A compact deep-space optical communications transceiver

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Objectives

- Develop a ‘flight-like’ laser communications terminal capable of hundreds of Mb/sec from Mars
- Incorporate advanced technology to simplify system design
  - Passive low-frequency vibration-isolation platform
  - Low power piezoelectric point-ahead system
  - Photon-counting tracking/receiving array
  - Two-photon absorption downlink beam tracking
- Develop a prototype for testing and analysis
  - Testing of background rejection techniques
  - Testing of thermal distortions to optical system
  - End-to-end testing with mock ground station

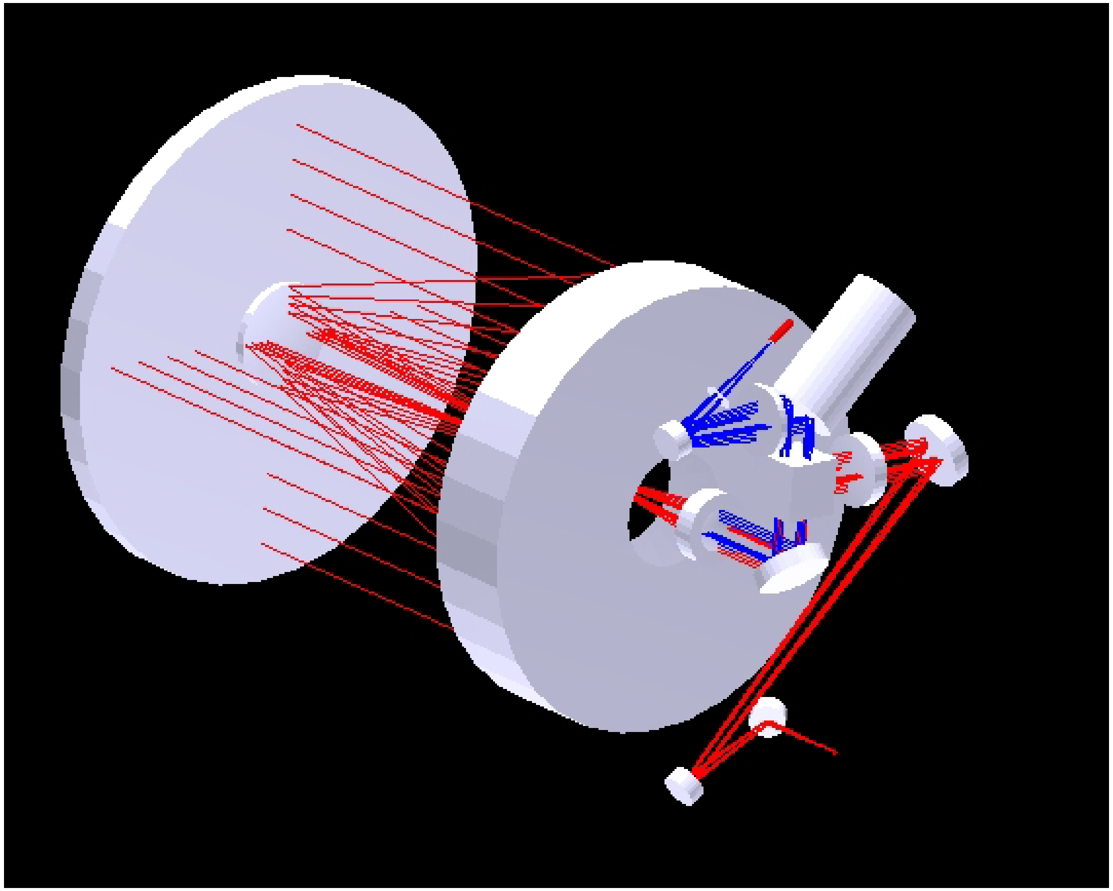
Optical System Requirements

- Basic optical requirements for deep-space transceiver concept

Parameter	Requirement	Rationale
Aperture	15 cm	Achieve link goals (multiple Mb/s from Mars) in small package
Focal Length	2500 mm	Provides a 400 μrad FOV using a 2 mm focal plane array
Telescope Magnification	~10:1	Allows limited throw of the Point Ahead Mirror to address full FOV
Linear Obscuration	~35%	Maintain a far-field obscuration loss of less than 2 dB [8] while controlling coma
Transmit Wavelength	1550 nm	Leverage off of efficient telecom laser development
Receive Wavelength	1060 nm	Allows the use of high-power ground based beacon lasers and provides for good transmit/receive isolation
Strehl Ratio	>0.2	Allows detection of the beacon across the full FOV
Solar Environment	Full Range	Must be able to survive direct Sun pointing, operate at peak performance within 3 degrees of Sun, and operate while pointing at opposition

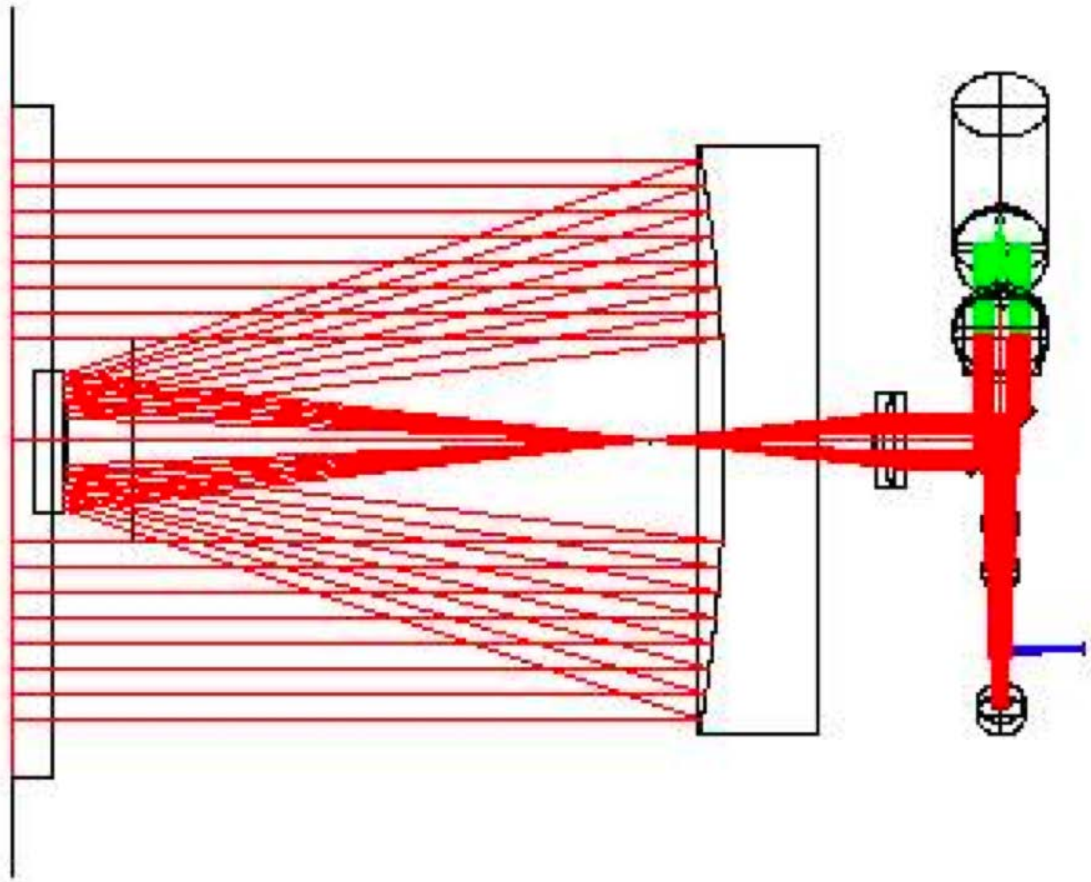
Approach to Optical Design

Design separate systems and integrate
- Design front telescope
- Design aft optical bench with off-the-shelf parts
- Optimize telescope to work with aft optics



