Liquid Lenses for Free Space Optical Communications (FSOC)

Shreeyam Kacker, Kerri Cahoy
MIT STAR Lab

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mosaic-nasa@mit.edu

Agenda

- Liquid Lens Technology Review
- MOSAIC Overview
- Environmental Testing
- Optical Performance
- Transceiver Prototyping
- Conclusions
- Future Work
- Publications & Research Products

Liquid Lens
Technology Overview

Liquid Lenses

Corning Varioptic A-39N0

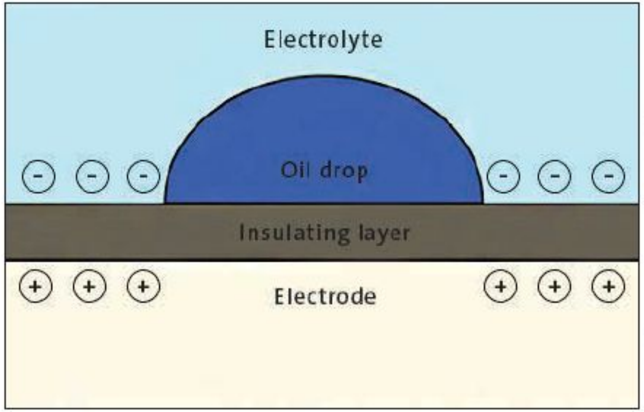
- 3.9 mm aperture
- Electrowetting driven type
- +15 to -5 diopter focal range
- -20 °C to 65 °C operating range

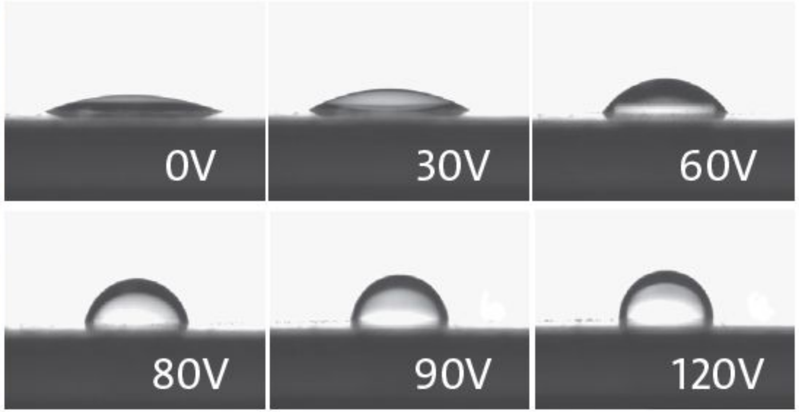
Optotune EL-16-40-TC-VIS-20D

- 16 mm aperture
- Pressure driven type
- ±10 diopter focal range
- -20 °C to 60 °C operating range

Liquid Lens Types

Image From: Corning Varioptic Lenses Dev Kit Documentation (PDF), Corning [1]





The shape of the drop then changes as voltage increases

Electrowetting
Driven Liquid Lenses (Corning)

Pressure
Driven Liquid Lenses (Optotune)

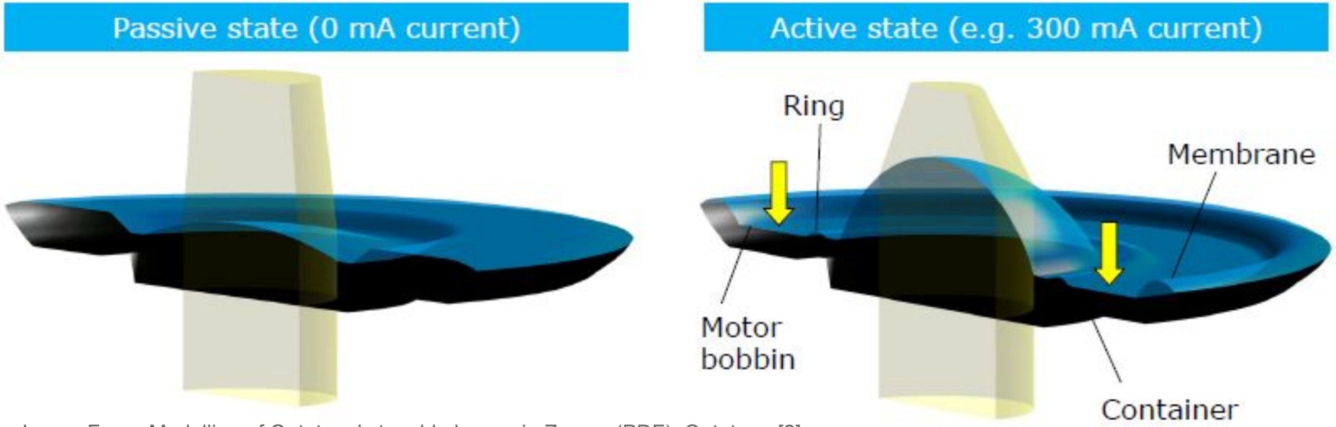


Image From: Modelling of Optotune's tunable lenses in Zemax (PDF), Optotune [2]

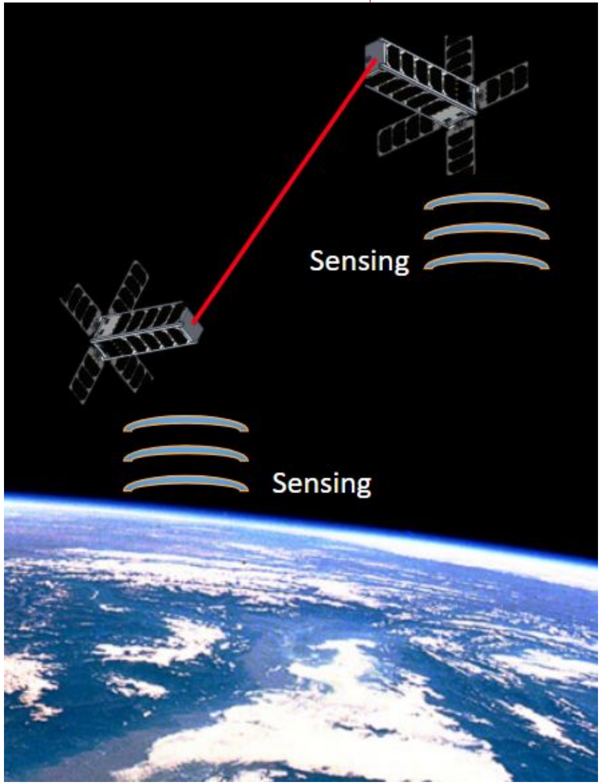
MOSAIC Overview
Miniature Optical Steered Antenna for Intersatellite Communication

Statement of Innovation

MOSAIC will investigate the use of ***liquid lenses*** as a potential steering method by which to develop a hemispherical multi point-to-point small satellite laser “antenna”

Motivation

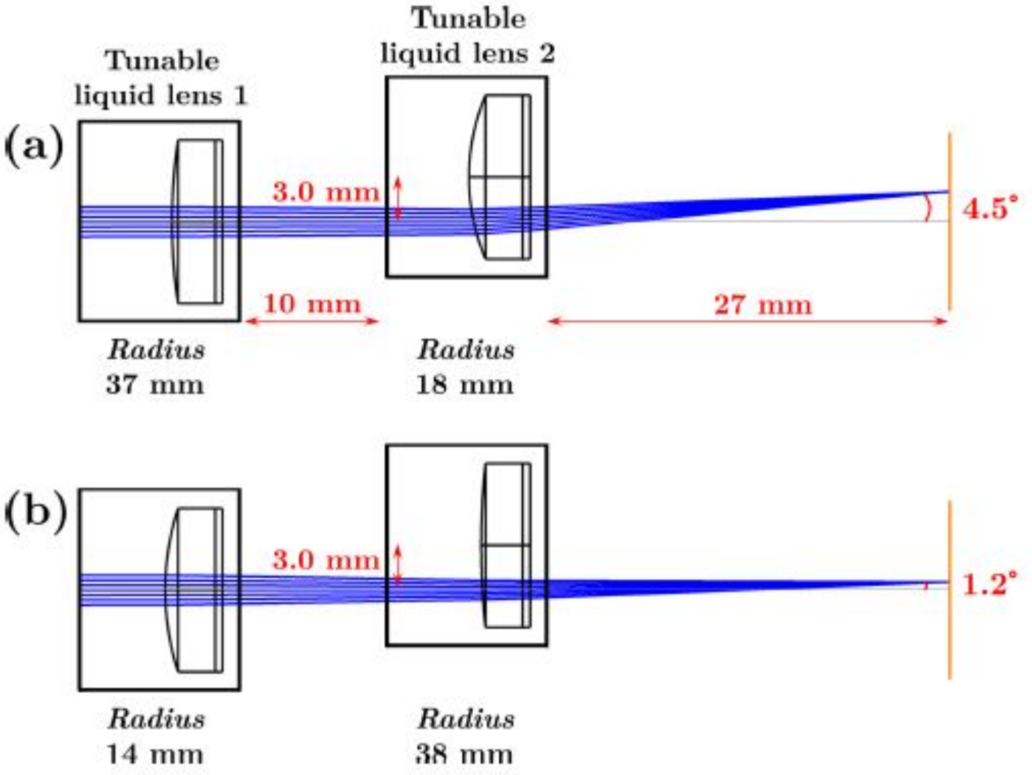
- Higher data rates needed for CubeSat payloads
  - RF spectrum crowded and regulated
  - Laser communications (lasercom)
    - Power efficient, currently unregulated spectrum
- Need multiple-access or multicast solutions
  - Satellite swarms and distributed sensing
  - Lasercom typically point-to-point
- Pointing Acquisition & Tracking (PAT)
  - Mechanical solutions are large, power-hungry
  - More efficient Fast Steering Mirrors (FSMs) have small apertures
  - Desire independence from spacecraft body pointing



There is a need for a compact beam steering device with large angular throw

Prior Work

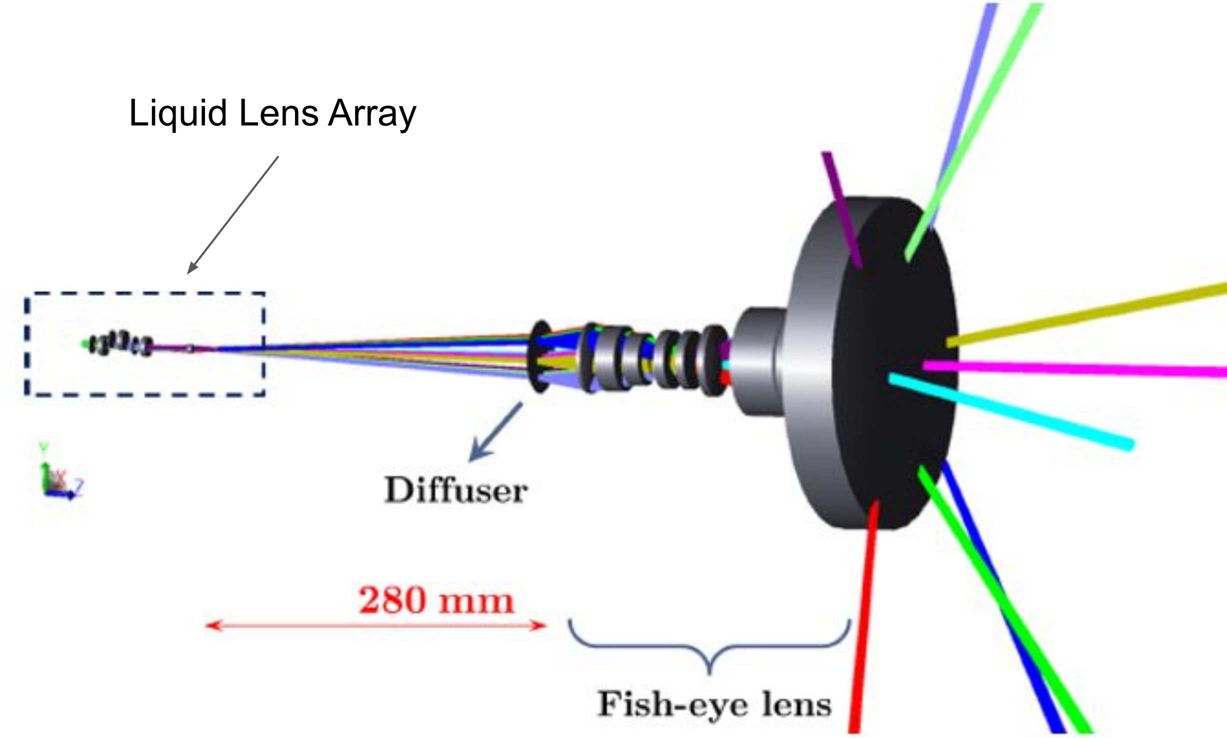
- Zohrabi et al. 2016
  - University of Colorado, Boulder
- Refract laser through **off-axis tunable lens**
  - Lens on-axis to control beam divergence
- 3 lenses for 2D steering
  - 1 on-axis for **divergence control**
  - 2 offset in **x and y** for steering



M. Zohrabi, R. H. Cormack, and J. T. Gopinath "Wide-angle nonmechanical beam steering using liquid lenses," Optics Express, Vol. 24, No. 21, Oct. 2016.

