Experimental Investigation of Secondary Back-Reflection

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LISA X - Gainesville, Fl
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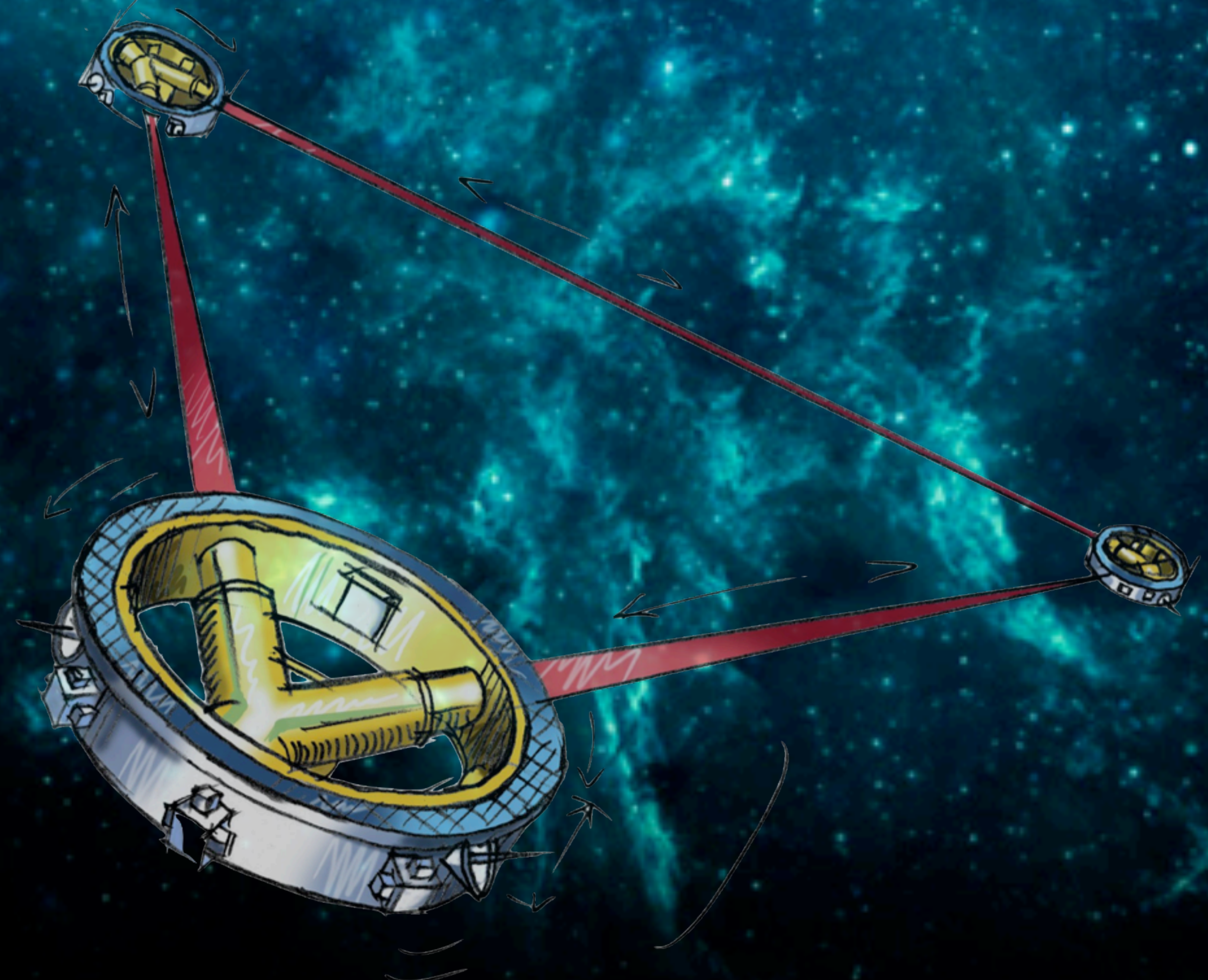
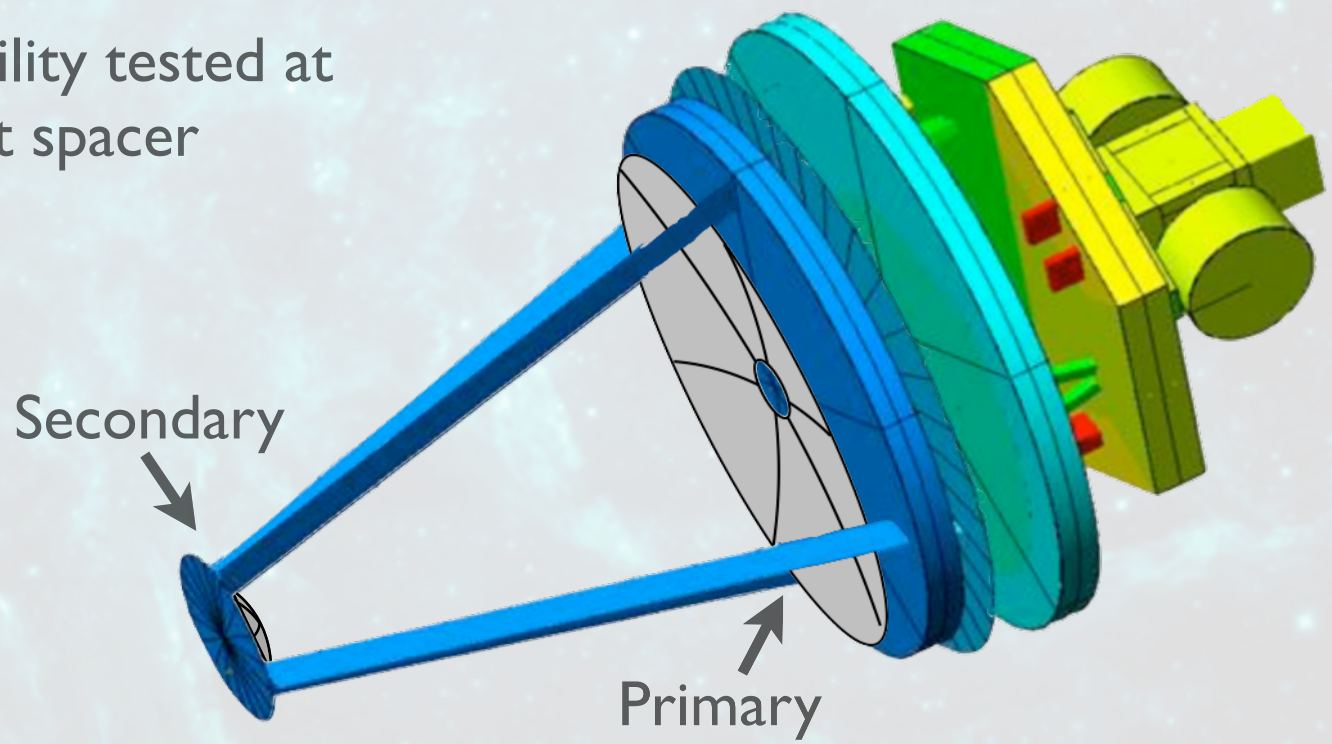