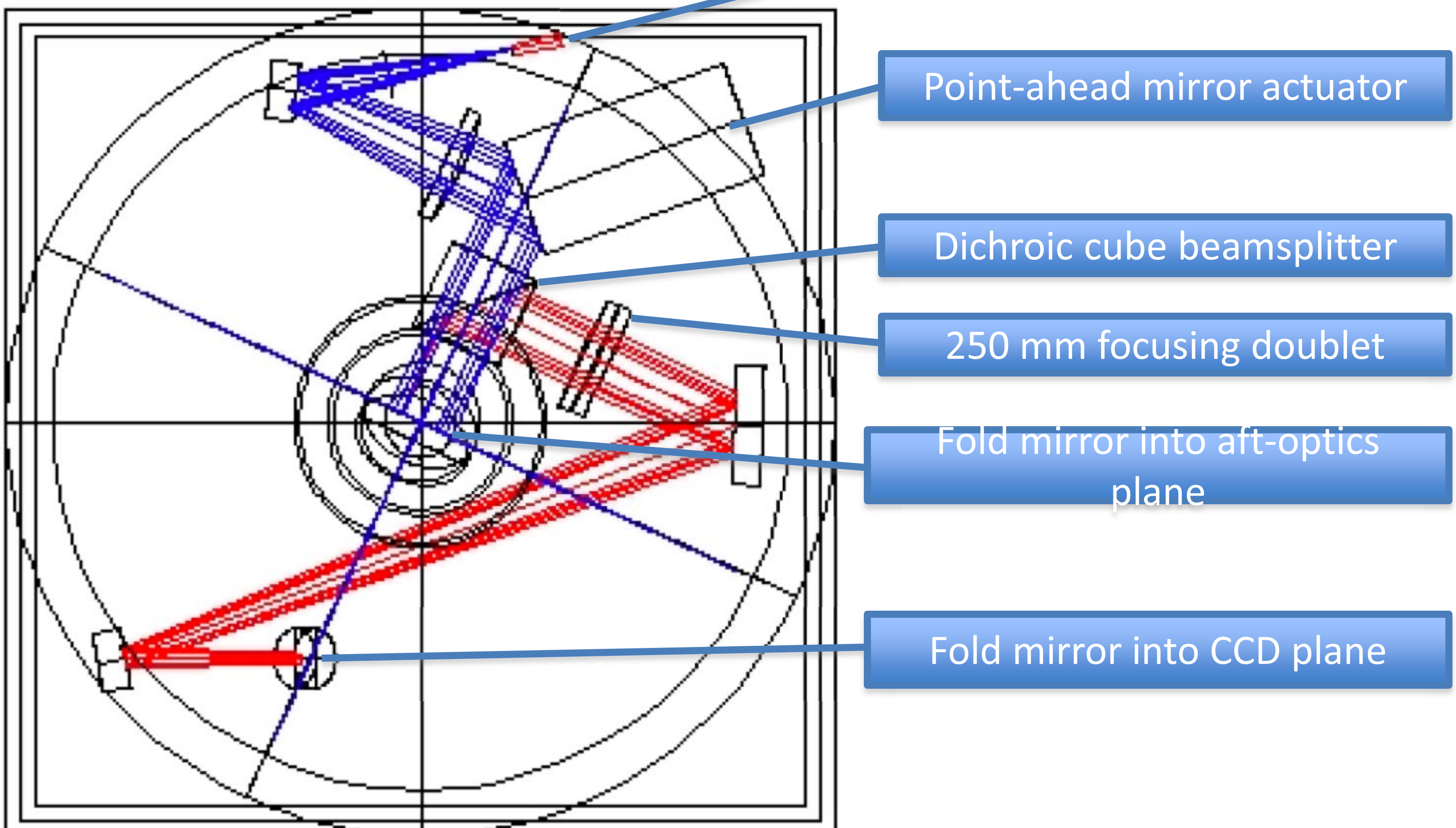
Optical Design - Telescope

- Classical Cassegrain Telescope Design
  - Fast F/1.5 paraboloidal primary mirror
  - Hyperboloidal secondary mirror generating close focus
  - Tilted BK7 plate supports secondary mirror and solar rejection filter