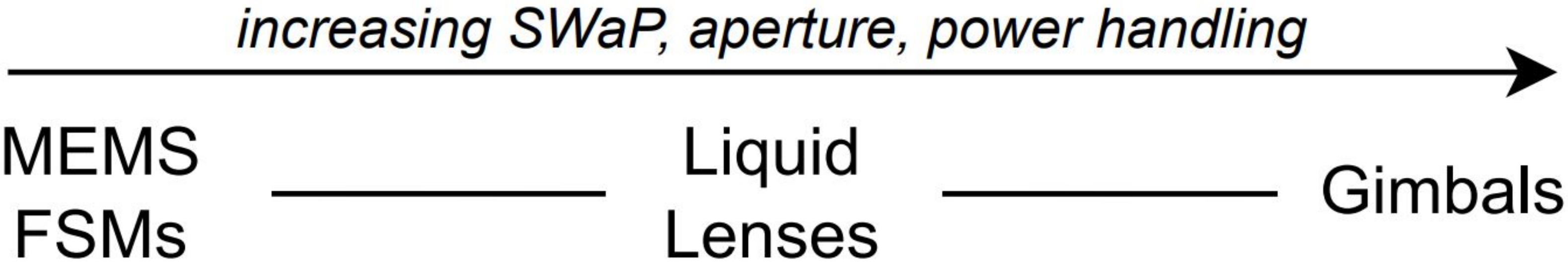
Prior Work

- Diffuser and fisheye increases steering
- Liquid lenses steer focused “dot” on diffuser
- Point source at focal length of fisheye lens
    - Fisheye lens creates collimated light with wide angle (154°) steering



M. Zohrabi, R. H. Cormack, and J. T. Gopinath “Wide-angle nonmechanical beam steering using liquid lenses,” Optics Express, Vol. 24, No. 21, Oct. 2016.

Beam Steering Technologies



Environmental Testing

Environmental Testing Campaign

- TVAC
- Radiation
- Power Handling
- Zero G

Initial Survivability Test

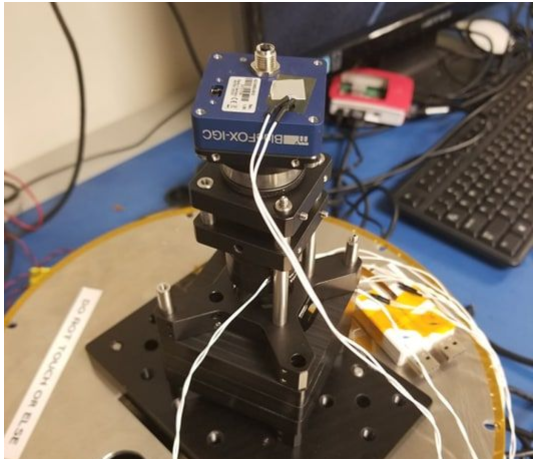
- 72 hours of soft vacuum exposure in inexpensive chamber
  - Soft vacuum of 0.04 Torr (5Pa)
- Corning lens had no visually apparent changes
- Bubbles in Optotune lens aperture
  - Formed immediately on pump-down
  - Diffused from lens membrane after two weeks of soft vacuum exposure
  - Repeated with 3 separate lenses
  - **No bubble formation on newer lenses**

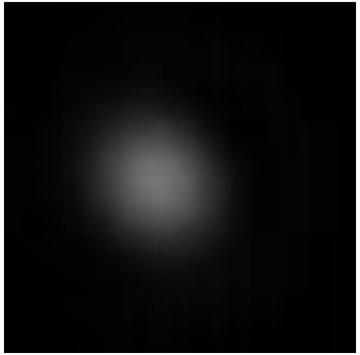
Corning

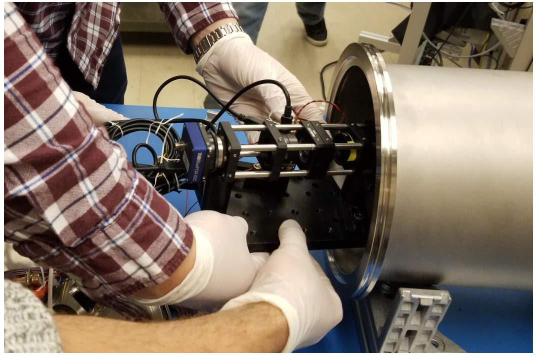
Optotune

Thermal Vacuum (TVAC) Testing - Ongoing

- Purpose
  - Analyze liquid lens operation in vacuum & thermal extremes
  - See how thermal impacts predictable performance of the lens
  - Steering transfer functions over temperature range
- Overview
  - Initial testing from -20 C to 60 C (specified operating range)
  - Stress testing from -40 C to 85 C (specified storage range)
  - Cooled in liquid nitrogen shroud, heater adhered to lens mounts
  - RTDs to monitor temperature
  - 635 nm (red) used for testing

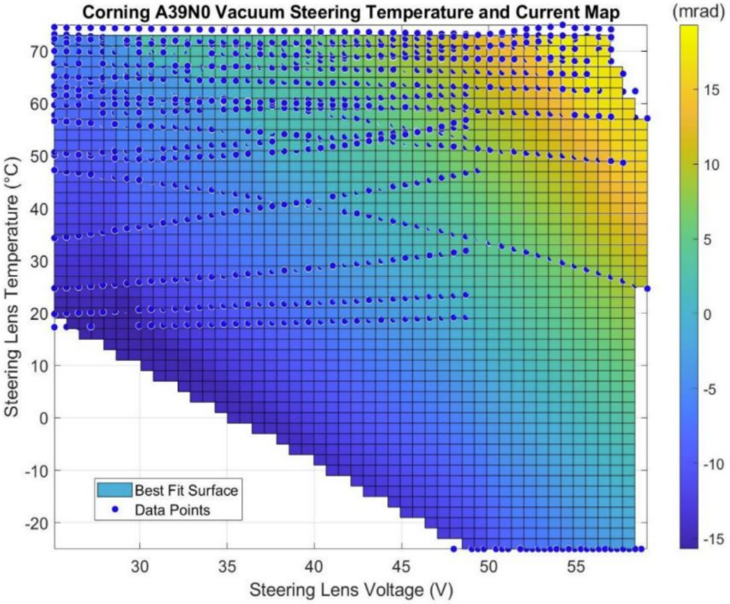


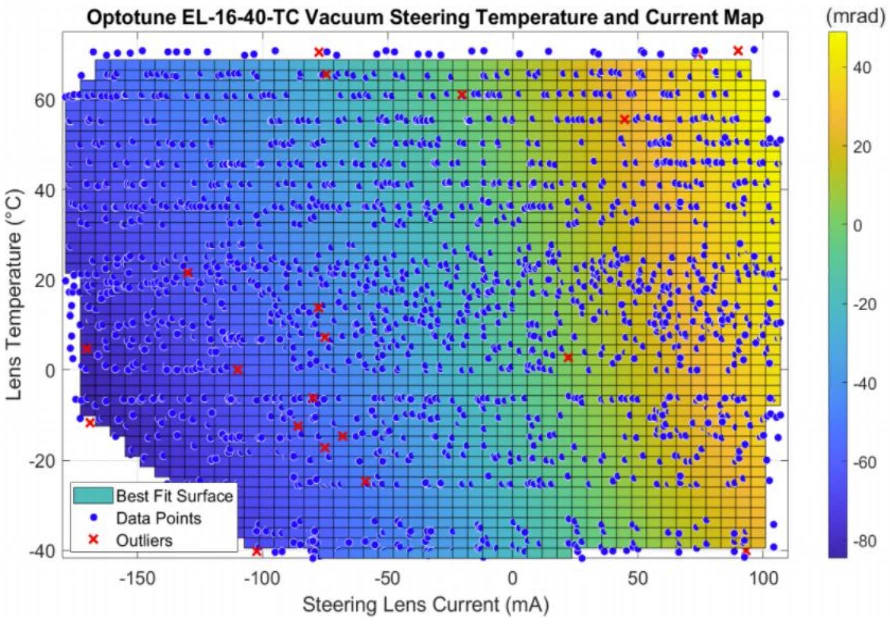




Thermal Vacuum Testing

- Stress testing from -40°C to 85°C (specified storage range)



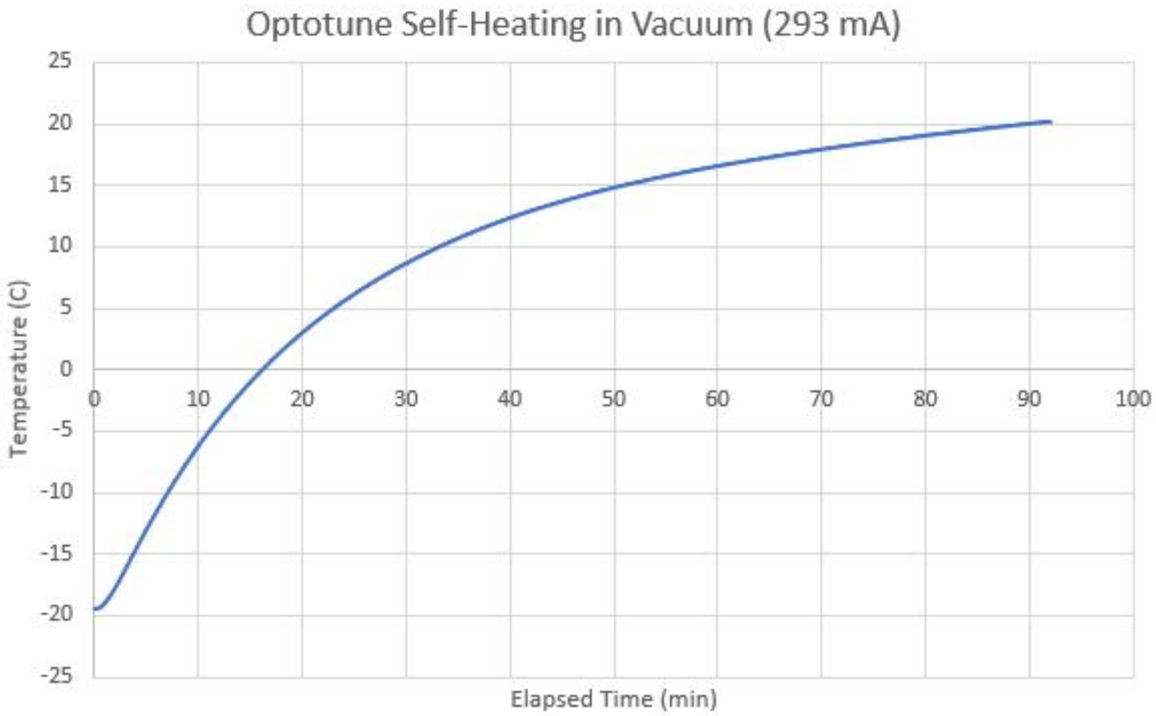


- Thermal drift found to be mostly linear with some change around high steering current or voltage
  - 0.24 mrad/°C (Corning), 0.19 mrad/°C (Optotune) [2]

Optotune Vacuum Self-Heating

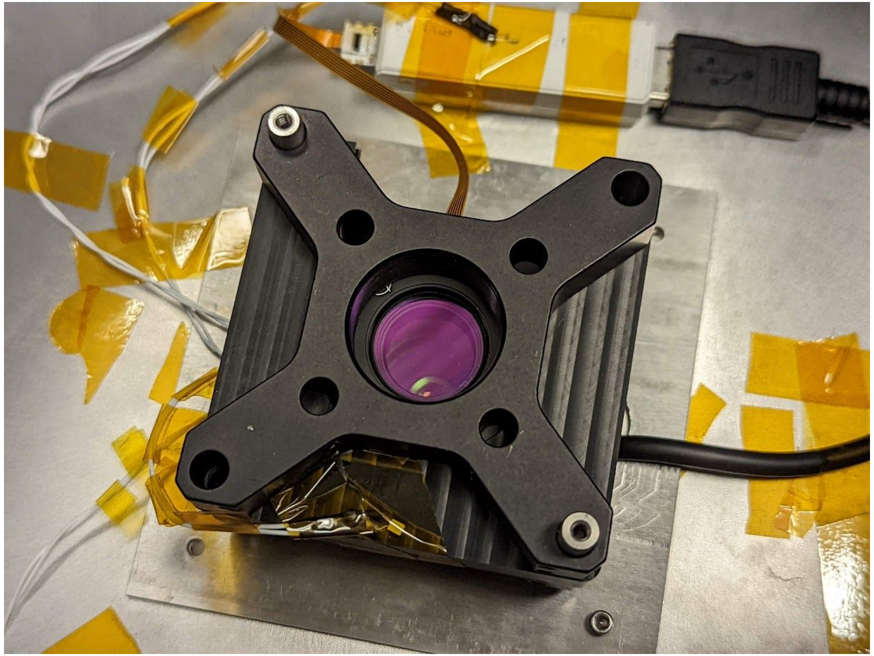
- Heat management concern for Optotune lens in vacuum
  - Supplied current up to 293 mA
  - Operational range during steering between -100 and +100 mA
  - Corning, however, has negligible power draw