On-Axis Telescope

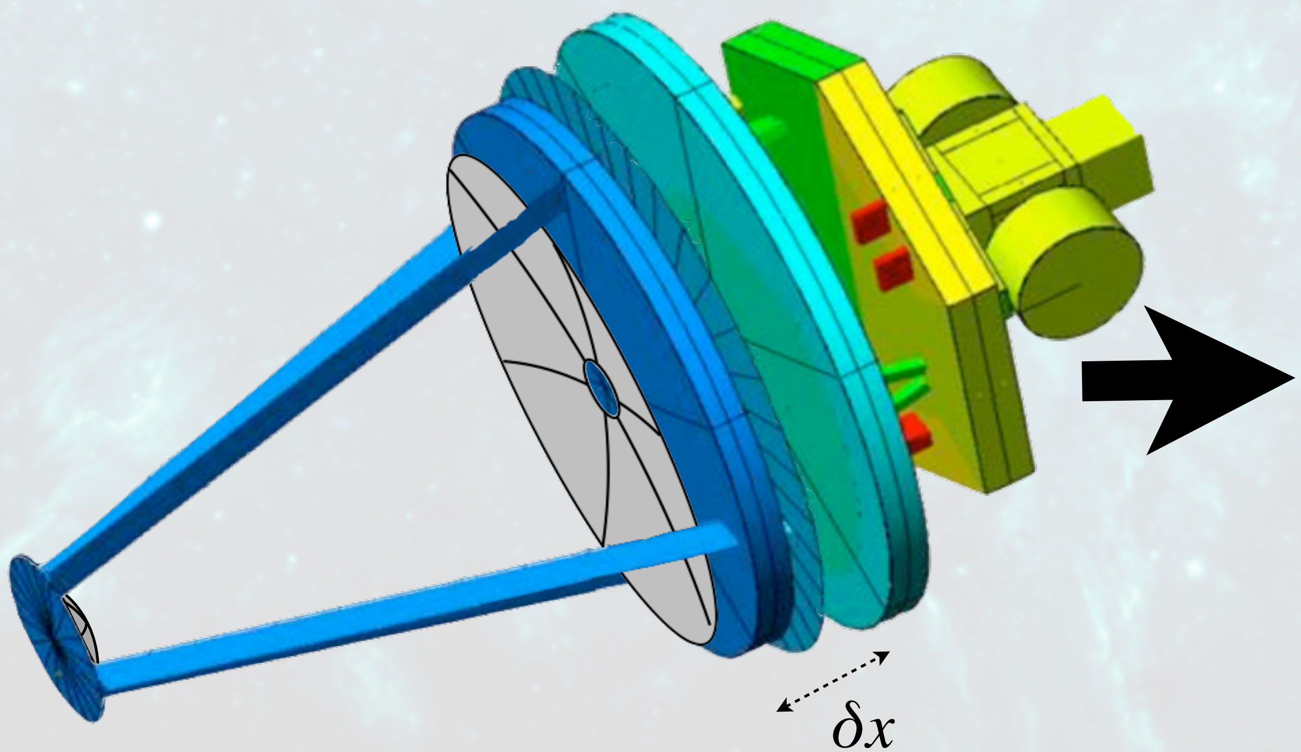
- Telescope transmits and receives lasers between SC
- On-axis quadpod (Cassegrain) design
  - Larger aperture to weight ratio than off-axis designs
    - 5% of light lost to shadows from Secondary support and struts
    - Symmetric shadows on quadrant photodetectors
  - Material stability confirmed to meet requirements
    - Thermal and dimensional stability tested at UF with GSFC using a SiC test spacer
      - J Sanjuan et al.
    - Potential Problem:

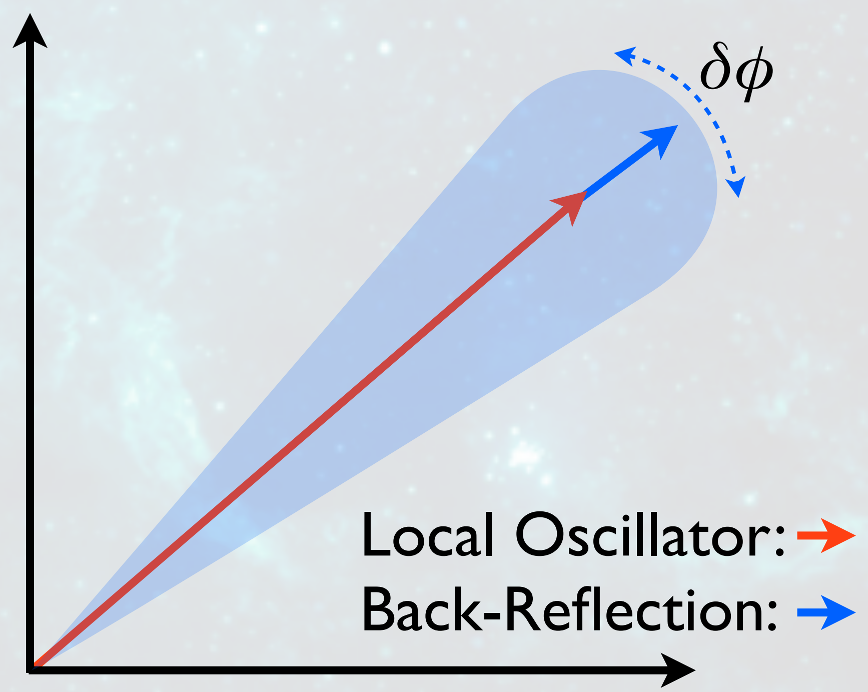
      Back-reflection from the secondary mirror



Telescope Back-Reflection

- Secondary and primary mirrors axially aligned
  - Outgoing beam incident normal to secondary mirror
    - Light reflected from secondary back to the optical bench
- Distance between OB and telescope not stabilized
  - Motion between the OB and telescope introduces phase noise to the BR light
    - Couples into measurement signal via small vector phase noise





Back-reflected Phase Noise

- LISA pm phase noise requirements < 10^{-6} cycles/rtHz
  - BR phase noise proportional to spatial overlap (η) of the far-field and BR field

$$\delta\phi = \eta\sqrt{\frac{P_o}{\chi P_l}\frac{\delta x}{\lambda}} \qquad \delta\phi < 10^{-6}\frac{\text{cycles}}{\sqrt{\text{Hz}}} \rightarrow \eta < 5\times10^{-5}$$

variable	description	value
P_o	outgoing power	$\lesssim 2$ W
P_l	local oscillator power	$\gtrsim 500\ \mu$W
λ	laser wavelength	1064 nm
δx	distance changes between OB and telescope	10 nm/$\sqrt{\text{Hz}}$
χ	extinction ratio of polarizing beam splitter	1000
η	spatial overlap between recieved and BR fields	$< 5\times10^{-5}$

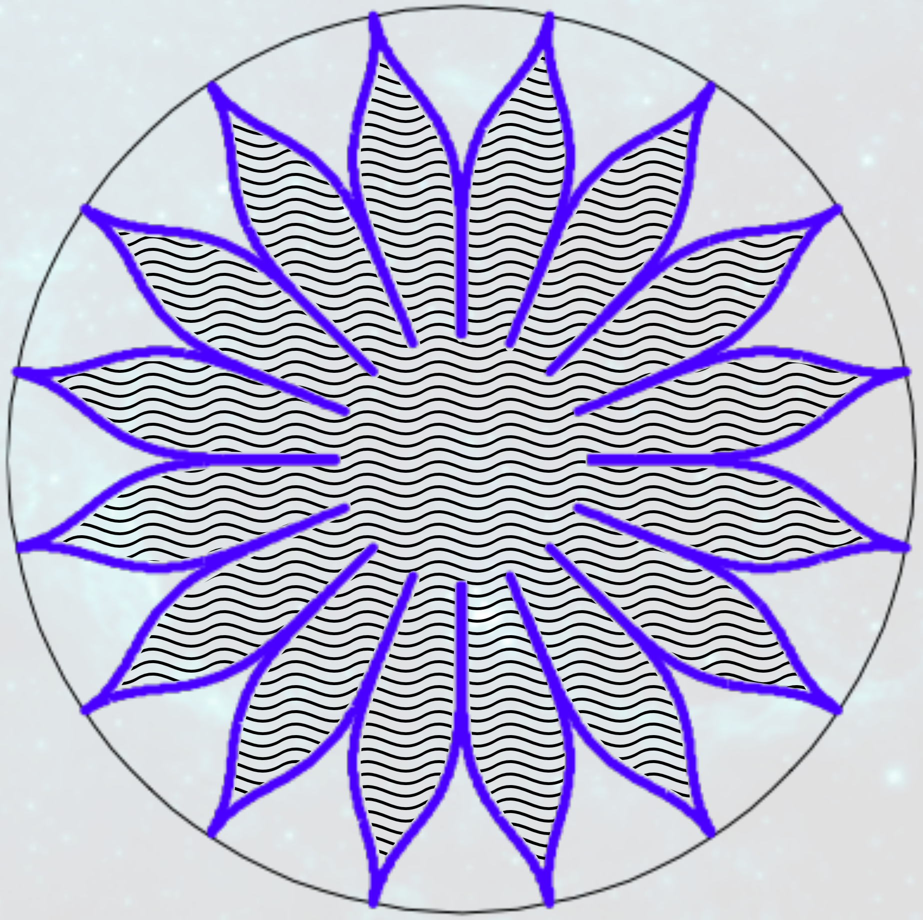
  - Technical noise sources must be a factor of 10 below the LISA requirements:

$$\boxed{\eta < 5\times10^{-6}}$$

- Unmitigated spatial overlap is 3×10^{-4}

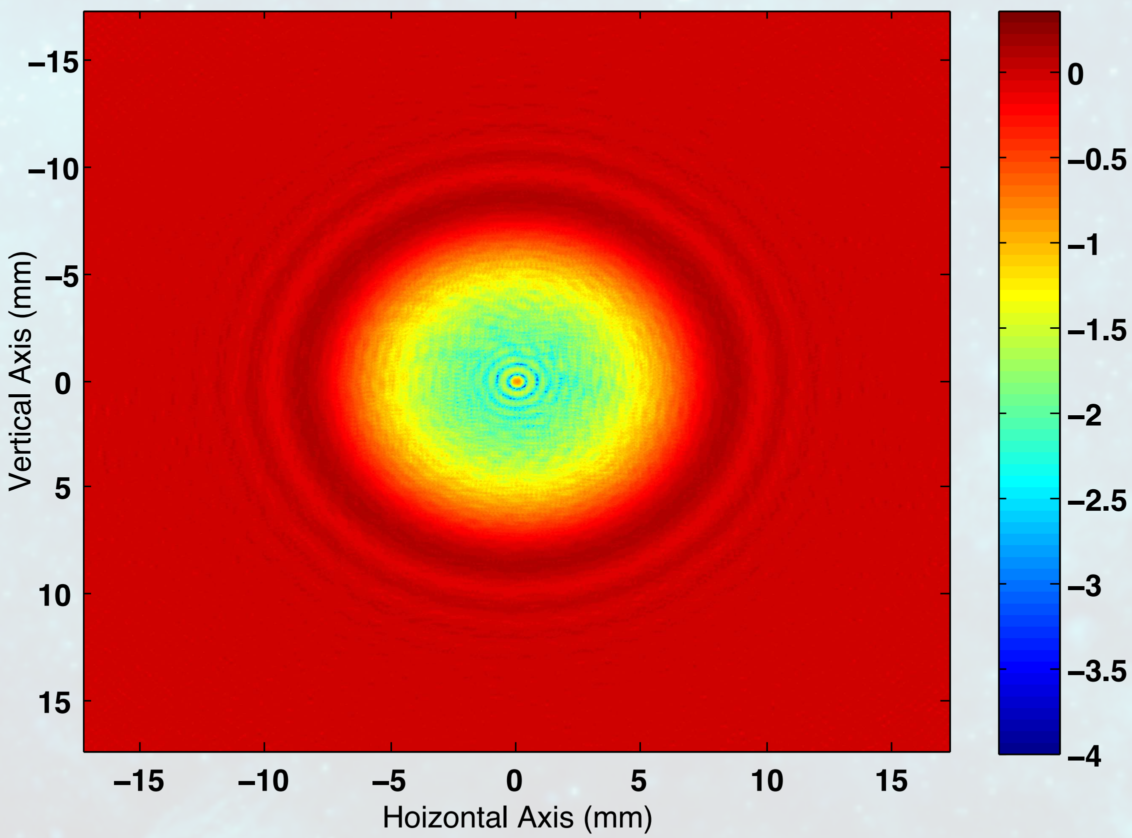
Lotus Shape

- Must cast shadow along optical axis
  - Use dark spot in the center of the Highly Reflective (HR) coating on the secondary
  - Initial simulations used a circular hole in the HR coating
    - Produces a bright spot along the optical axis (spot of Arago) $\eta = 8 \times 10^{-5}$
  - Must use irregular shape to break spatial coherence of the edge of the hole
- Simulations:
  - 10 shapes investigated
  - Huygen's integral and FFT propagation codes
  - **'Lotus'** shape chosen to investigate further
    - Axial power suppression limited by:
      - Petal tips minimum feature size (MFS)
      - Anti-Reflective (AR) coating reflectivity