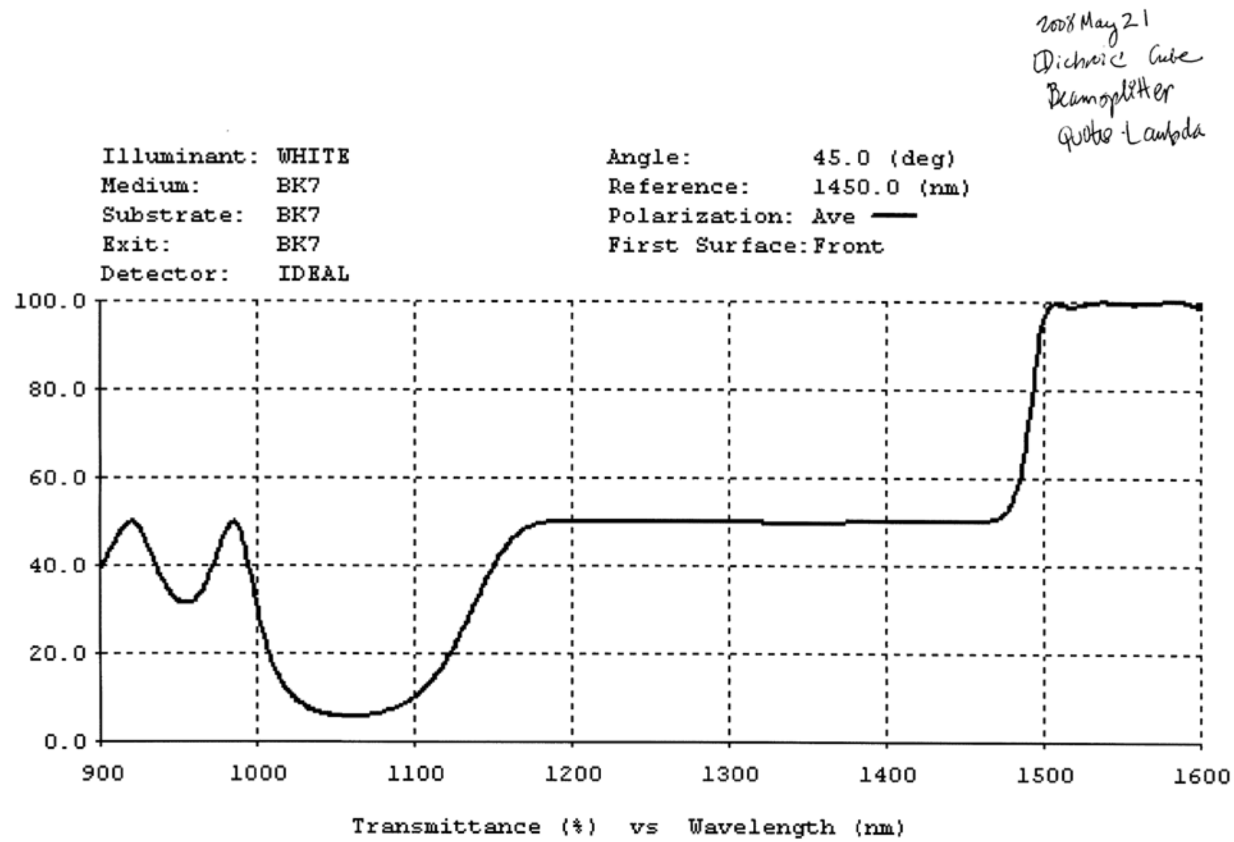
Optical Design – Aft Optics

- Aft-optics plane oriented normal to telescope optical axis
- Two channels separated by dicrhoic beamsplitter cube
  - Downlink laser channel at 1550 nm(in blue)
  - Uplink beacon/comm channel at 1060 nm (in red)

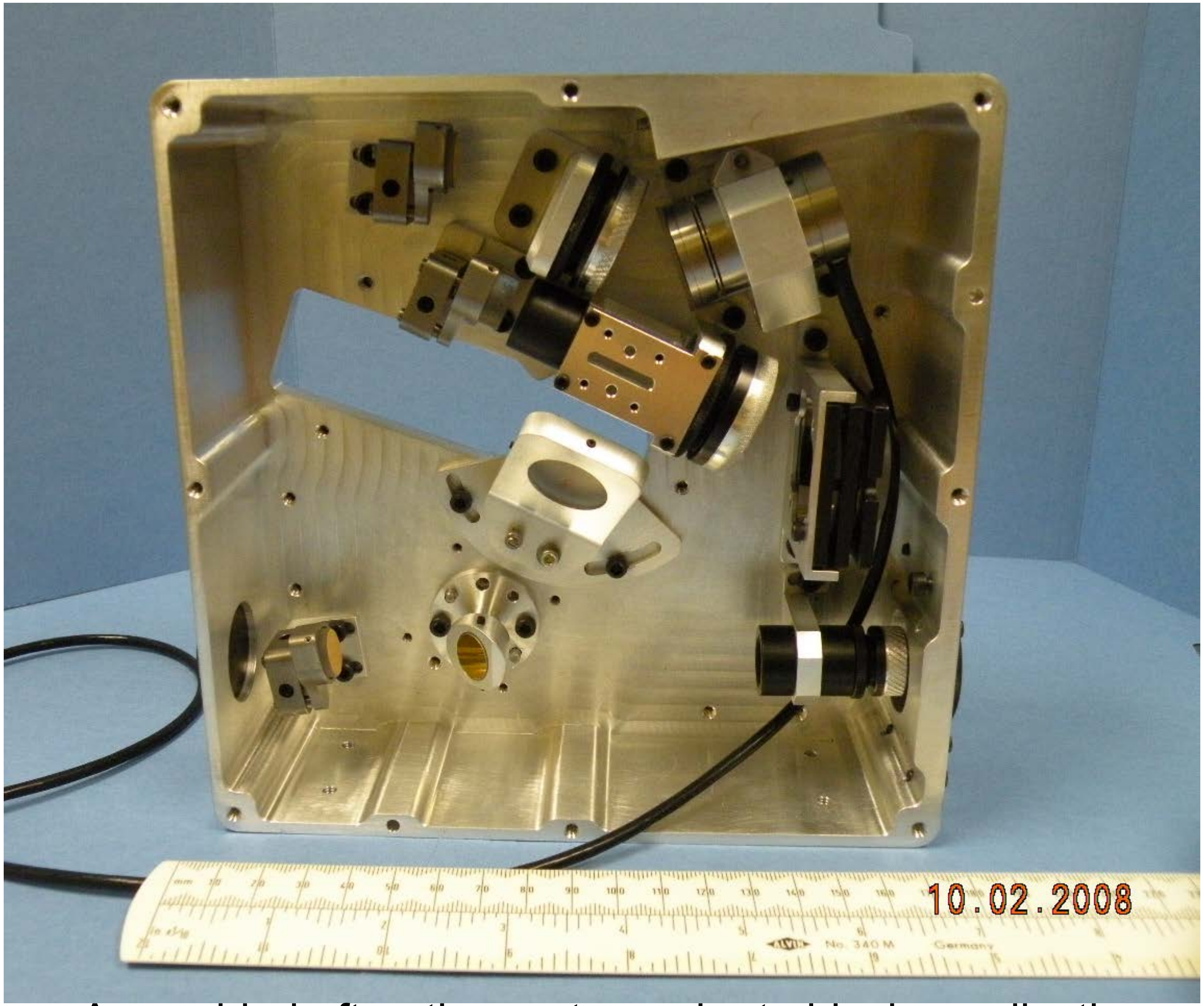


Dichroic Beamsplitter Cube

- Beamsplitter cube separates incoming 1060 nm beacon from emitted 1550 nm downlink
  - 93% reflectance of uplink
  - Near 100% transmission of downlink