- Optotune current set to maximum, temperature was recorded over time
  - 40 C rise over 1.5 hours of max current operation



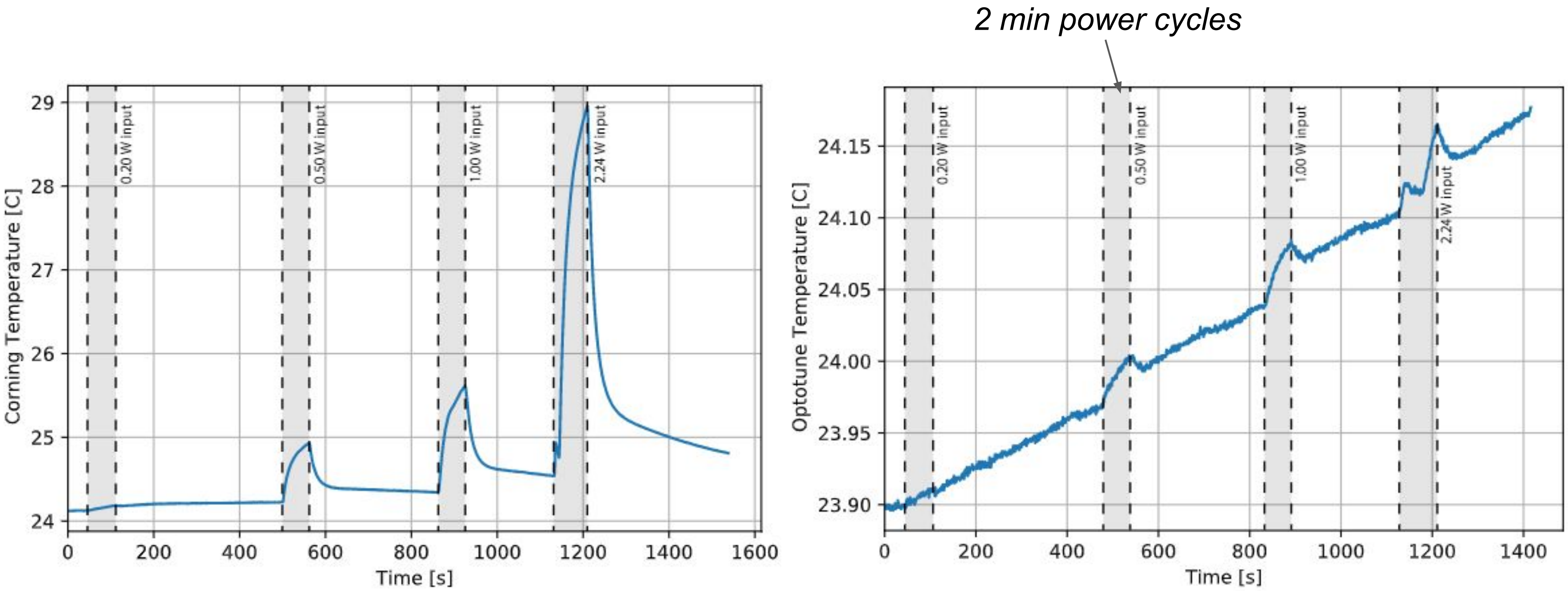
Power Handling (1/2)

- Experiment to determine laser induced damage threshold (LIDT) and transmission at 1550 nm
- NIR and 1550 nm optimized lenses tested
- Lenses placed in TVAC with fiber feedthrough
- Exposed to power levels up to 2.25 W and profiled in between runs
- Thanks to Tim for the EDFA :)



Optotune lens mounted in TVAC chamber

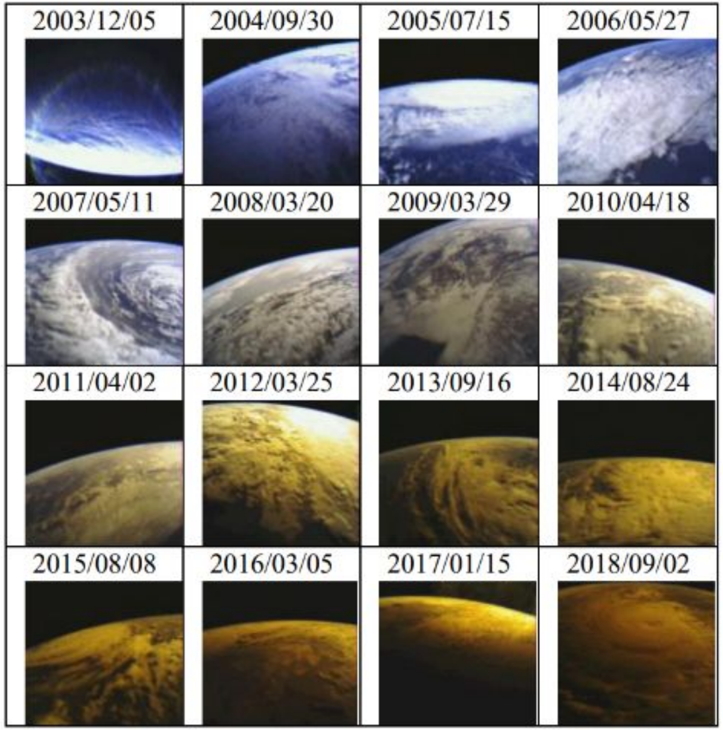
Power Handling (2/2)



Optotune (left) and Corning Varioptic (right) temperature rise during experiment
Corning Varioptic: 89% transmission, Optotune: 96% transmission at 1550 nm

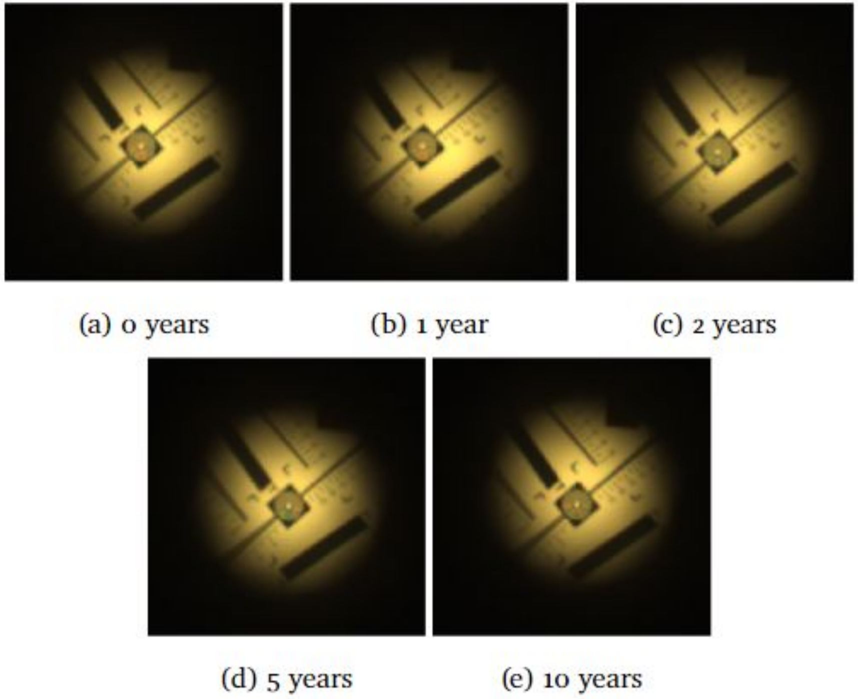
Radiation Testing (1/6)

- Radiation can cause yellowing and darkening of all optics in space
- Optical fluids are proprietary and not characterized in the radiation environment
- Lenses placed in Co-60 Gammacell at MIT and profiled in between irradiator runs to understand transmission loss

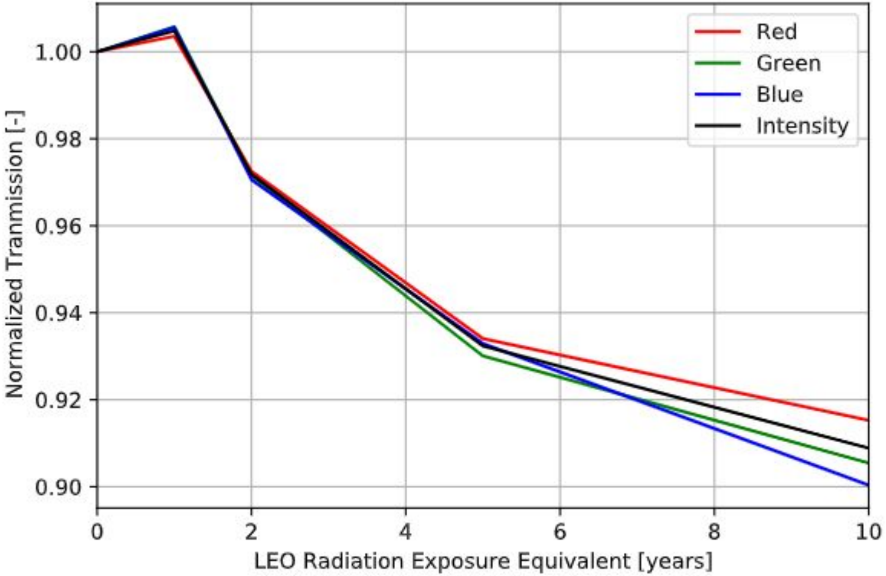


Selected images taken from XI-IV CubeSat taken over 15 years, showing yellowing of conventional glass optics due to radiation exposure

Radiation Testing (2/6)



Corning Varioptic test chart images after LEO equivalent radiation exposure



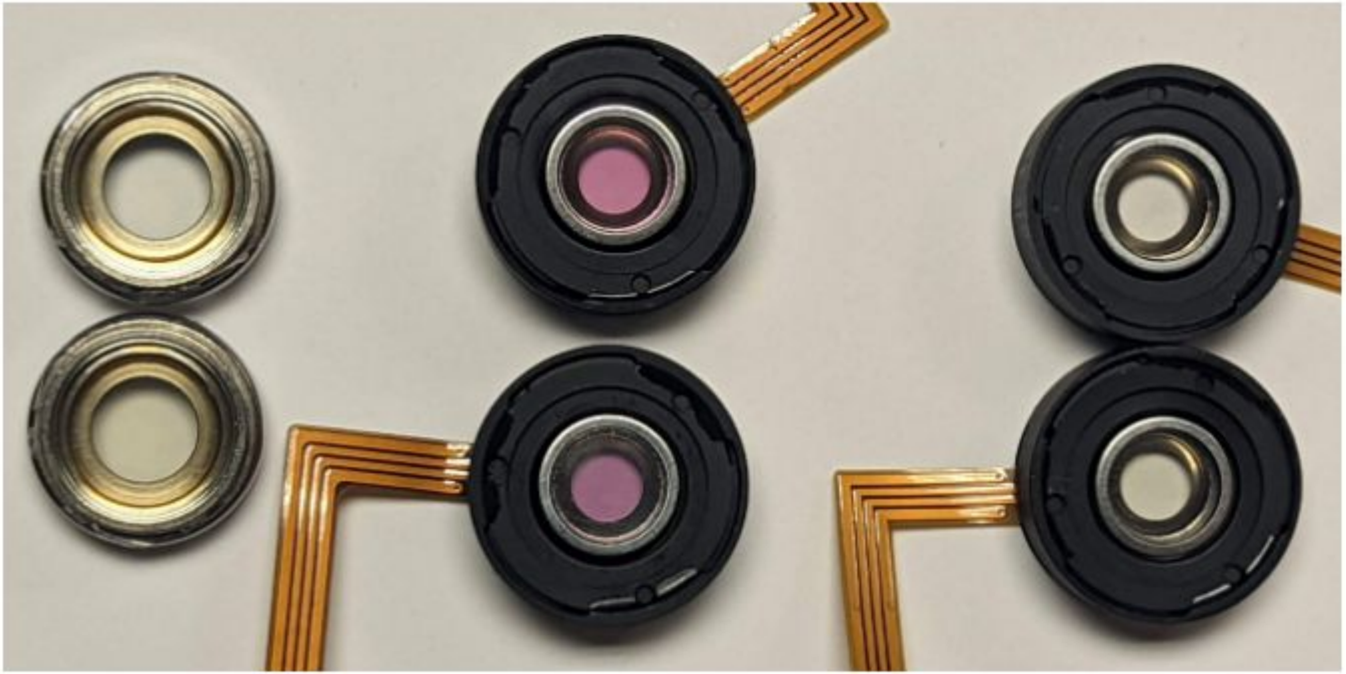
Corning Varioptic transmission after LEO equivalent radiation exposure