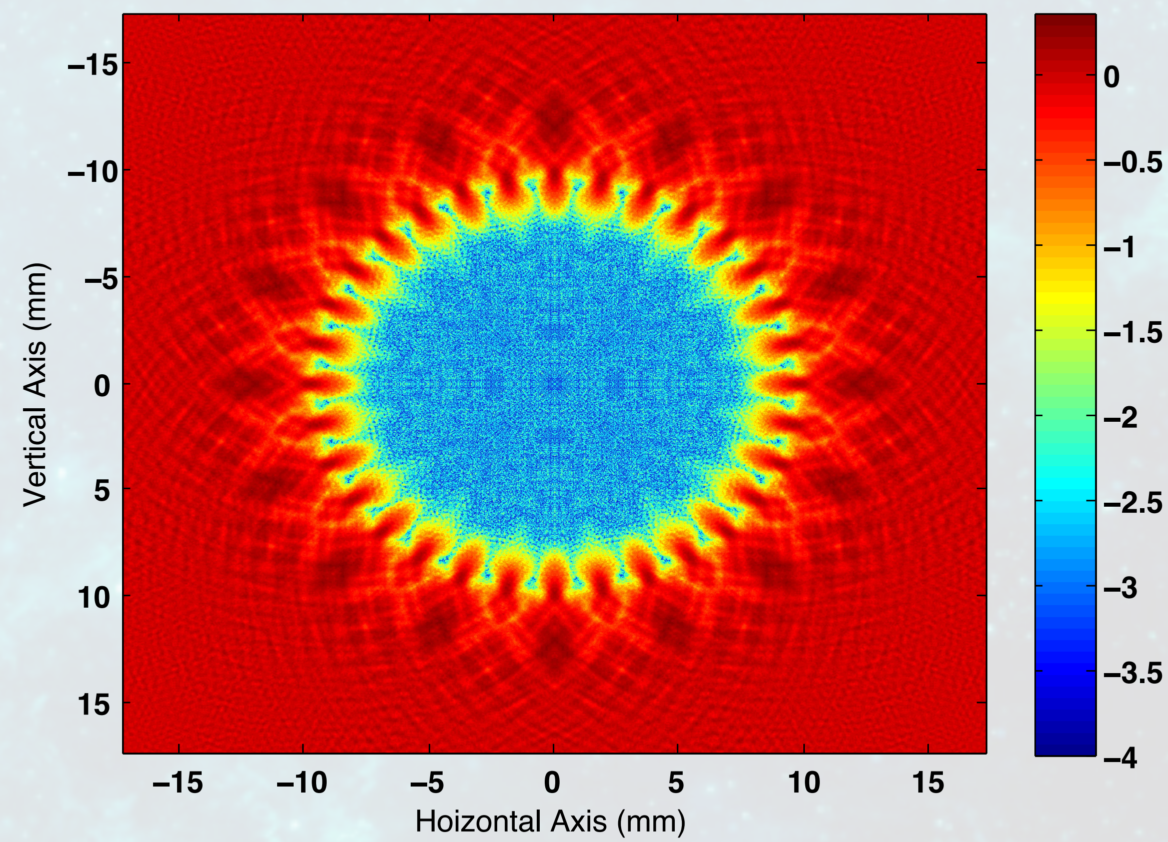


Simulated Distributions

Rough Circle



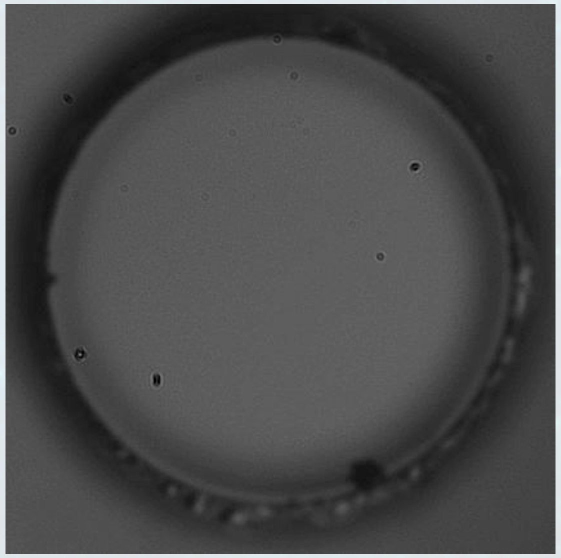
Lotus

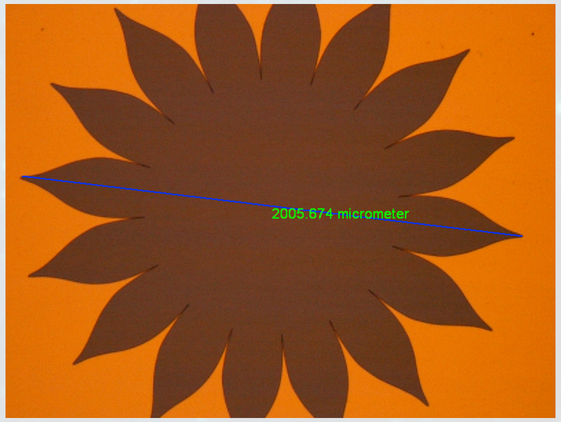


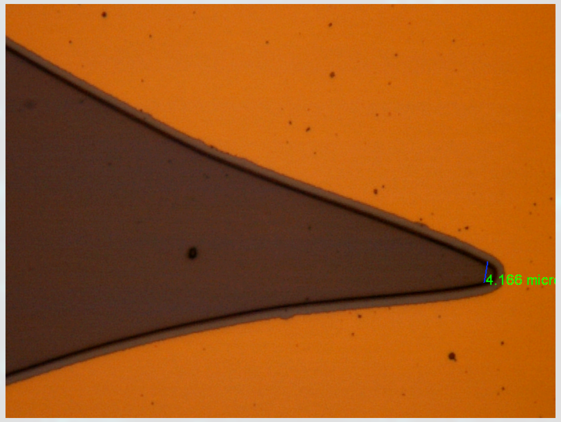
- Lotus is an improvement over the rough circle
  - Do not meet requirements with 2 micron petal tips (η = 1.1 to 3.8×10^{-5})

Secondary Prototypes

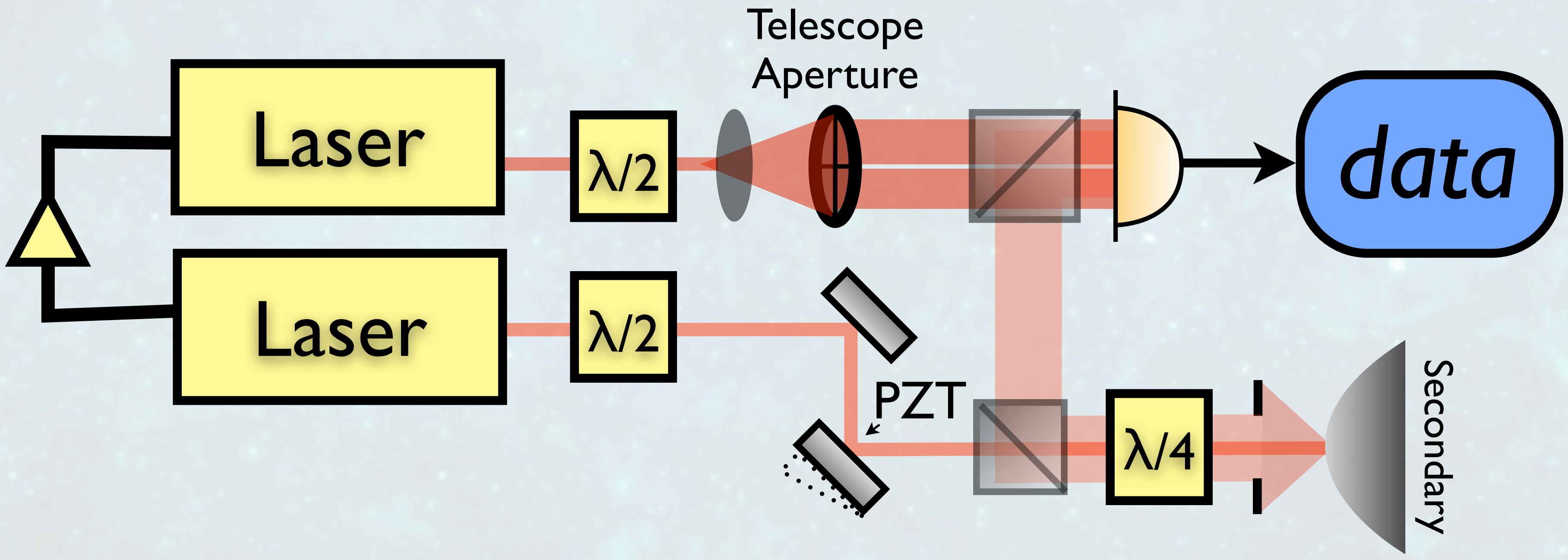
- Deposited dielectric HR coating over curved substrate
  - 16 mm radius of curvature
- 1mm diameter hole secondaries
  - 30 micron chipping region
- ‘Lotus’ secondaries manufactured using photo-lithographic techniques
  - 180 micron gold HR layer deposited over curved substrate (convex)
  - AR coating has reflectivity of 2.5×10^{-3}
  - 2 mm diameter pattern etched into gold
  - Minimum feature size in petal tips of 2 microns
  - 1 micron undercut at the edge of the structure