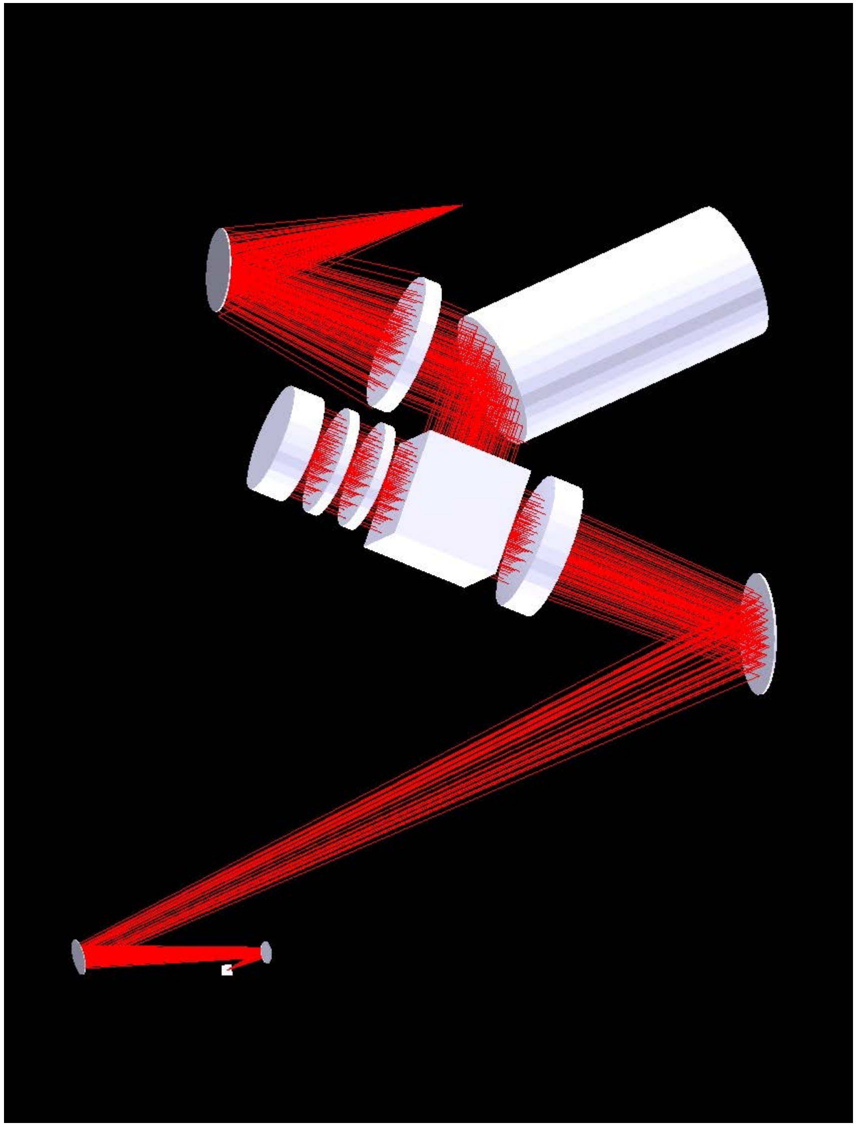
Aft Optics Assembled



Assembled aft-optics system prior to black anodization

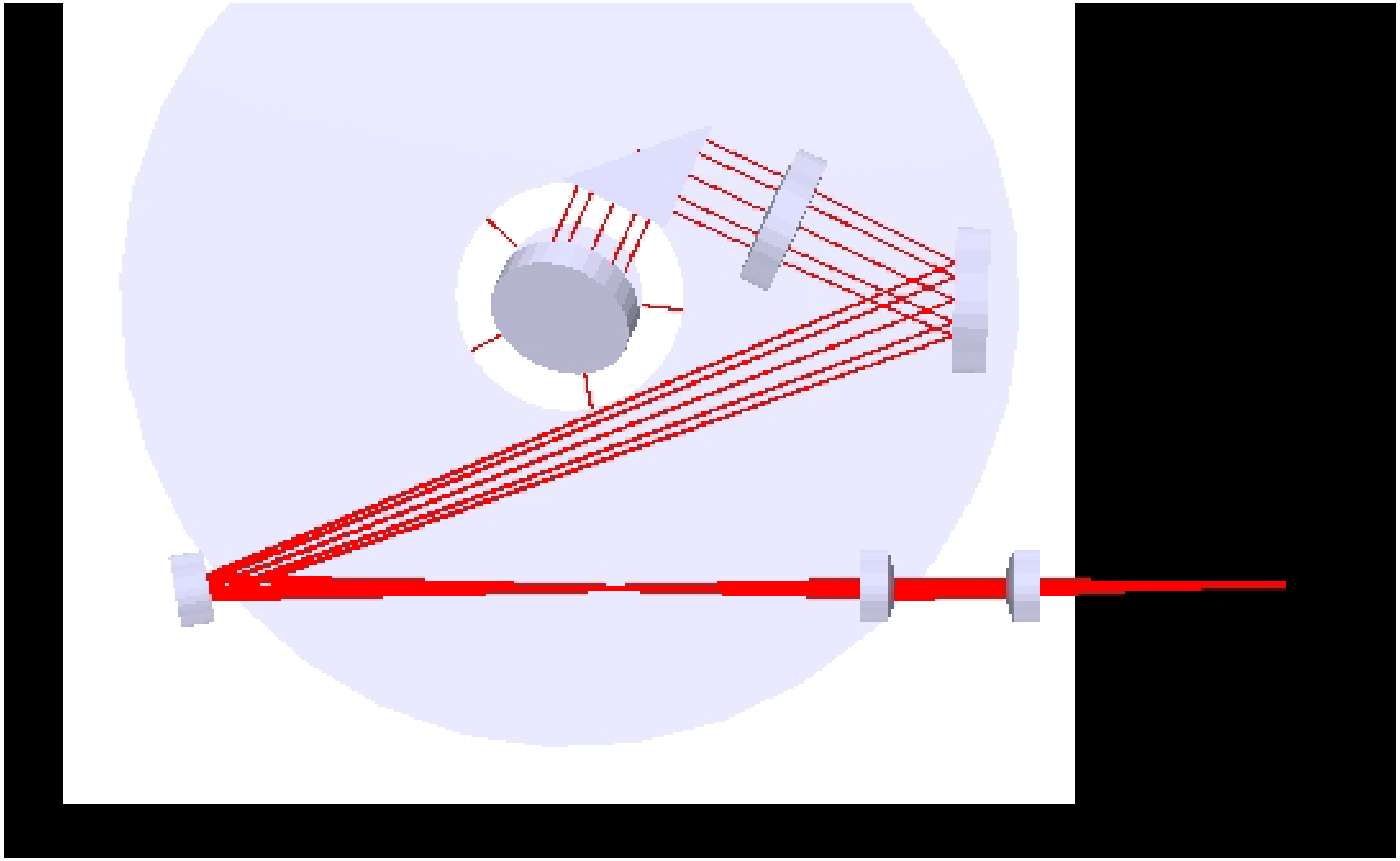
Retro-Mirror Tracking Assembly

- Allows both incoming beacon and emitted beam to be tracked simultaneously on array
  - Observe relative motion of spots
  - Measure point-ahead offset between incoming and emitted beam
- Uses residual reflection from BS cube internal surface
  - Outgoing beam is directed away from receive path
- Retro-mirror re-directs light into receive path
  - Allows for intentional angular offset
  - Places for two absorption filters to reduce intensity
- Curvature of retro-mirror corrects for chromatic focal shift