Radiation Testing (3/6)

1550 nm *NIR* *VIS*

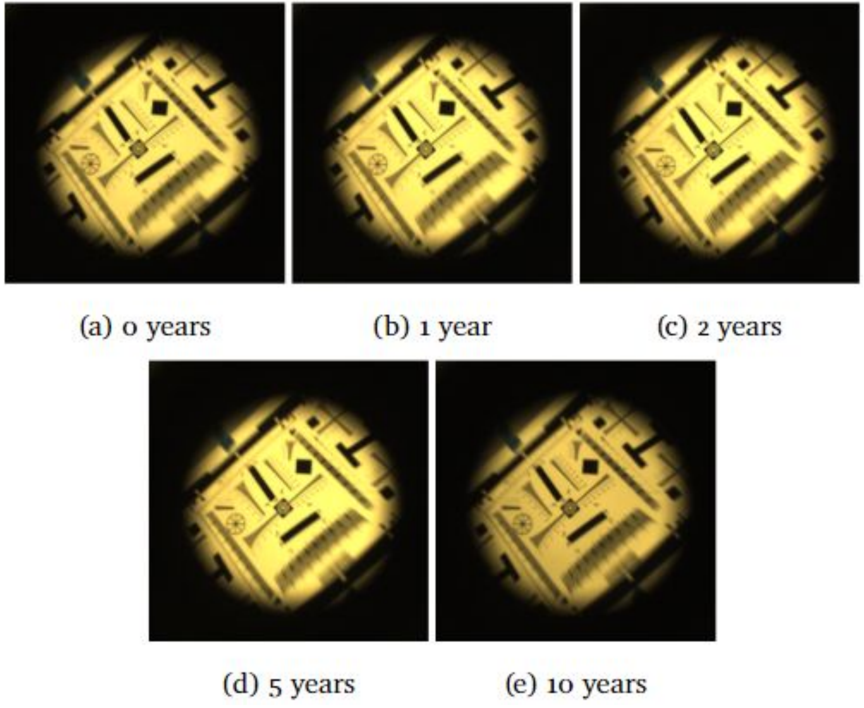
Before

After

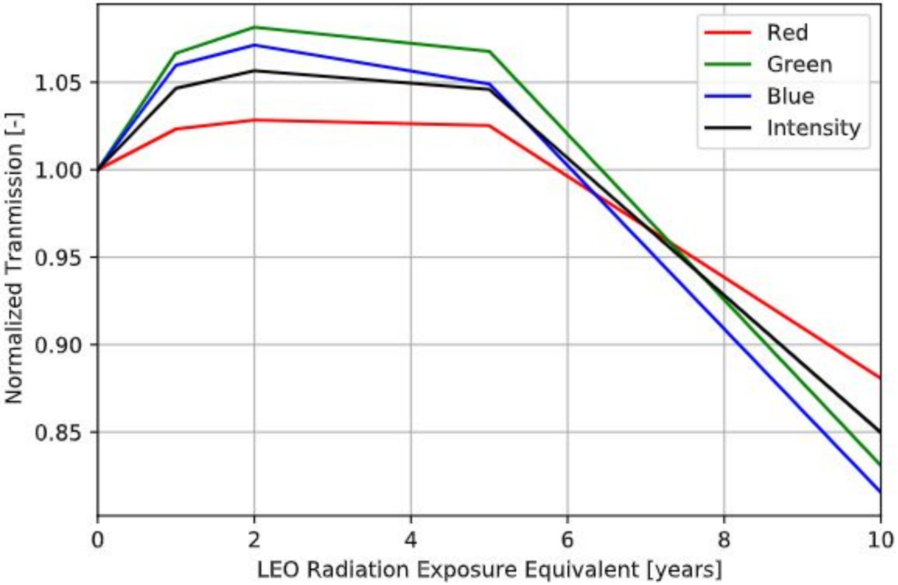


Corning Varioptic lenses before and after 70 krad of radiation exposure

Radiation Testing (4/6)

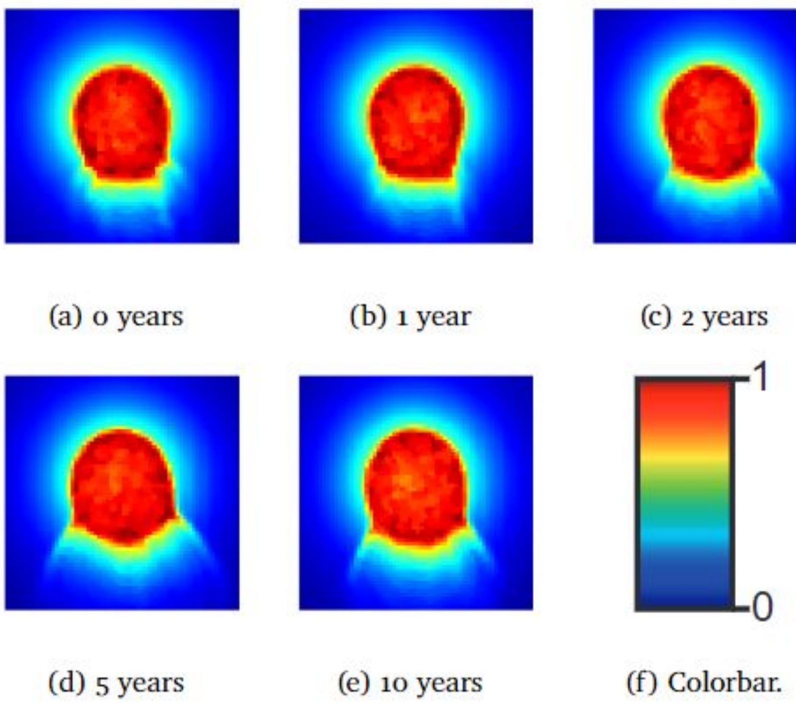


Optotune test chart images after LEO equivalent radiation exposure

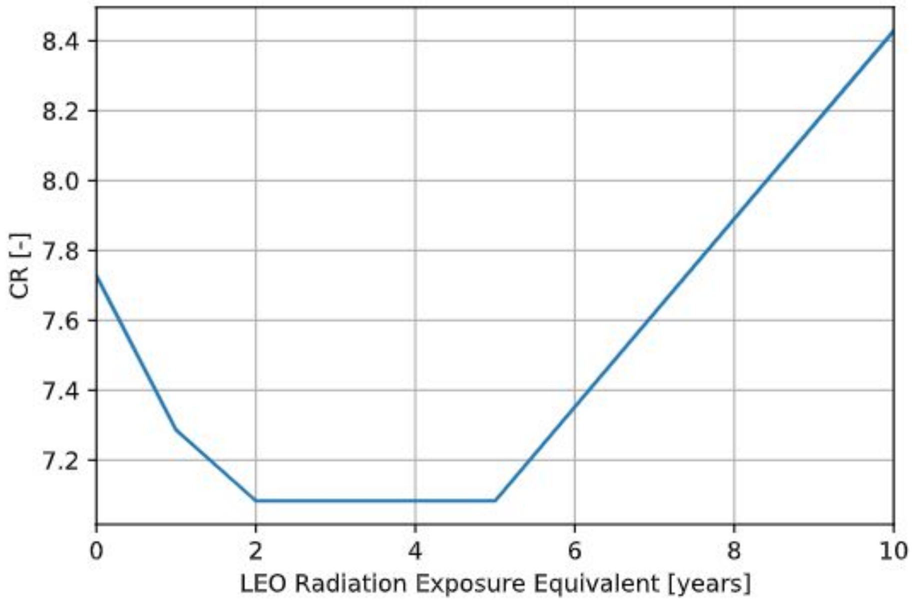


Optotune transmission after LEO equivalent radiation exposure

Radiation Testing (5/6)

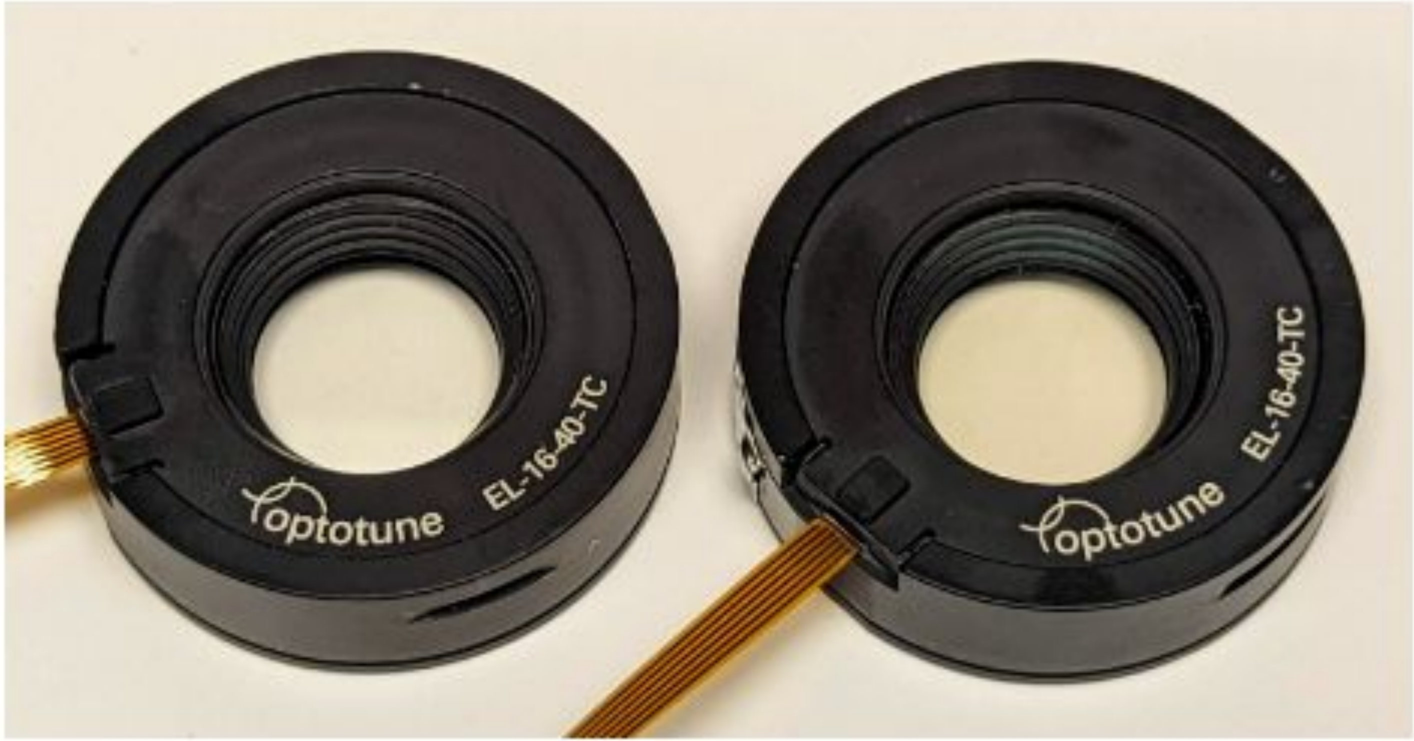


Optotune NIR lens focal spots after LEO equivalent radiation exposure



Optotune contrast ratio after LEO equivalent radiation exposure

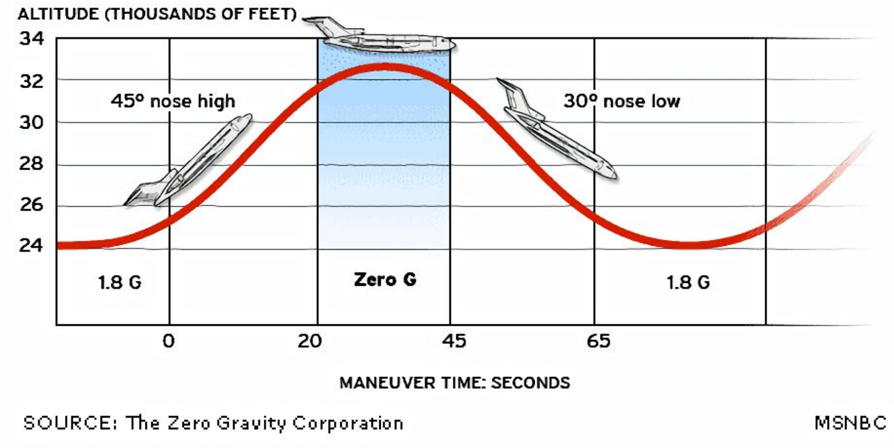
Radiation Testing (6/6)