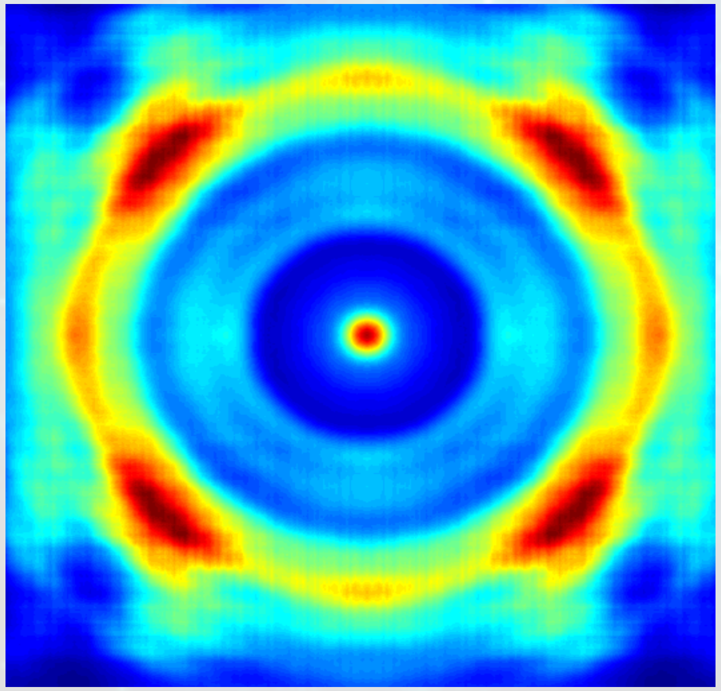


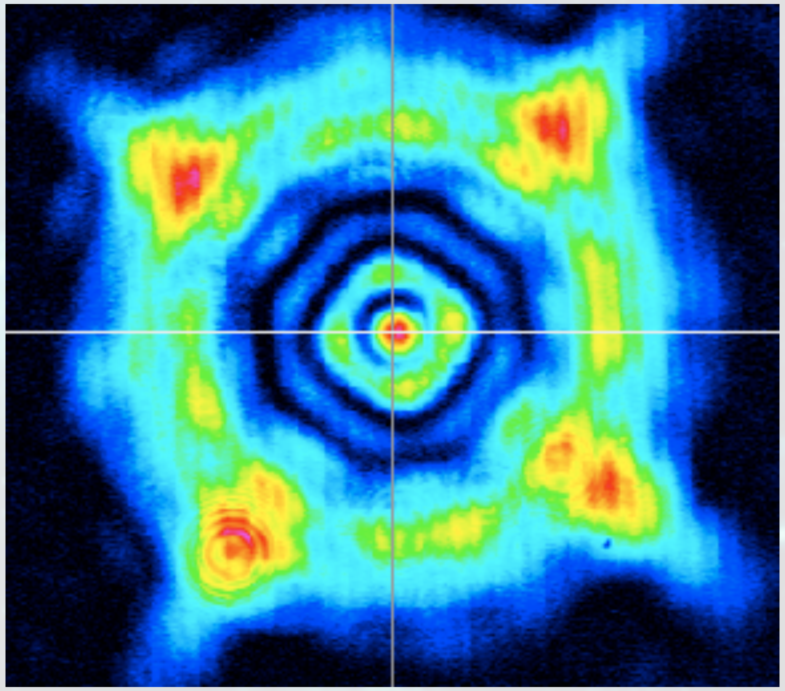


Experimental Testbed



- Secondary prototypes tested on optical bench
  - Telescope aperture beam shaping optics recreate simulated received field
  - Amplitude of interference signal between BR and received field measured on PD





Preliminary Results

- Results for Secondary Prototypes
  - ***Goal:*** $\boldsymbol{\eta < 5 \times 10^{-6}}$
  - Measured unmitigated BR $\eta = 3.2 \times 10^{-4}$ (theory: 3.0×10^{-4})
  - Rough circular hole: $\eta = 4.1$ to 6.2×10^{-5} (theory: $4.8 \pm 0.4 \times 10^{-5}$)
  - Lotus: $\eta = 0.8$ to 2.2×10^{-5} (theory: 1.1 to 3.8×10^{-5})

Shape	Radius of Curvature	Max η (Experiment)	Max η (Simulation)
No Hole	16 mm	3.2×10^{-4}	3.0×10^{-4}
Circular Hole 1	16 mm	4.1×10^{-5}	$4.8\pm0.4\times10^{-5}$
Circular Hole 2	16 mm	5.4×10^{-5}	$4.8\pm0.4\times10^{-4}$
Circular Hole 3	16 mm	6.2×10^{-5}	$4.8\pm0.4\times10^{-4}$
Lotus 1	39 mm	2.2×10^{-5}	1.7×10^{-5}
Lotus 1 (DL)	39 mm	1.5×10^{-5}	1.3×10^{-5}
Lotus 2	45 mm	9.8×10^{-6}	2.9×10^{-5}
Lotus 2 (DL)	45 mm	8.4×10^{-6}	1.1×10^{-5}
Lotus 3	51 mm	1.1×10^{-5}	2.2×10^{-5}
Lotus 3 (DL)	51 mm	1.2×10^{-5}	1.4×10^{-5}
Lotus 4	77 mm	1.7×10^{-5}	3.7×10^{-5}
Lotus 4 (DL)	77 mm	1.7×10^{-5}	3.8×10^{-5}

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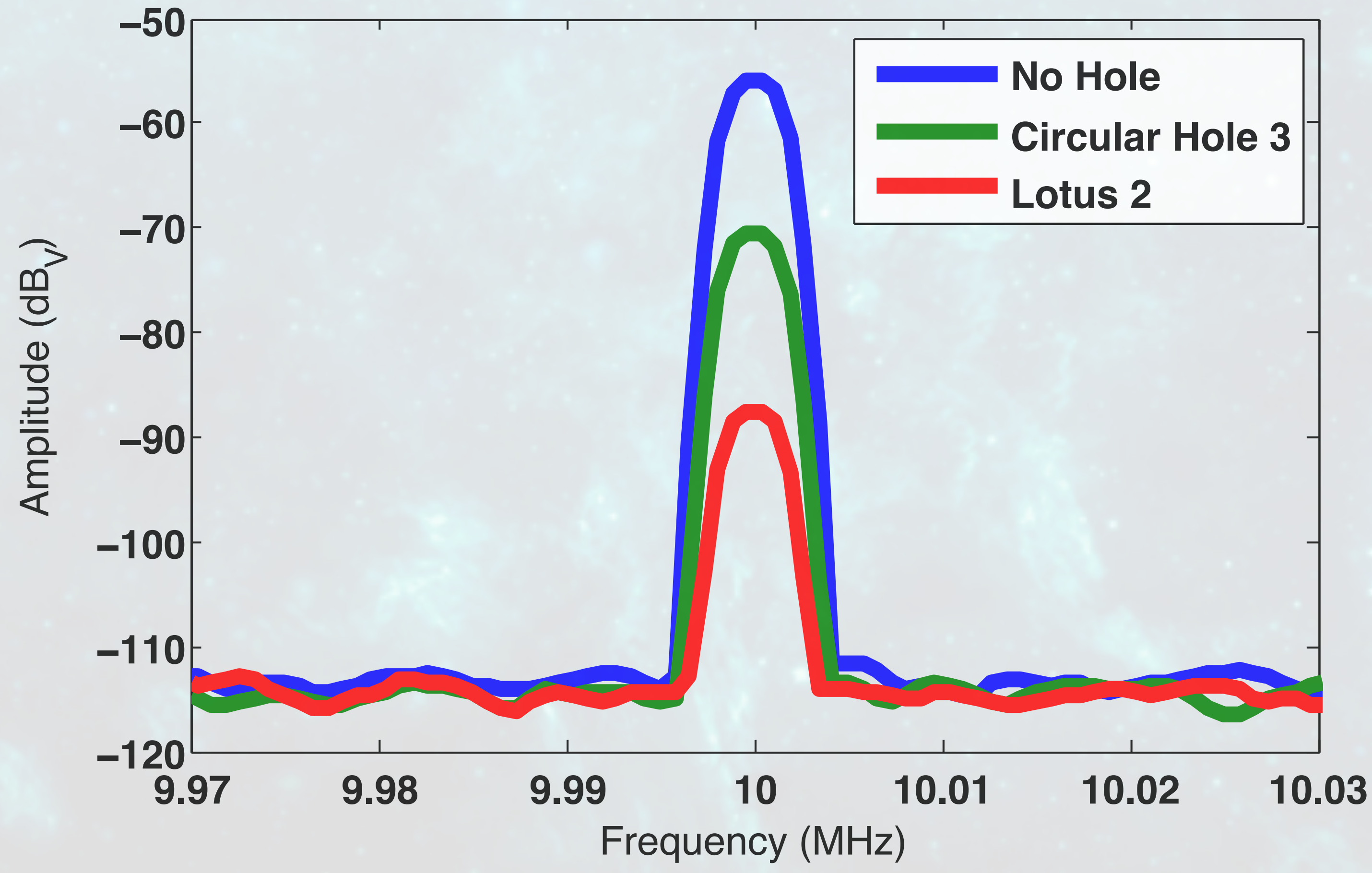
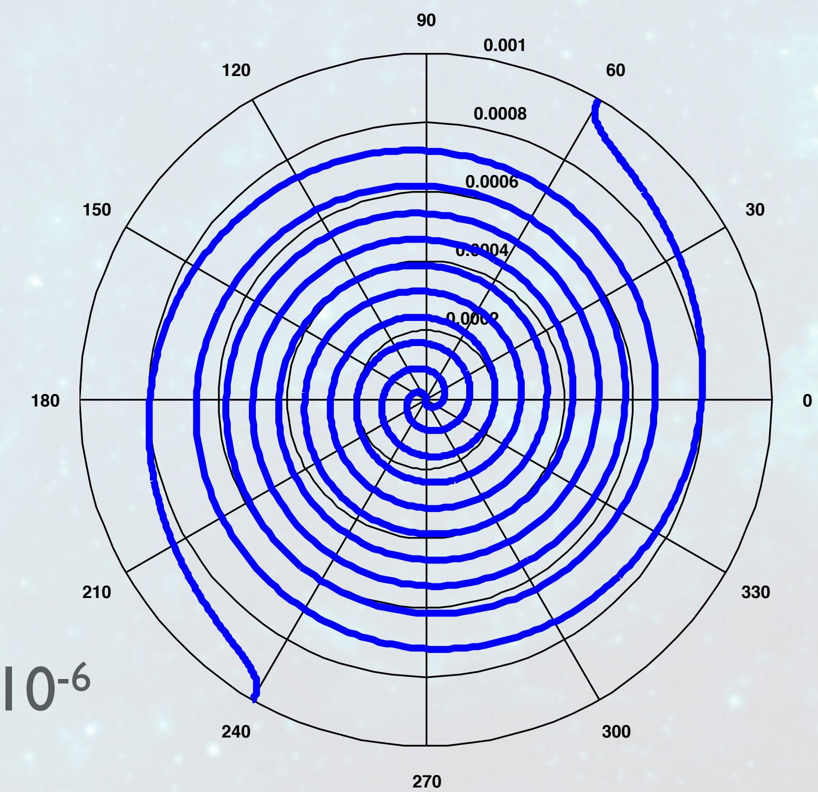
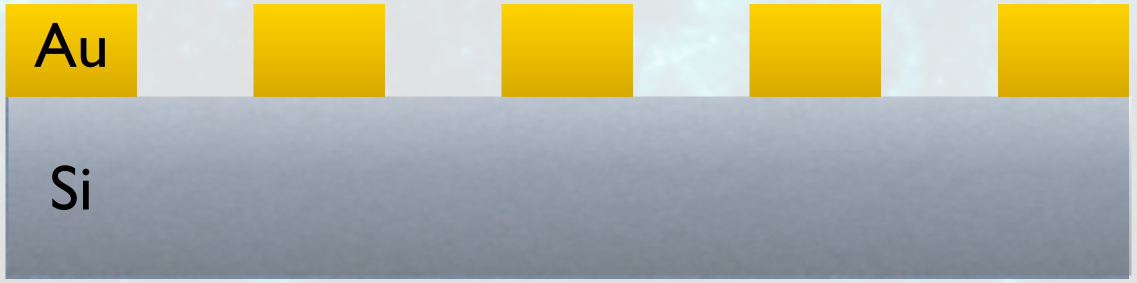