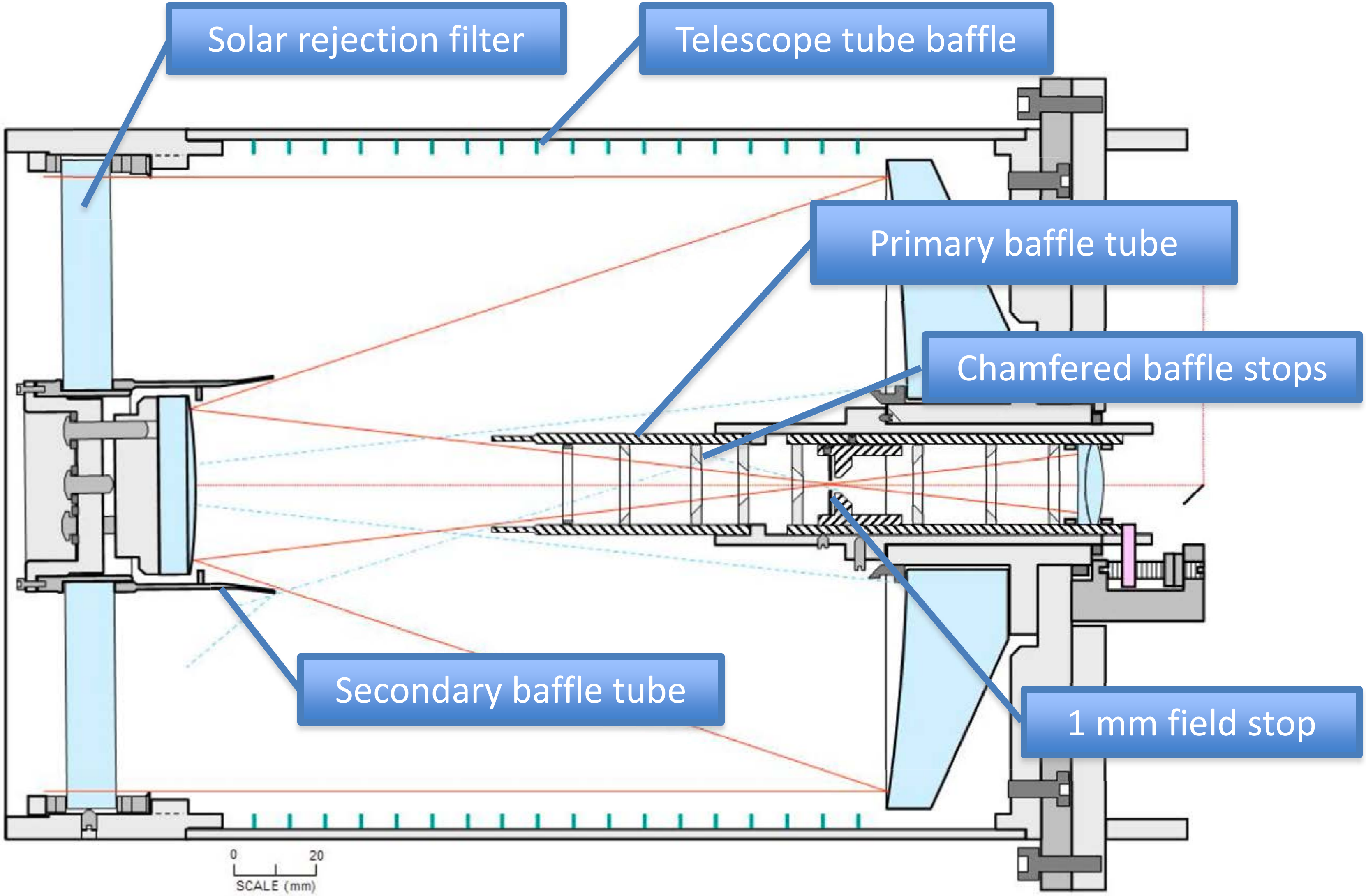


Auxiliary Optical Channel

- Optical channel allows use of transceiver as an optical testbed platform for evaluating candidate focal planes
- Provides external C-mount for attaching camera system
- Requires removal of single fold mirror

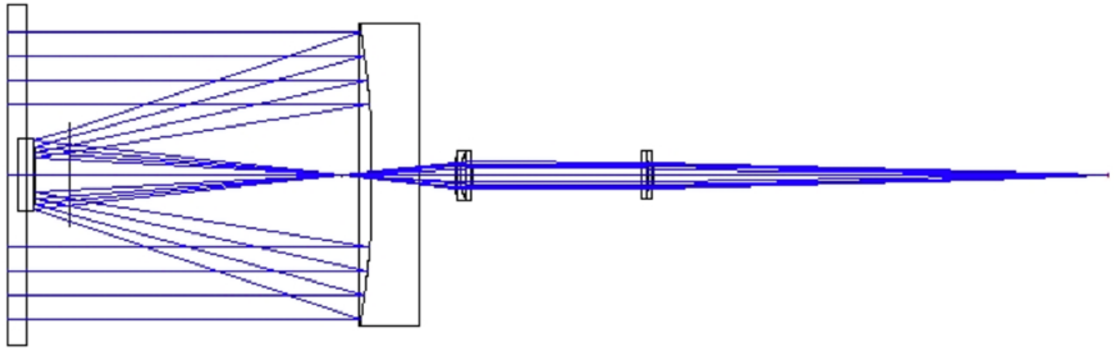


Baffle Design



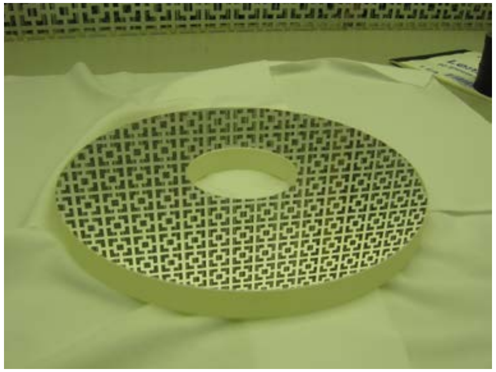
Optical Fabrication

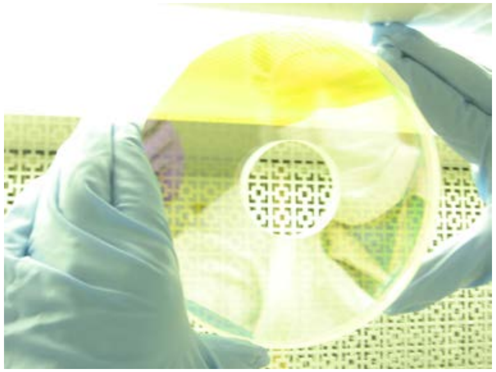
- Differences between fabrication and use drove an iterative approach to the design of the system
  - Fabrication and testing at 532 nm
  - Operation at 1064 and 1550 nm
- Development sequence
  - Design fore telescope
  - Modify telescope to work with off-the-shelf aft optics at wavelength of intended use
  - Supply off-the-shelf lenses (collimator and focuser) to fabrication team
  - Allow spacing of elements to change to minimize RMS spot size at fabrication wavelength (532 nm)
  - Fix element spacings and allow ROC and conic constant of secondary mirror to change to minimize RMS spot size at 532 nm
  - Fix figure of secondary mirror and again allow element spacings to change to minimize spot size at 1064 nm and desired effective focal length
- Results
  - Expected 'As-Built' design performance closely matches original intended performance

