Dec 2012 - Flight Bus Arrives
  - Feb 2013 - Payload Flight Model Finished
  - Aug 2013 - FS-7 Integration and Testing Complete

- **Ready for Launch Nov 2013**
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
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