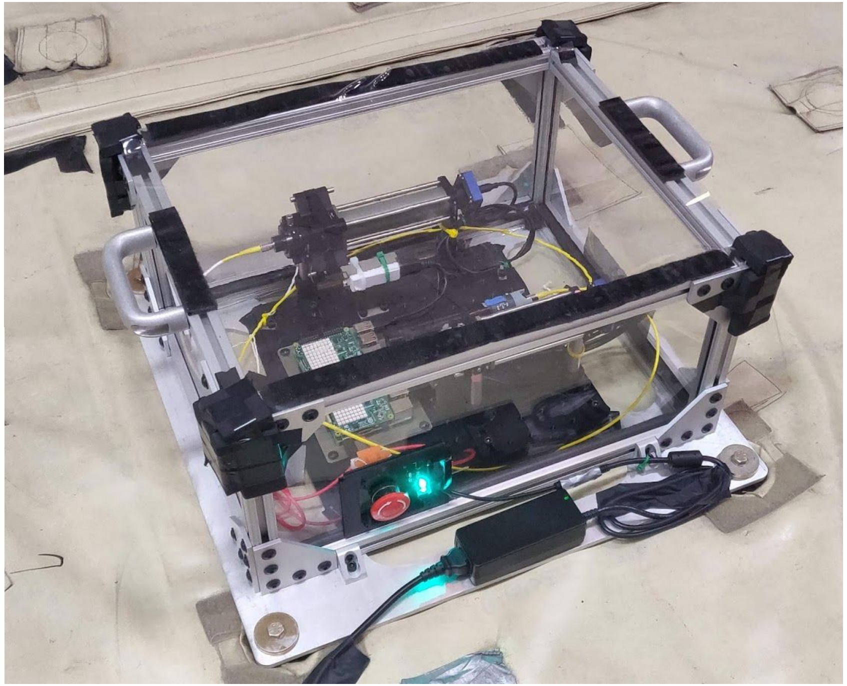


Optotune VIS lenses before and after 70 krad of radiation exposure

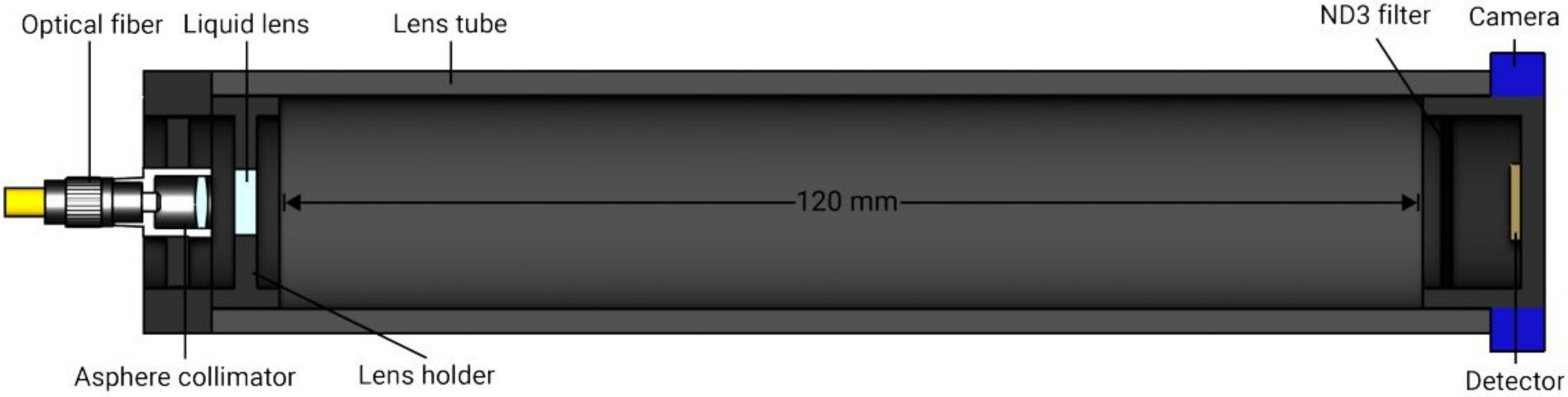
Zero G Testing (1/2)

- Liquid lenses flown zero-gravity flight to assess performance difference in space environments
- Liquid can potentially sag in presence of gravity, creating coma aberration
- Single liquid lens with 633 nm collimated beam used to focus spots on a detector (intensity only)
- Data of liquid lenses in 0g, 1g, and 1.5+g obtained



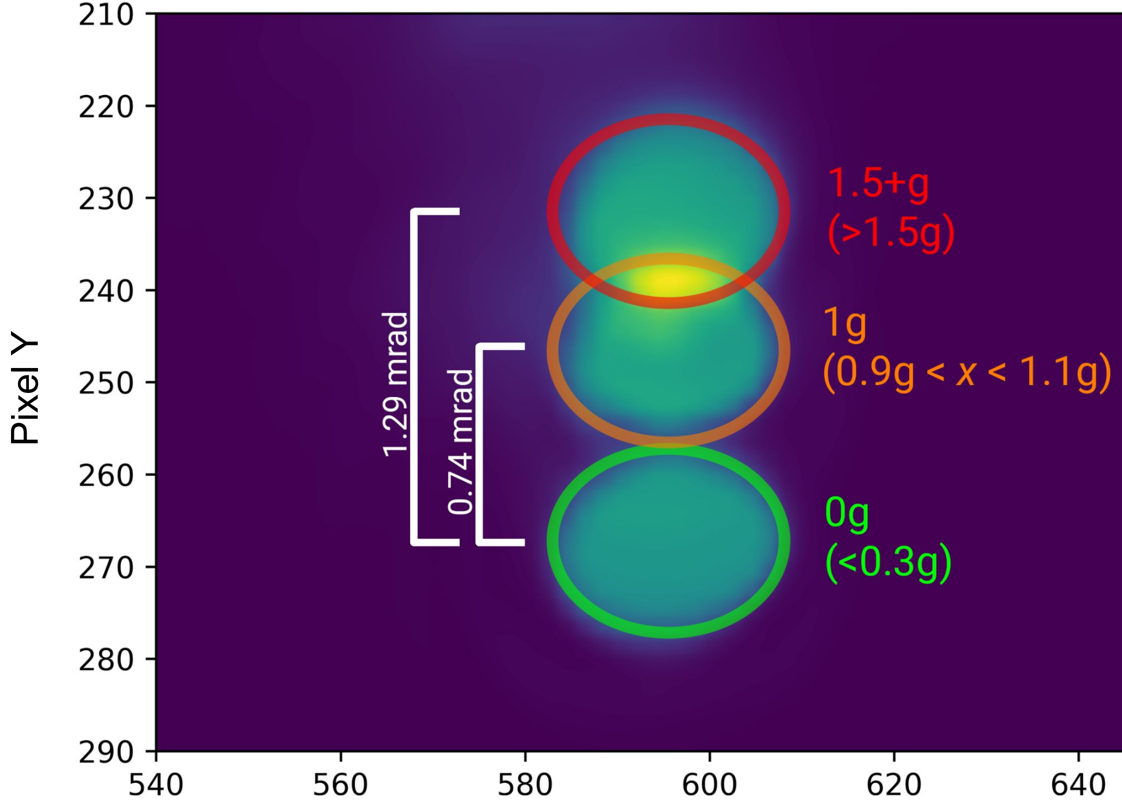


Zero G Testing (2/2)



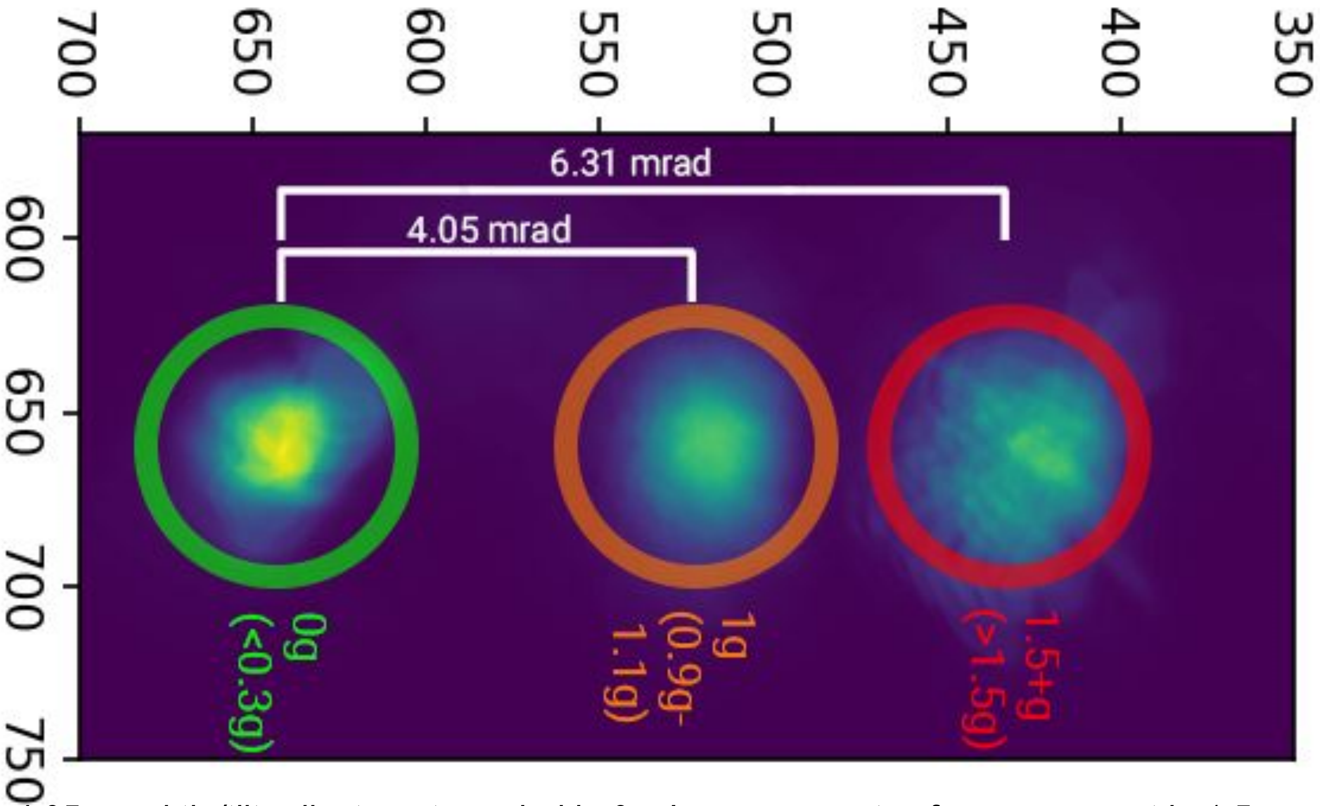
Microgravity experiment optical train

Zero G Results (Corning Varioptic)



Small (0.74 mrad) tip/tilt adjustment needed in 0g. No visible change in coma.

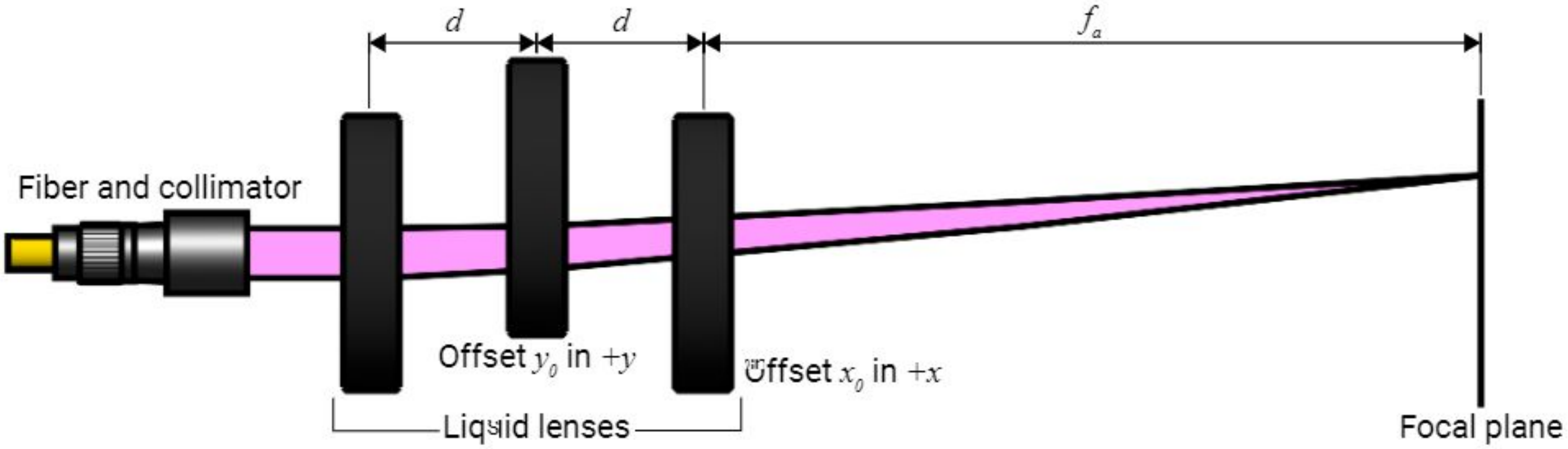
Zero G Results (Optotune)



4.05 mrad tip/tilt adjustment needed in 0g. Large amounts of coma present in 1.5+g.