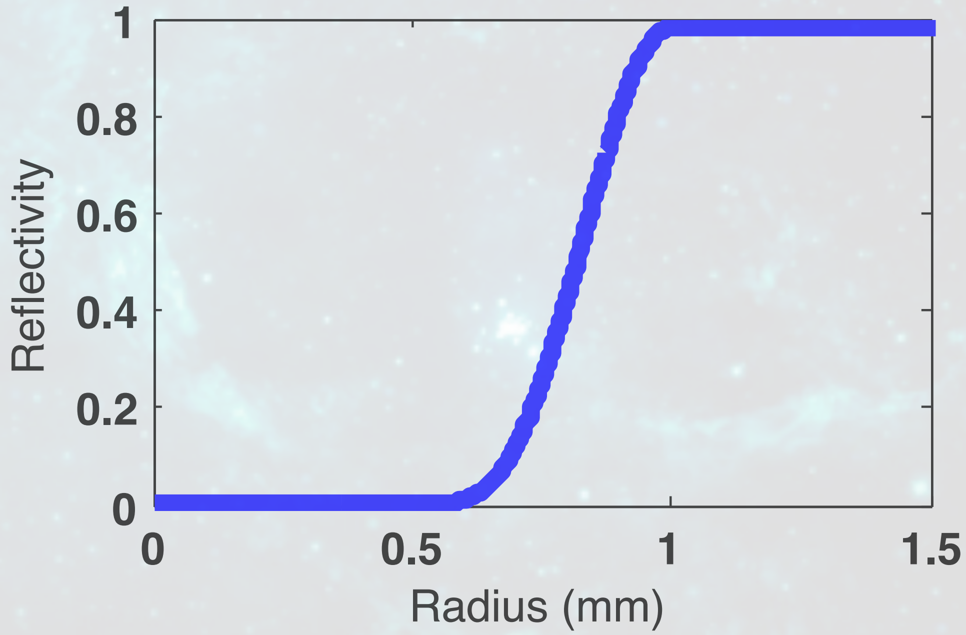
Future Work

- Apodized Shapes
  - Etch sub-wavelength features into gold coating
  - Forms a tunable effective index of refraction
  - Allows for smooth transition from AR to HR
    - Reduces light scattered due to diffraction effects
      - For ideal AR coating η = 1 to 4×10^{-7}
      - For practical AR coating (R = 0.25%) η = 2 to 4×10^{-6}



$$R = \left| S_{\mathrm{Au}} \frac{1 - N_{\mathrm{Au}}}{1 + N_{\mathrm{Au}}} + (1 - S_{\mathrm{Au}}) \frac{1 - N_{\mathrm{Si}}}{1 + N_{\mathrm{Si}}} e^{i\phi} \right|^2$$





Conclusions

- Results: We are close but not quite there
  - Best Lotus pattern etching within a factor of 1.7 of the requirements
  - Different results for different telescope designs
  - Simulations: limited by minimum feature size in the petal tips
- Future: Apodized coatings present a possible solution
  - Simulated back-reflection below spatial overlap requirements
  - Work with practical AR coatings
  - Have procedure to manufacture coatings at UF, with help from the NRF

Thank You!

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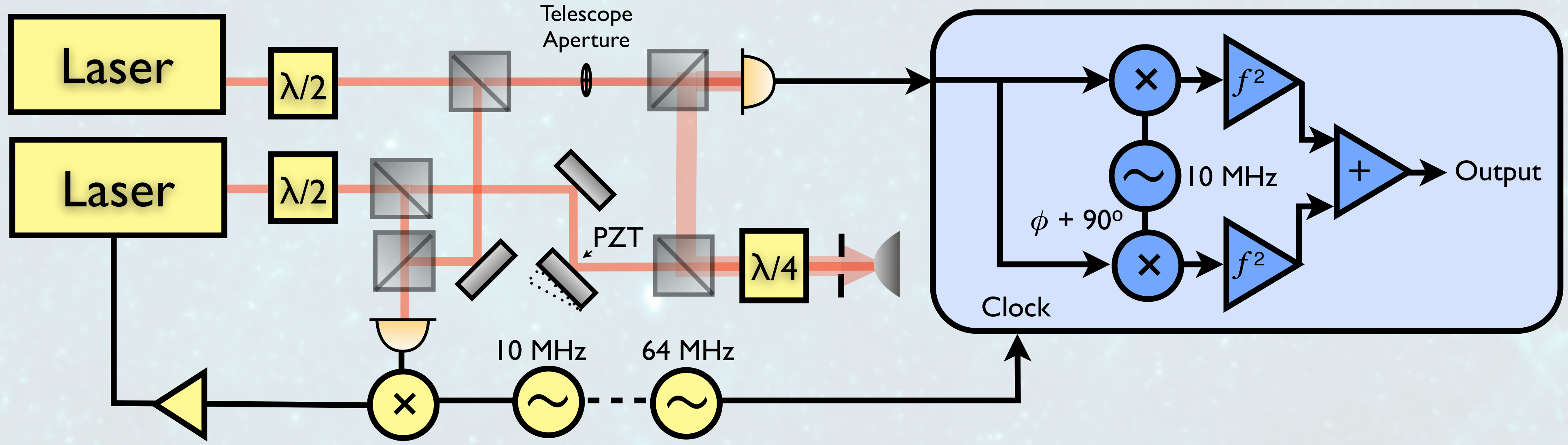