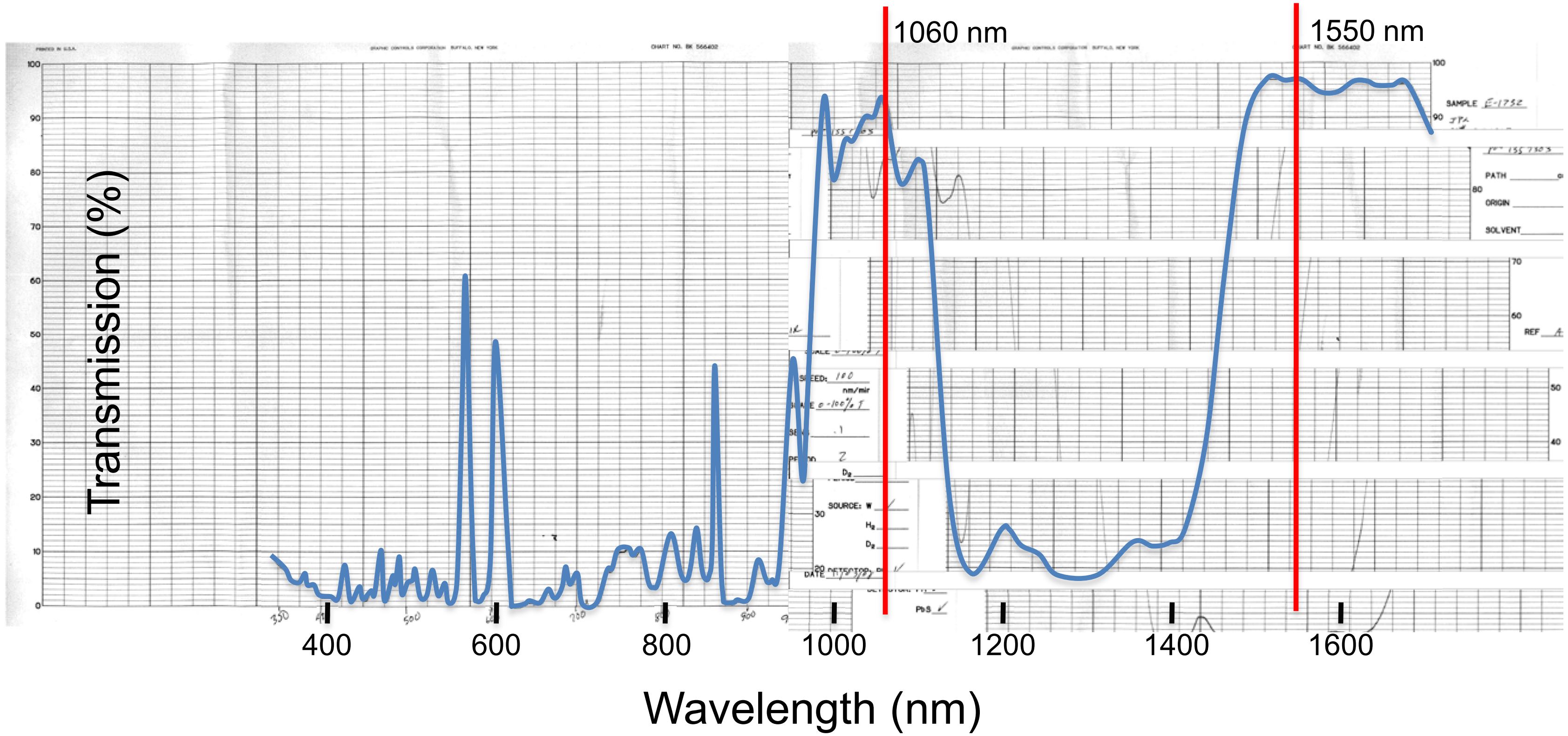


Solar Rejection Filter Window

- Low visible transmission
  - (for alignment and testing)
- 94% transmission at 1060 nm
- 96% transmission at 1550 nm
- 80% of solar power rejected