Optical Performance

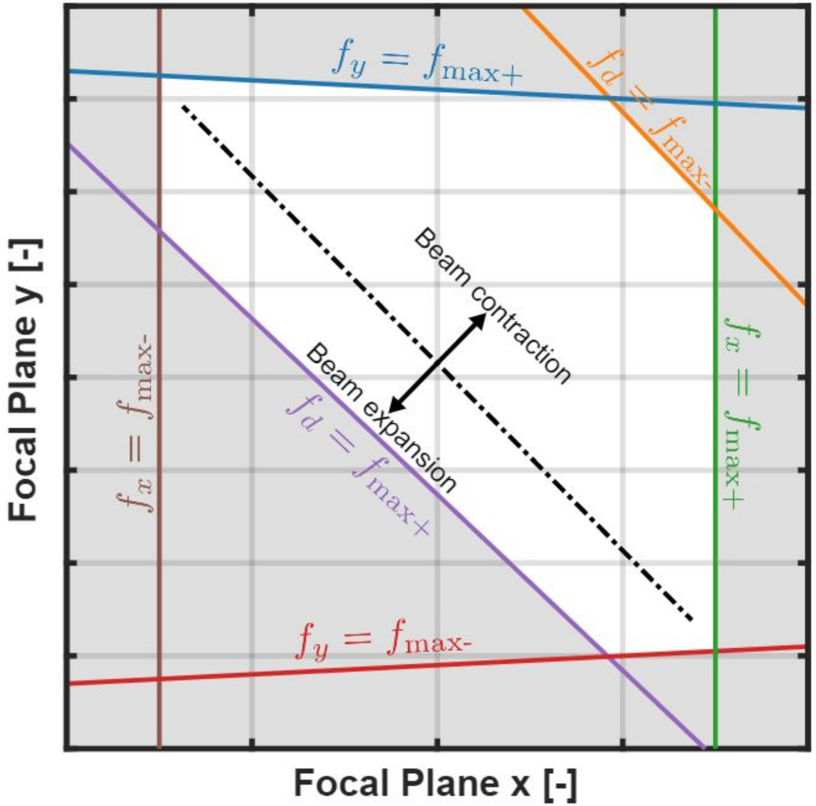
Analytic Formulation (1/2)



Liquid lens optical system with labeled properties

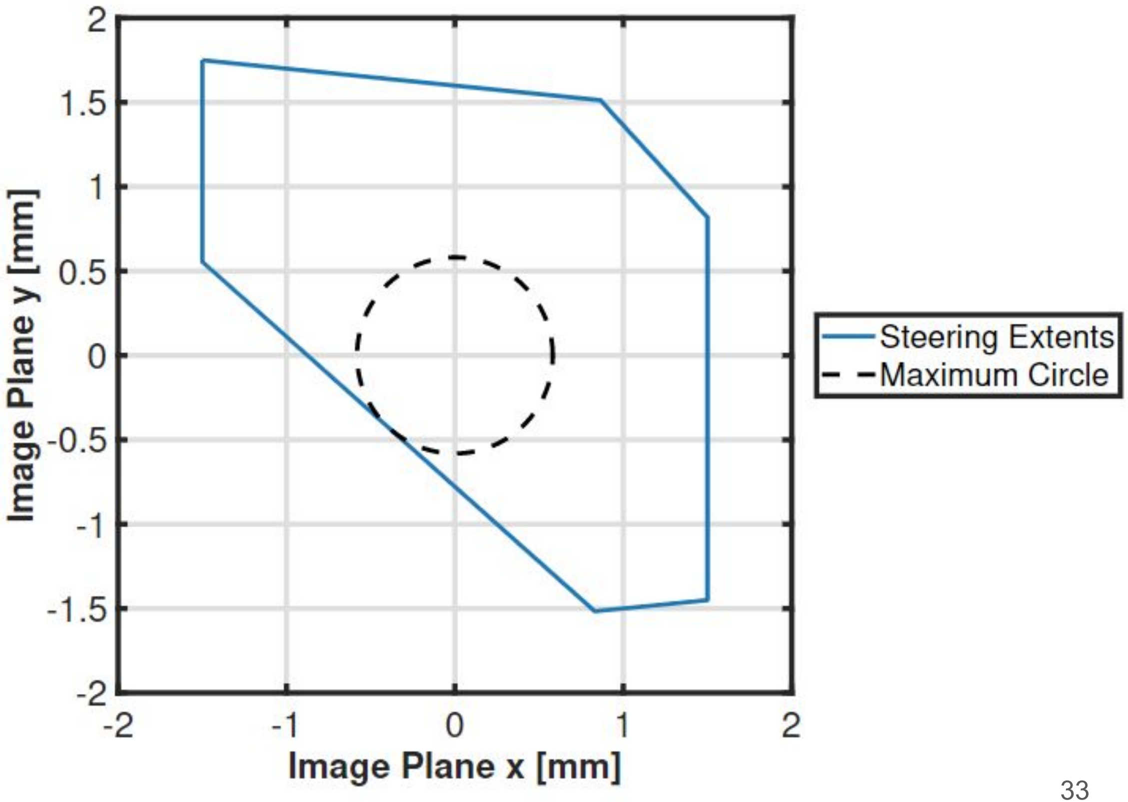
Analytic Formulation (2/4)

Reference constraint space showing relative locations of all six constraints on focal plane. Units omitted since this is a reference and is not meant to represent any specific system.



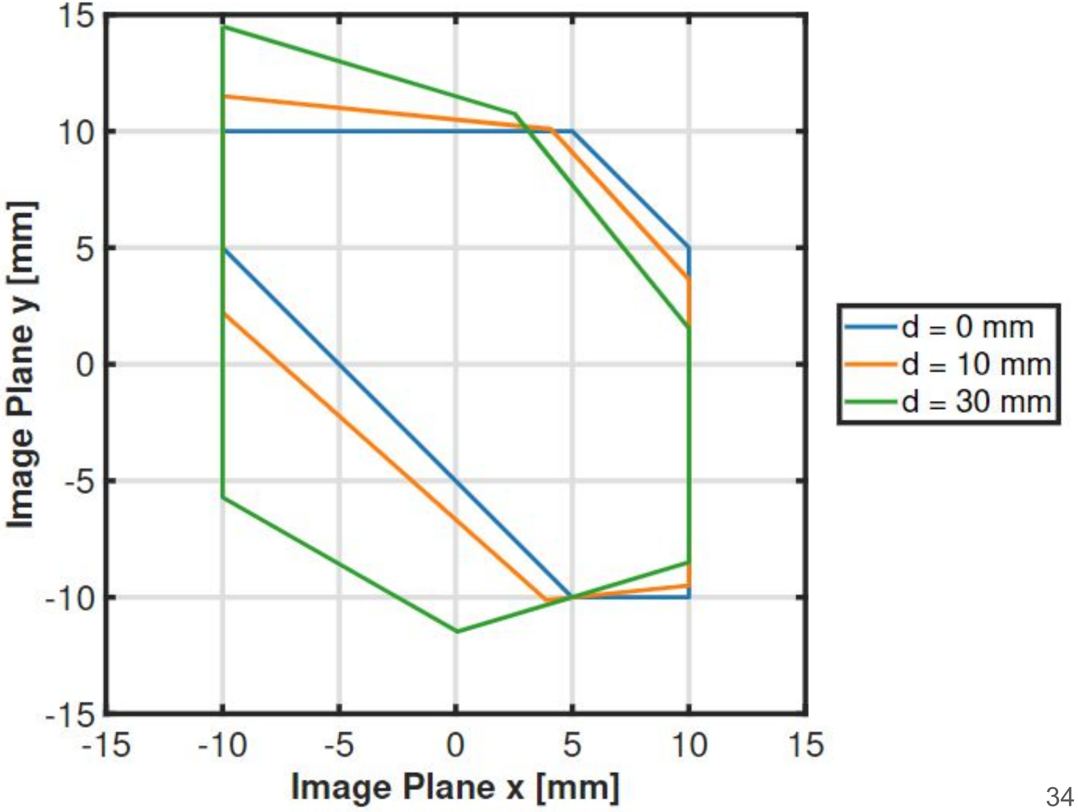
Analytic Formulation (3/4)

Image plane limits with varying lens offsets showing skew in image plane caused by lens separation.



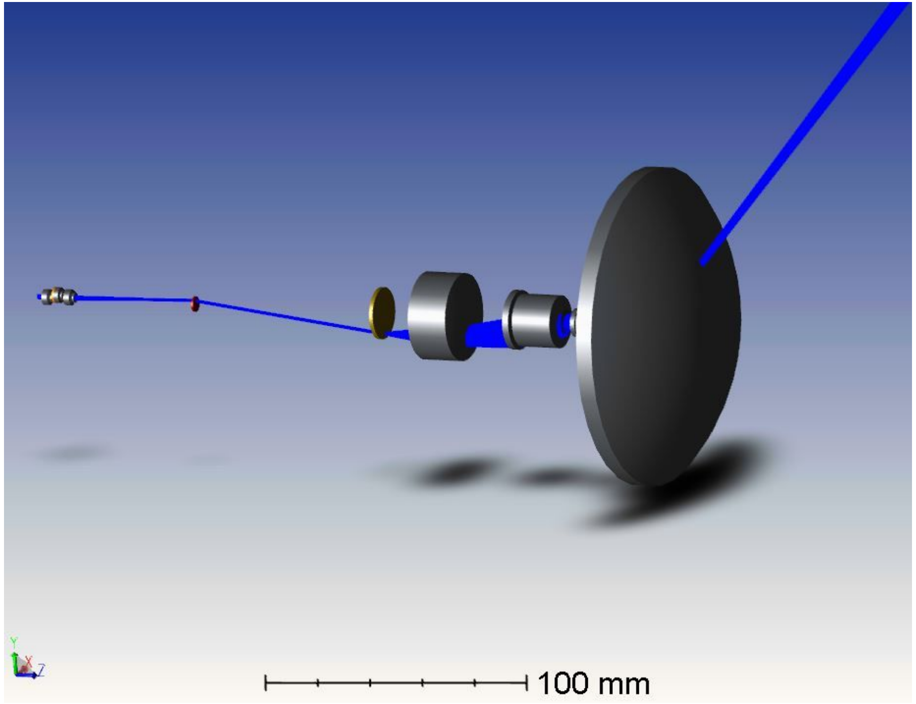
Analytic Formulation (4/4)

Image plane limits with varying lens offsets showing skew in image plane caused by lens separation.



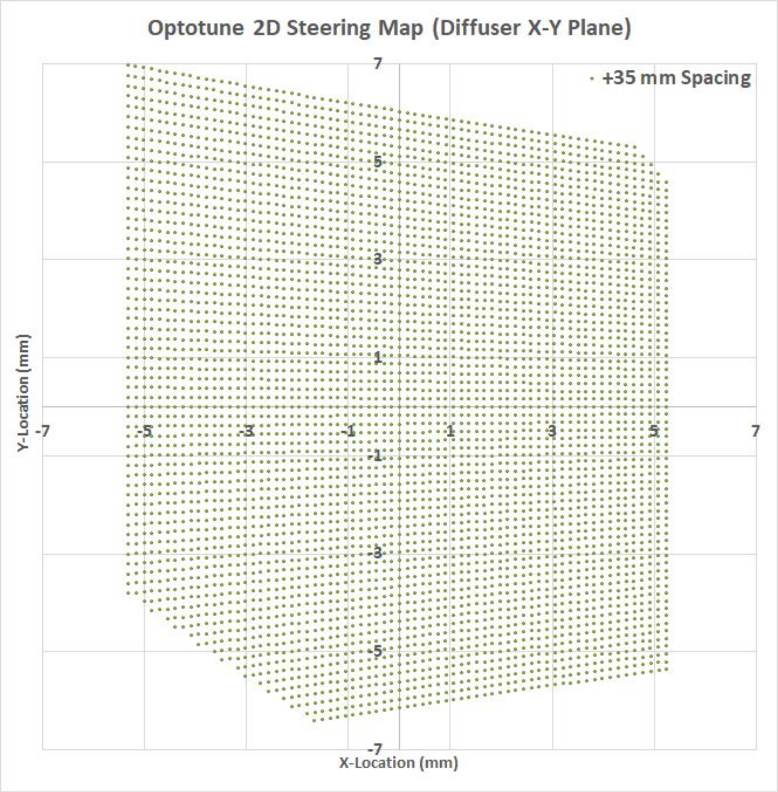
Zemax Modeling - Hemispherical Steering

- Full Zemax simulations for hemispherical beam steering
- Constructed to understand effect of beam quality and divergence
- Physical optics propagation allows for high fidelity simulations of beam quality



2D Steering Map (Zemax Simulations)