- Secondary prototypes tested on optical bench
  - 2 Lasers phase locked at 10 MHz with clocks synchronized to acromag card
  - Telescope aperture beam shaping optics recreate simulated received field
  - $\lambda/4$ wave plate and PBS used to separate back-reflected and incident beams
    - PZT mirror scans incident beam over mirror positions
  - Interference signal of far-field and BR field sent from PD to acromag card
    - Amplitude of both quadratures measured to eliminate path length noise
    - Amplitude of the signal is calibrated to give the spatial overlap

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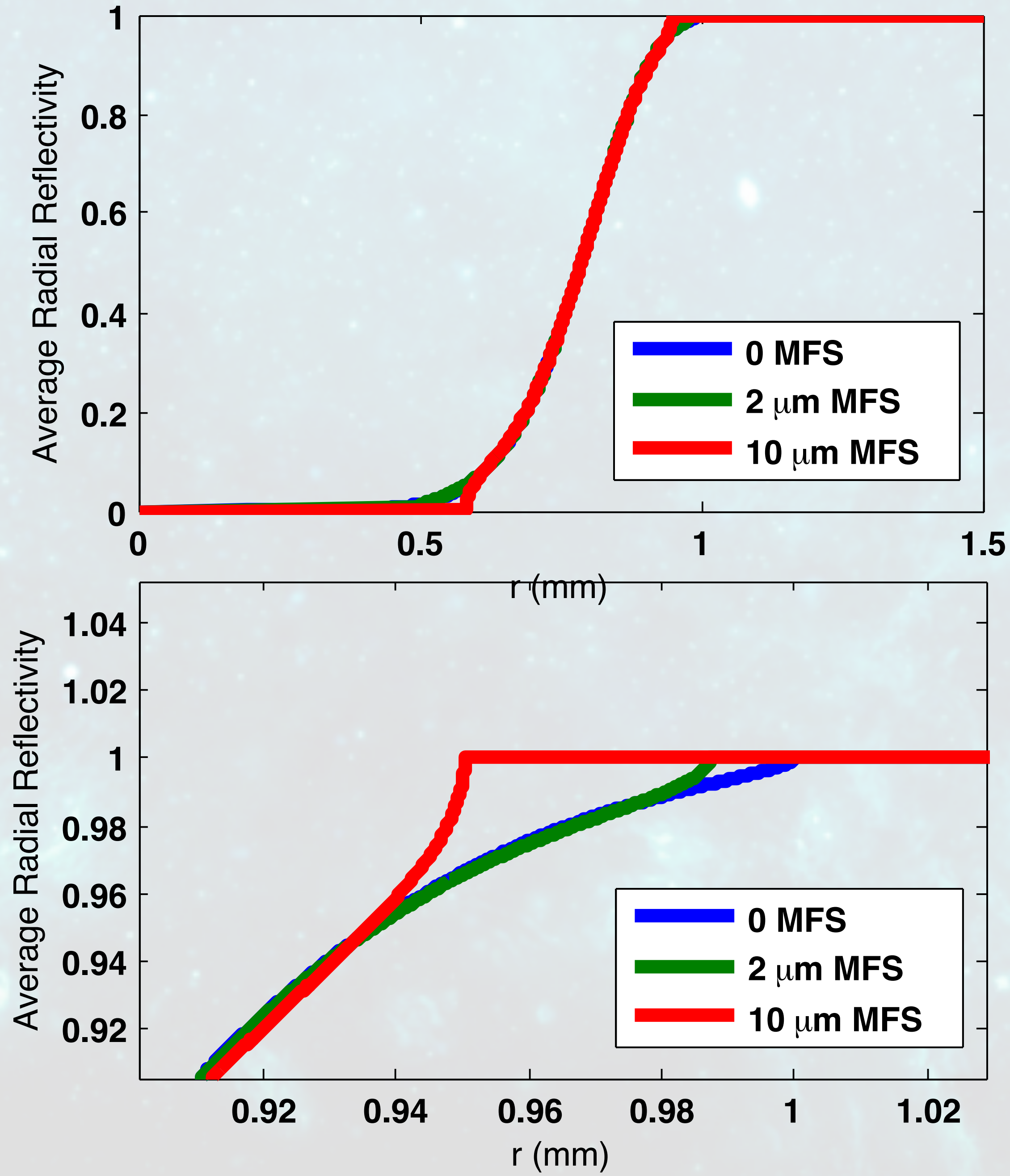
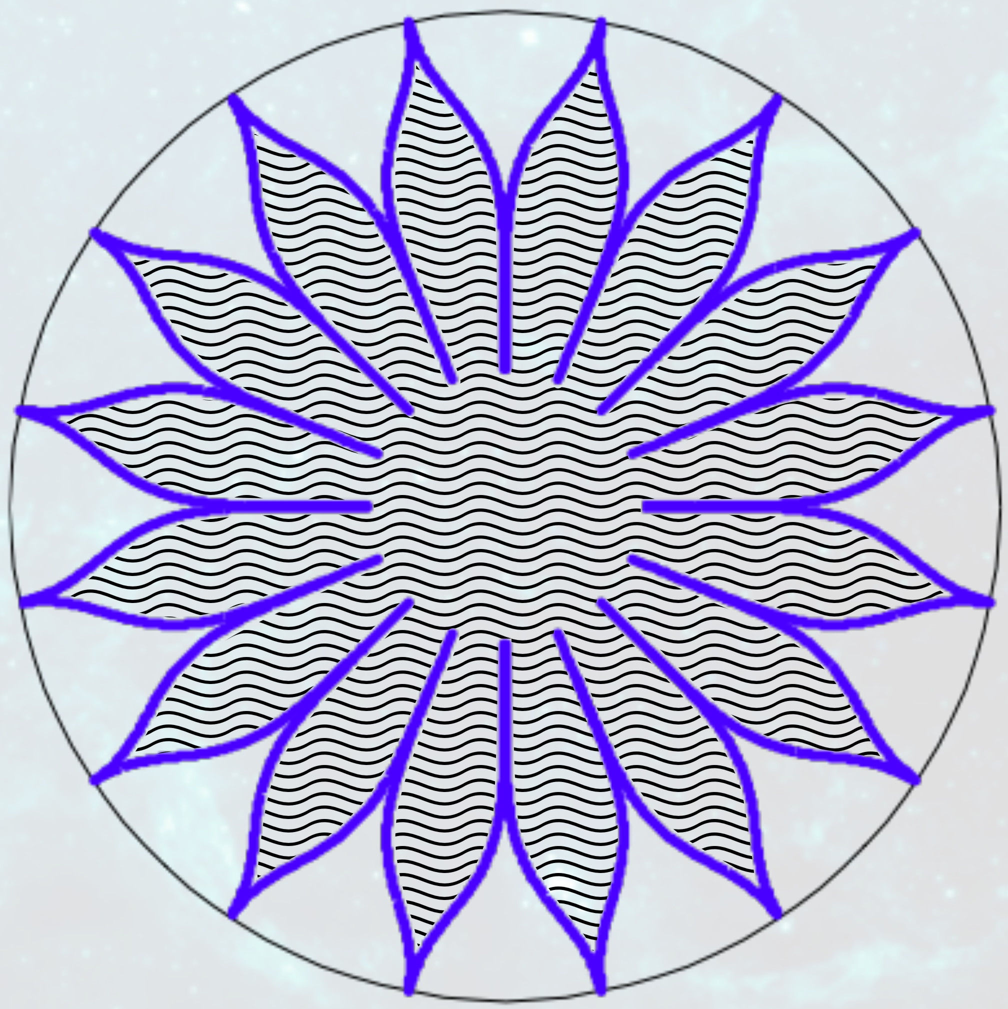
Lotus Shape