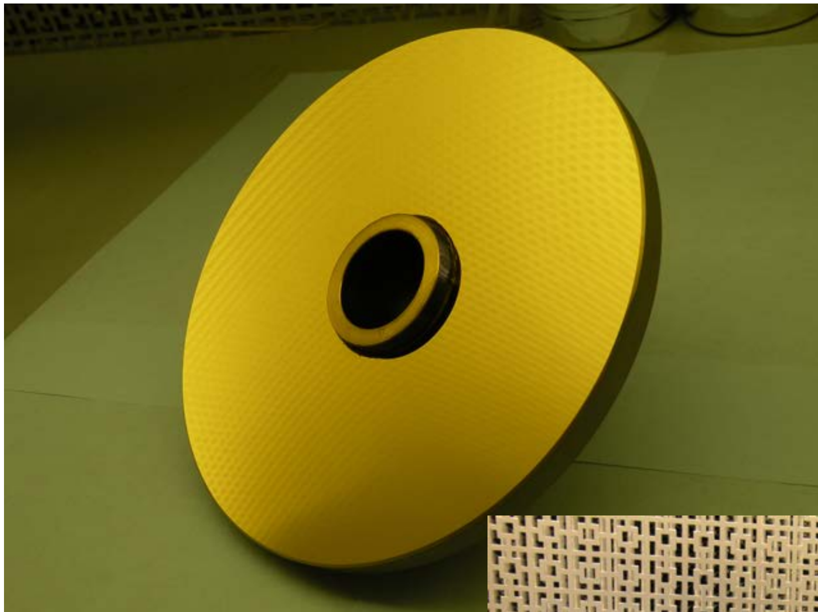


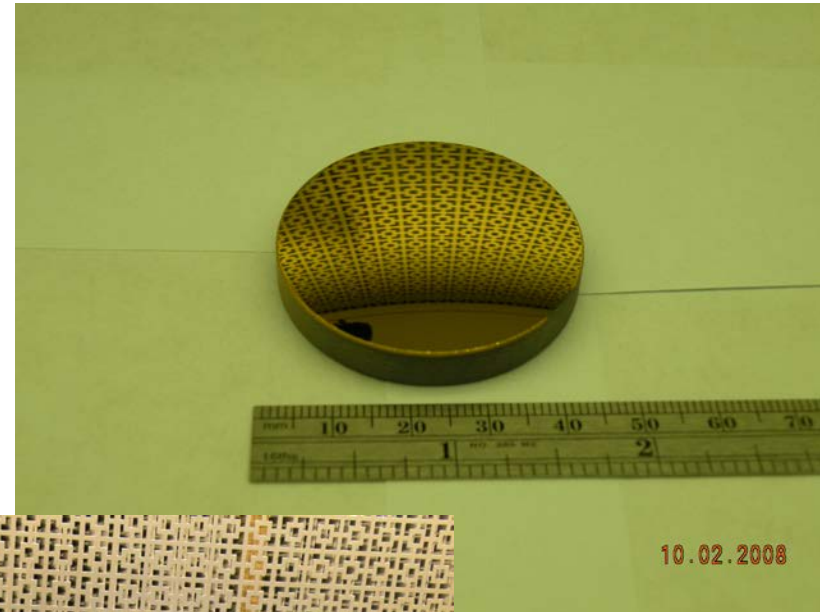


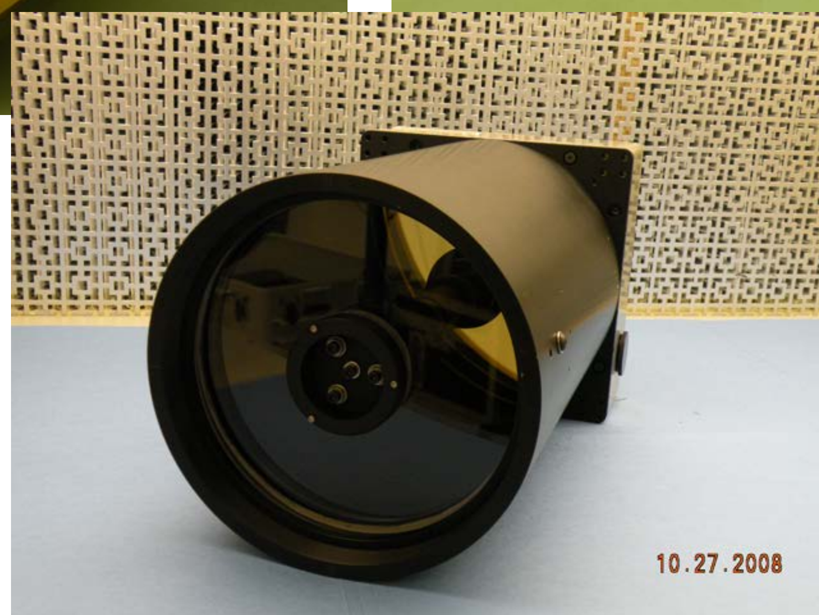


Telescope Assembly

- Telescope components and assembly

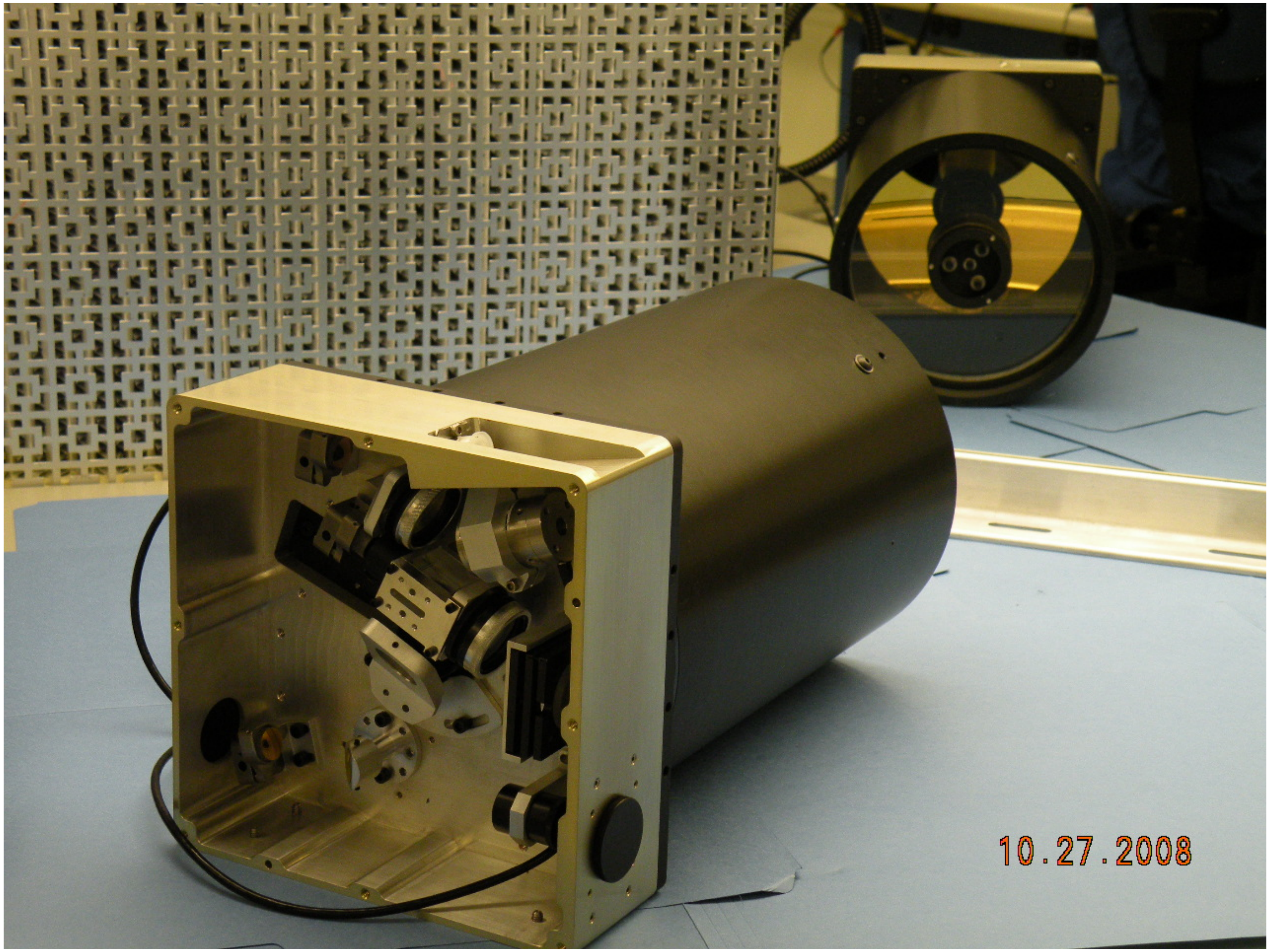






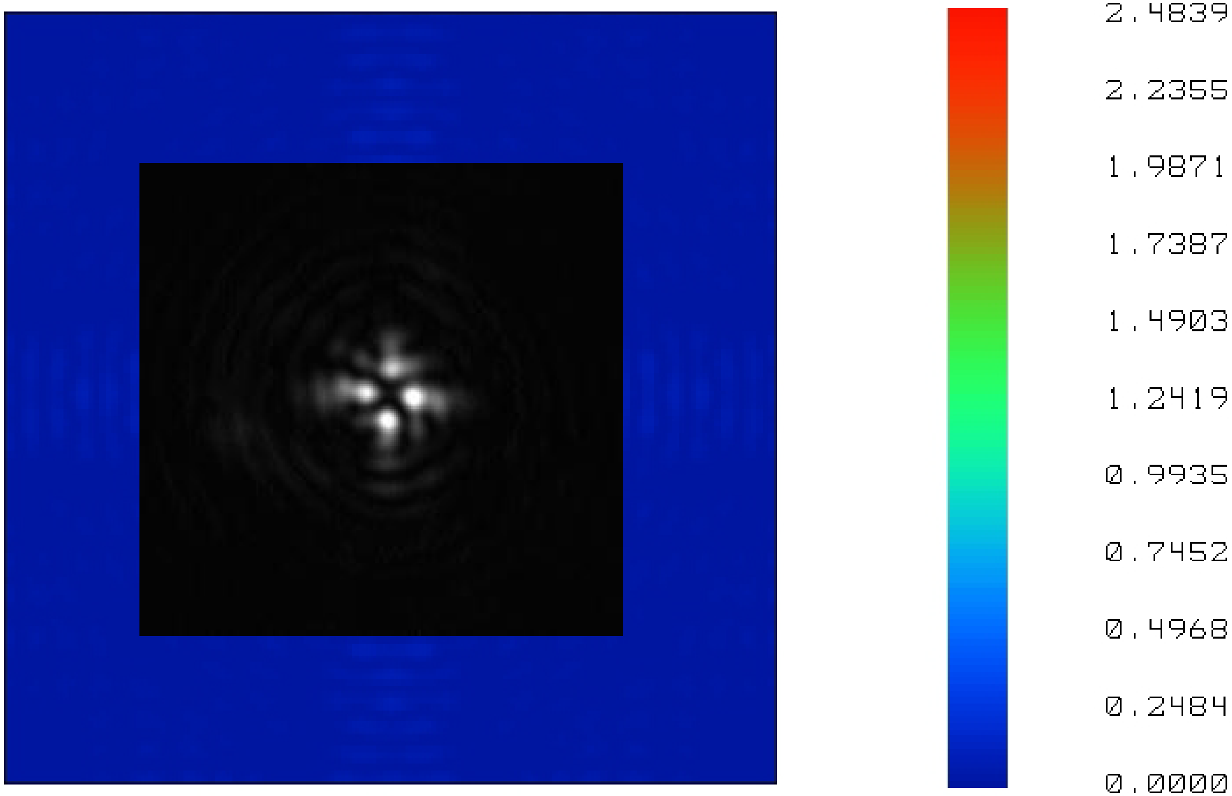
Assembled Optical System

- Integration of aft optics onto telescope assembly



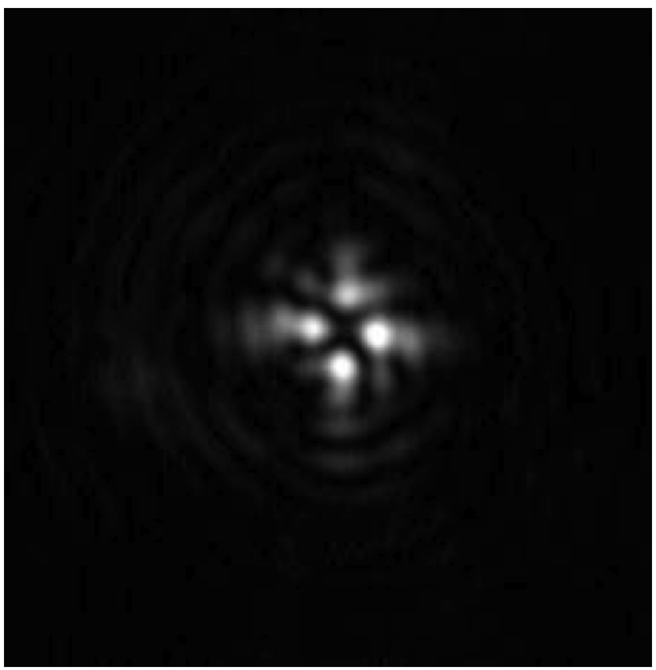
Modeling Primary Mirror Manufacturing Error

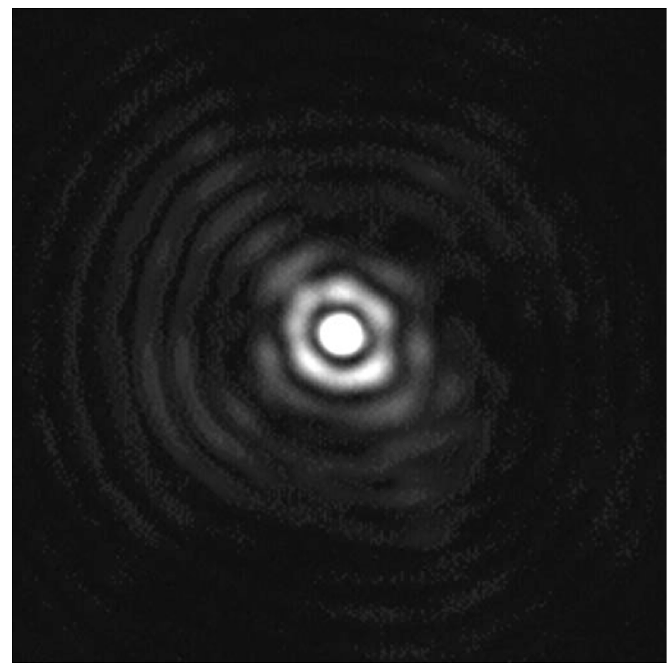
Parameter	Nominal Value	X-axis	Y-axis
Radius	-457 mm	-457.04	-456.96
Conic	-1.00	-1.02	-0.98



Results of Primary Mirror Warping

- Applied ~6.5 pounds of force (29 N) to top and bottom of primary mirror, about 2 cm from the mirror edge
- Recovered annular-aperture diffraction pattern at 0.633 nm
  - Better than required for diffraction limited performance at 1064 nm





Lessons Learned

- Telescope design
  - Future designs will likely be based on Dall-Kirkham telescopes
    - Less troublesome fabrication of spherical secondary
    - Allows for potential autonomous alignment system
- Lens selections
  - Move away from use of gradient-index lenses
    - More difficult and costly to get flight certification
    - Selection and availability are limited
  - Use custom designed and fabricated lenses
    - Higher quality control
    - Custom correction of aberrations (especially chromatic)
    - Minimize iterative development
- Configuration control
  - Implement and enforce configuration control
  - Avoid re-work by rigorous adherence to ICD

Conclusions

- We have designed and implemented an advanced optical communications transceiver
  - Brassboard implementation using custom and off-the-shelf optics
  - Supports uplink tracking and comm. as well as downlink
  - Small volume houses telescope/optics/electronics systems
  - Significant effort expended to limit stray-light background
  - Passive rejection of solar thermal loading
- This system will support multiple efforts in optical communications development
  - Demonstrates advantages of advanced-technology systems
  - Supports field-test programs
  - Acts as a platform for evaluation of advanced detector arrays