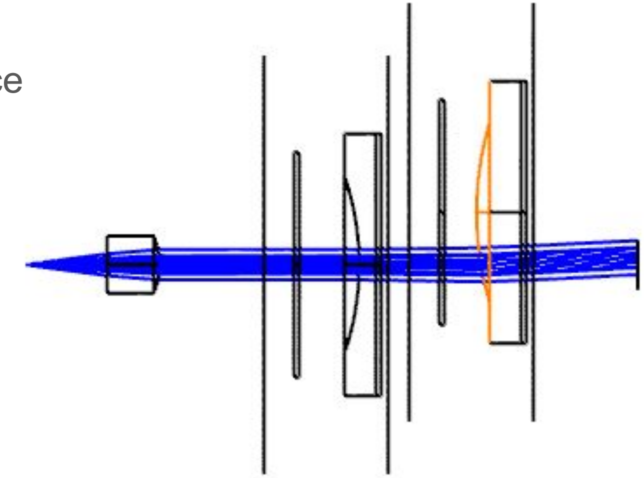
- Mapping focused spot locations on diffuser surface
  - Area grows with distance between fisheye and focusing liquid lens
    - More distance = less required optical power
- Asymmetric
  - Steering lenses expand/contract beam too
- Angular fisheye output determined by spot location (x,y) on diffuser
- ***Actual output steering angle dependent on fisheye geometry***



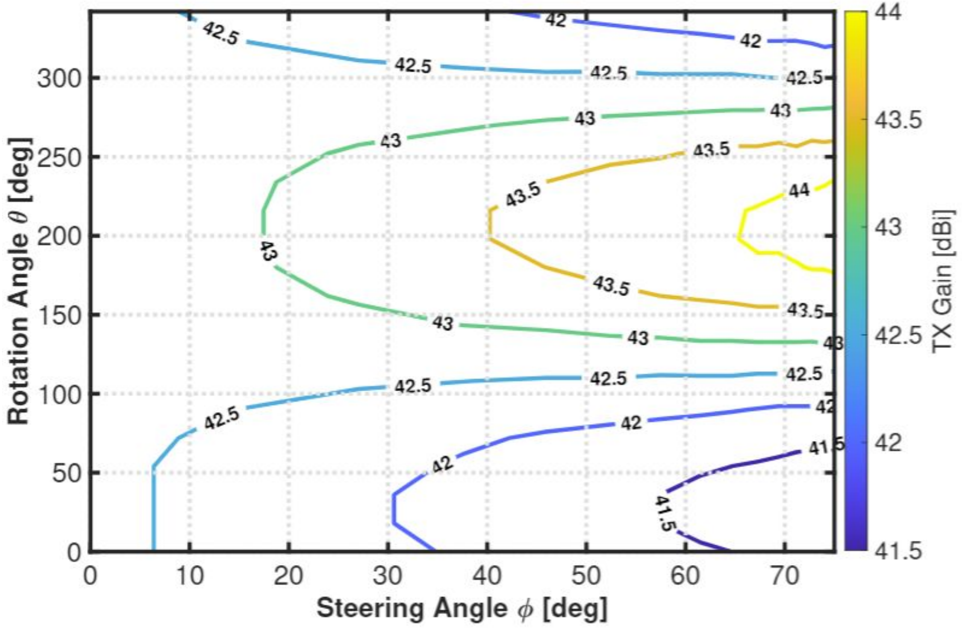
Factors Impacting Beam Quality

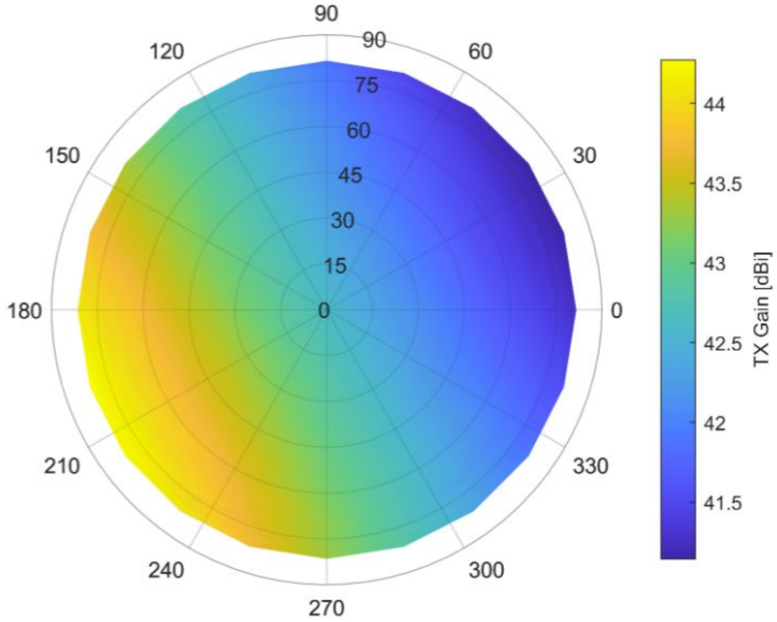
- Aberrations: spherical, surface error, off-axis decenter

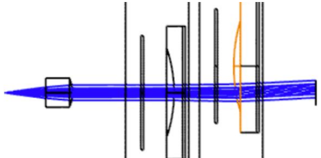
- The liquid lenses act as a tiny beam expander (Galilean telescope)
  - If first lens is negative, beam is expanded by a small amount causing divergence to shrink
  - If **first lens** is positive, beam is reduced and divergence gets worse (higher beam divergence)
  - Divergence is a function of wavelength and beam diameter



Transmit gain maps (1/2)

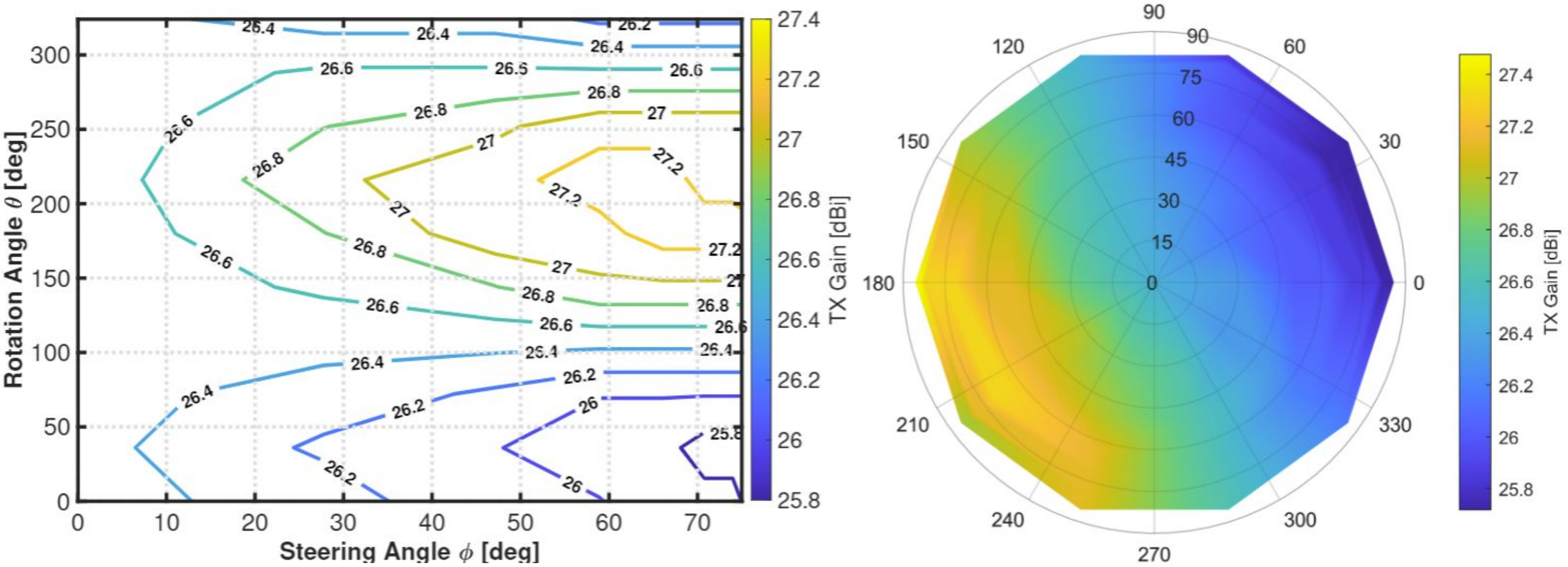






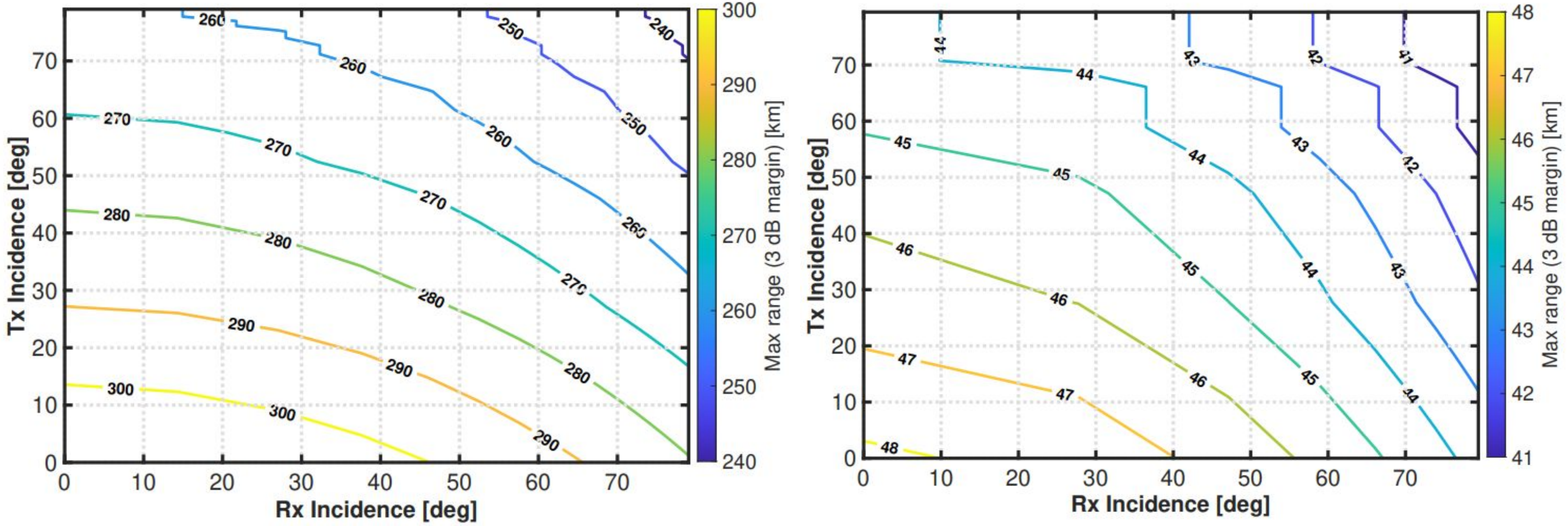
Optotune gain map (left) and axial projection (right)

Transmit gain maps (2/2)



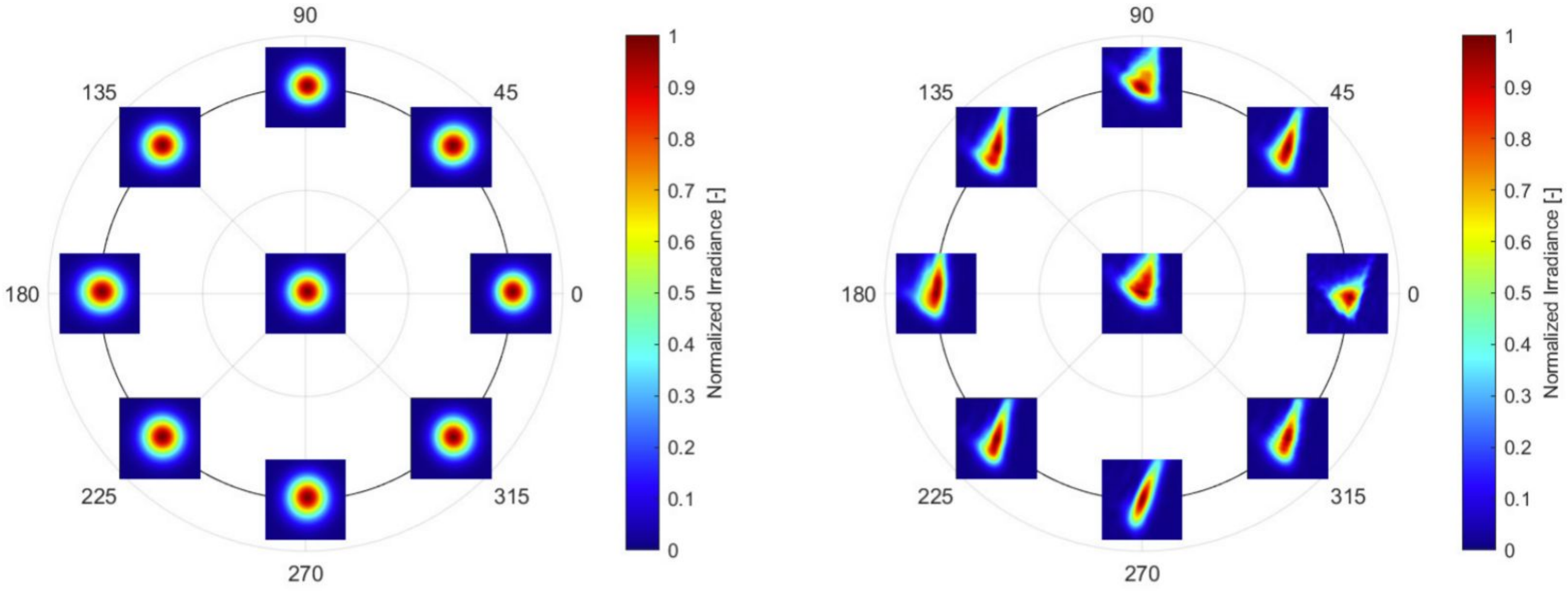
Corning gain map (left) and axial projection (right)