- Average Reflectivity for a given radial length





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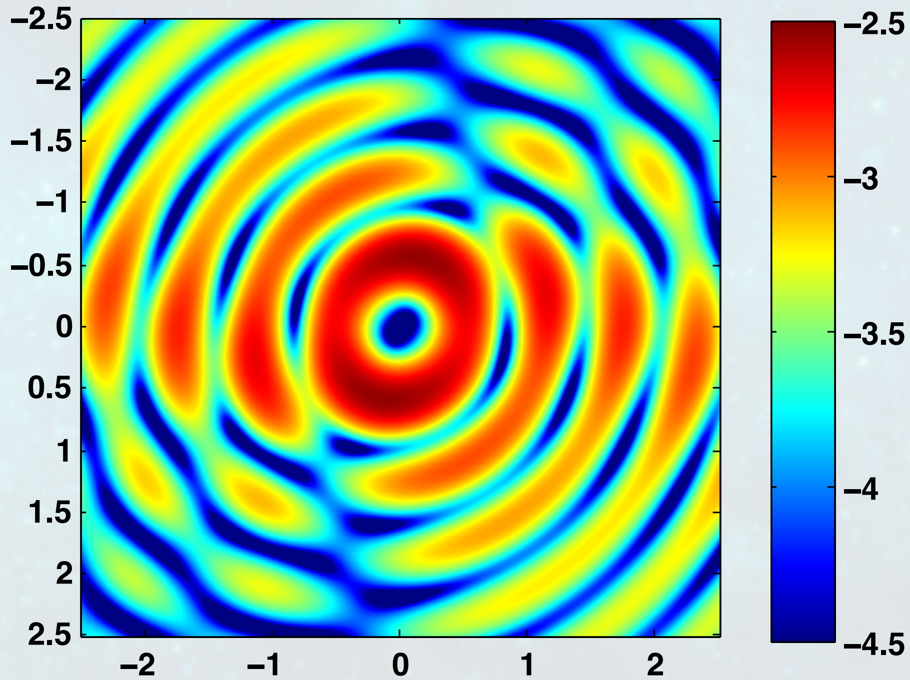
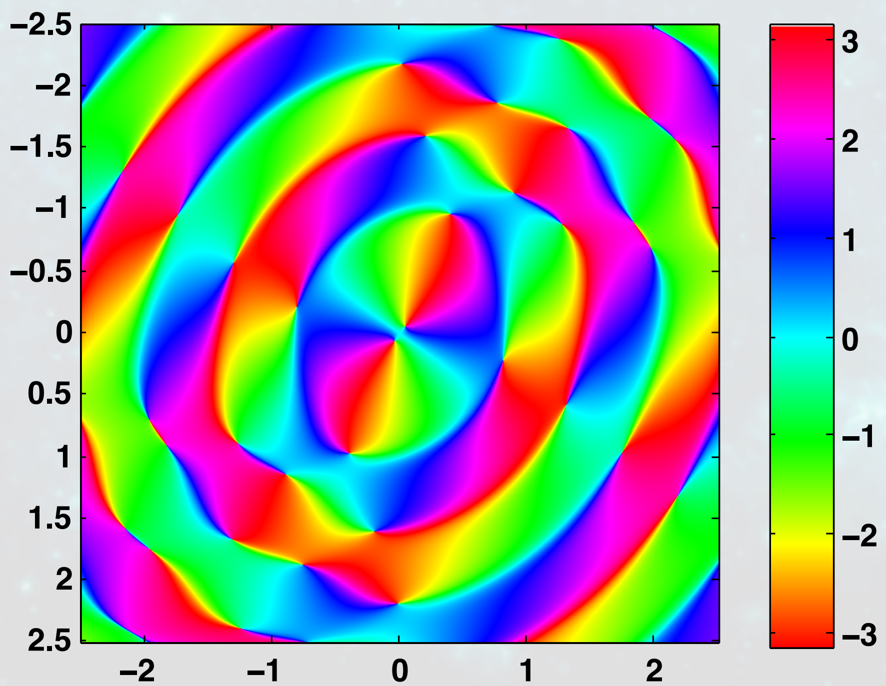
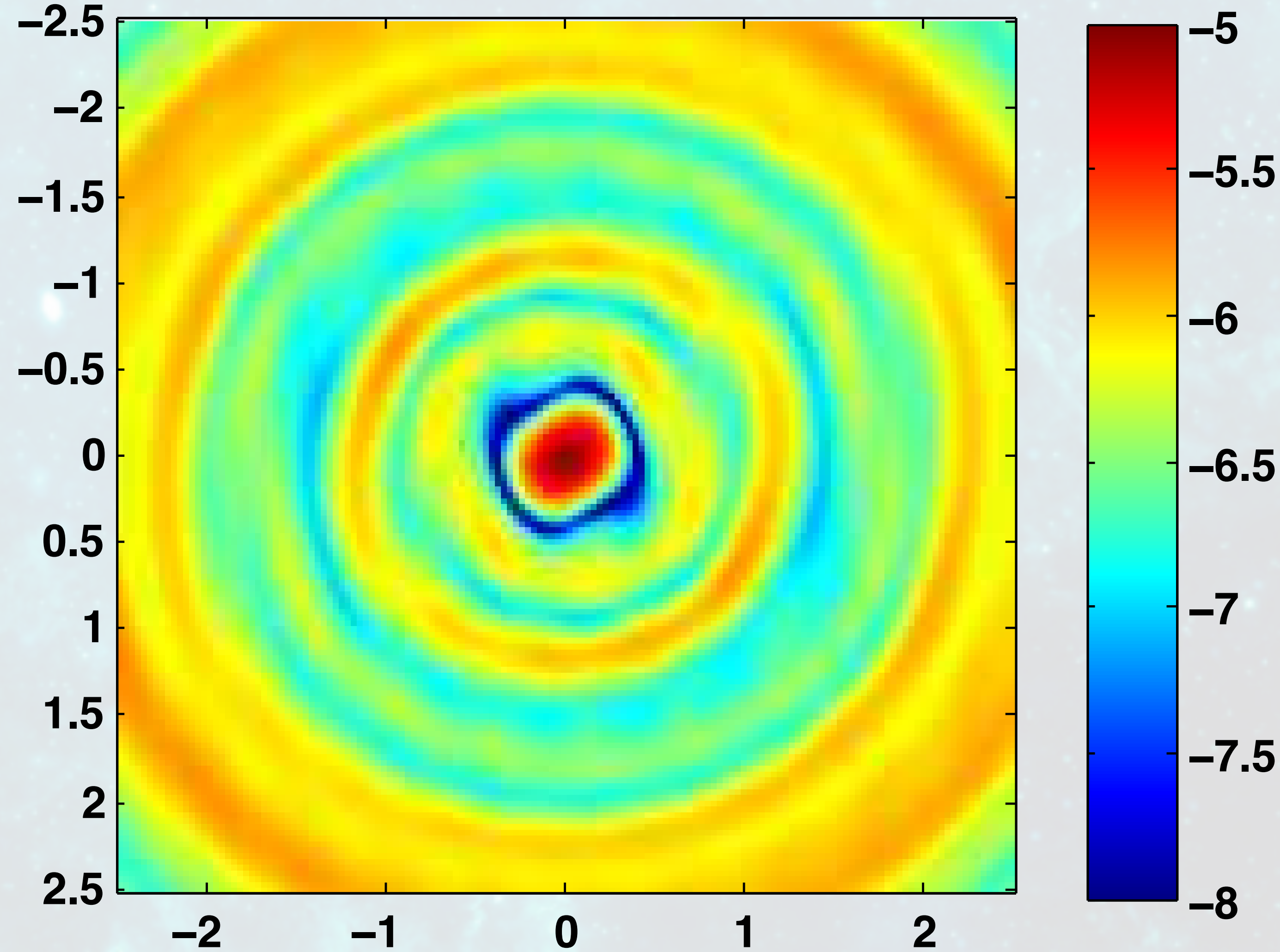
Spiral Simulations







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