Link ranges



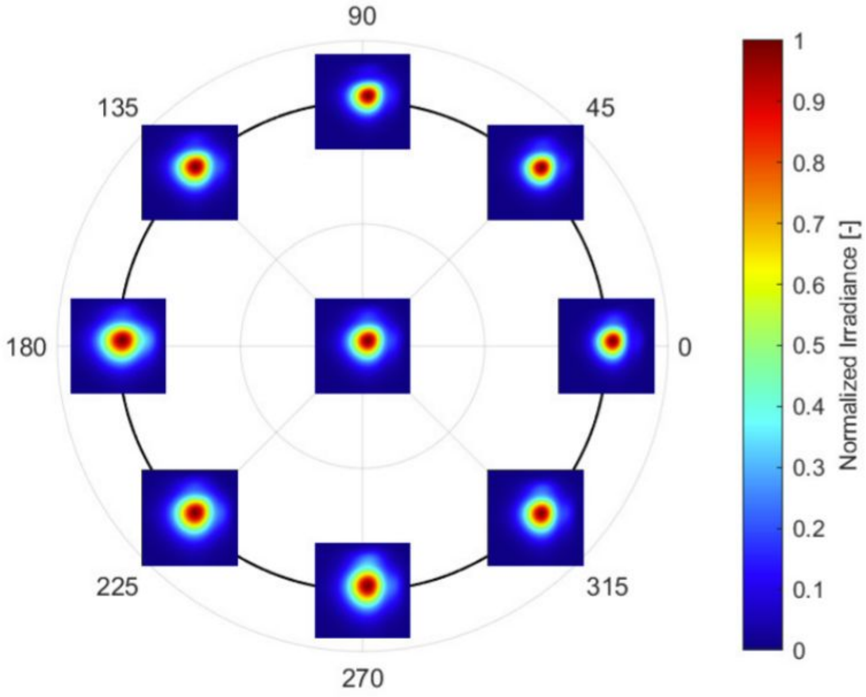
Optotune range map (left) and Corning Varioptic range map (right) (4 W Tx power)

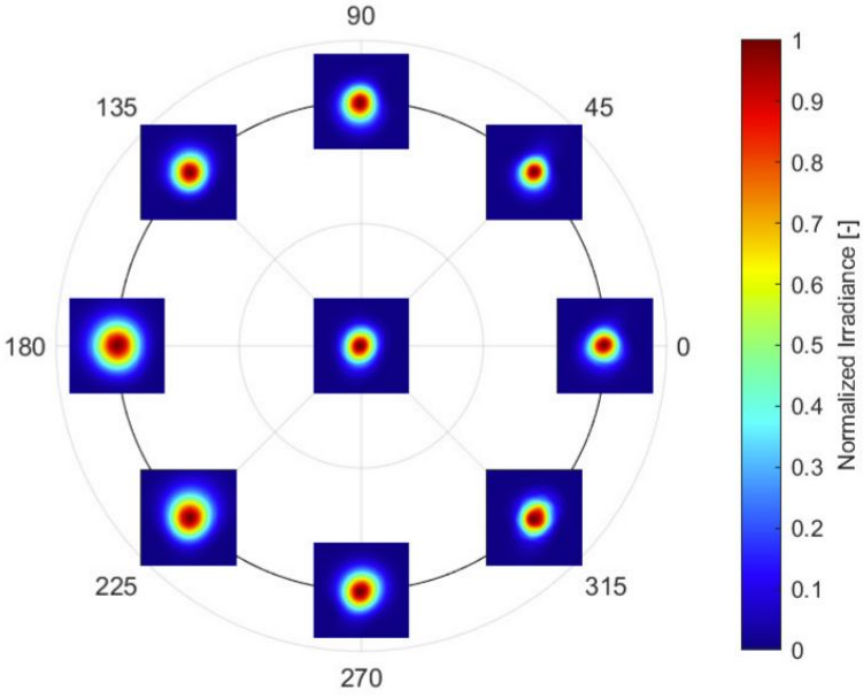
Liquid lens beam profile (1/2)



Optotune simulated beam profile (left) and experimental (right) (2 deg steering)

Liquid lens beam profile (2/2)





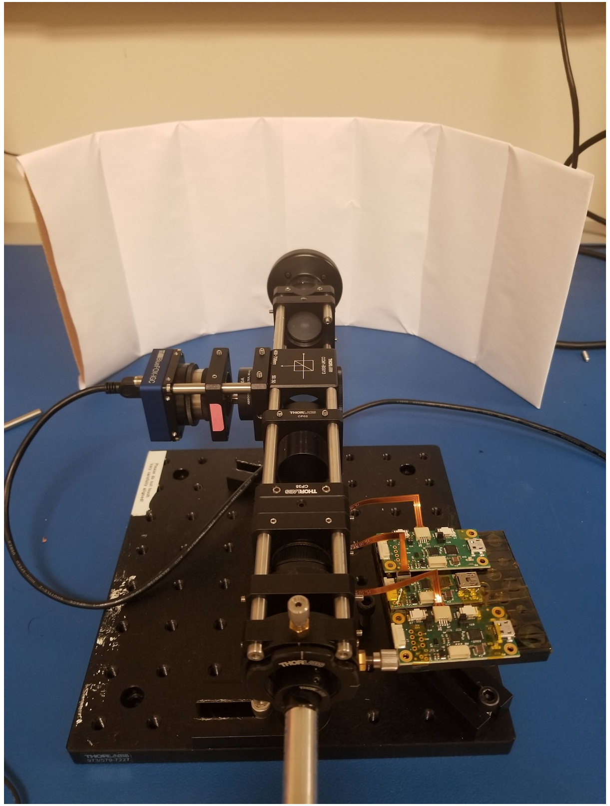
Corning simulated beam profile (left) and experimental (right) (0.7 deg steering, LL only)

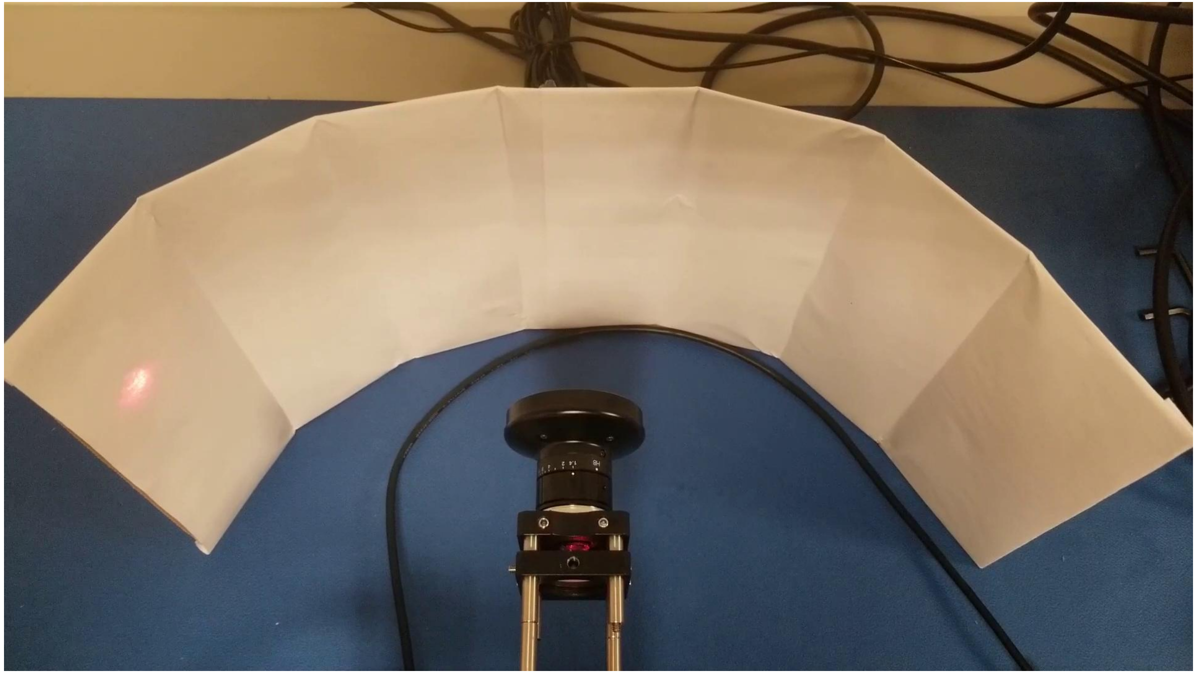
STAR lab
Space Telecommunications Astronomy Radiation

Transceiver Prototyping

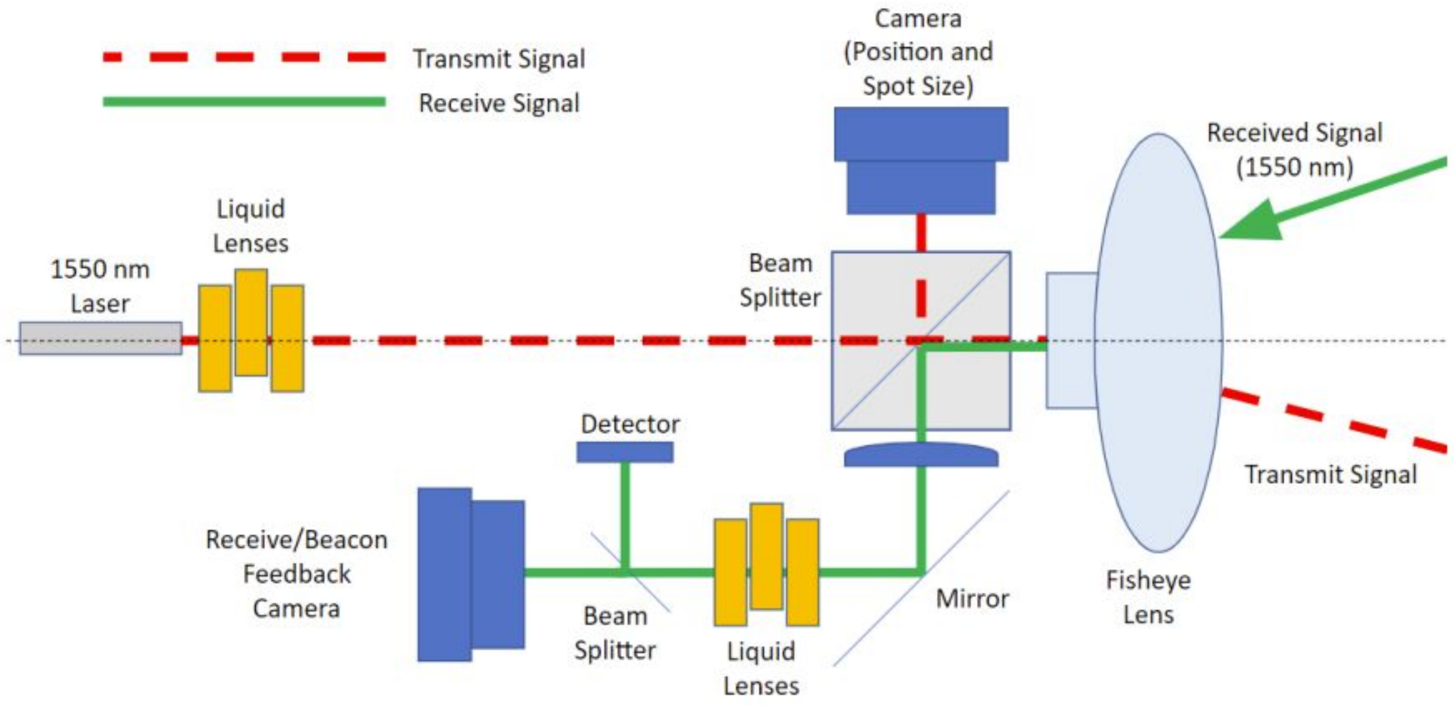
STAR lab
Space Telecommunications Astronomy Radiation

Lab Prototype (Hemispherical 2D Steer)





Transceiver Design (1/3)



Baseline transceiver design, showing the required peripherals and receive and transmit paths separated by the beam splitter

Transceiver Design (2/3)

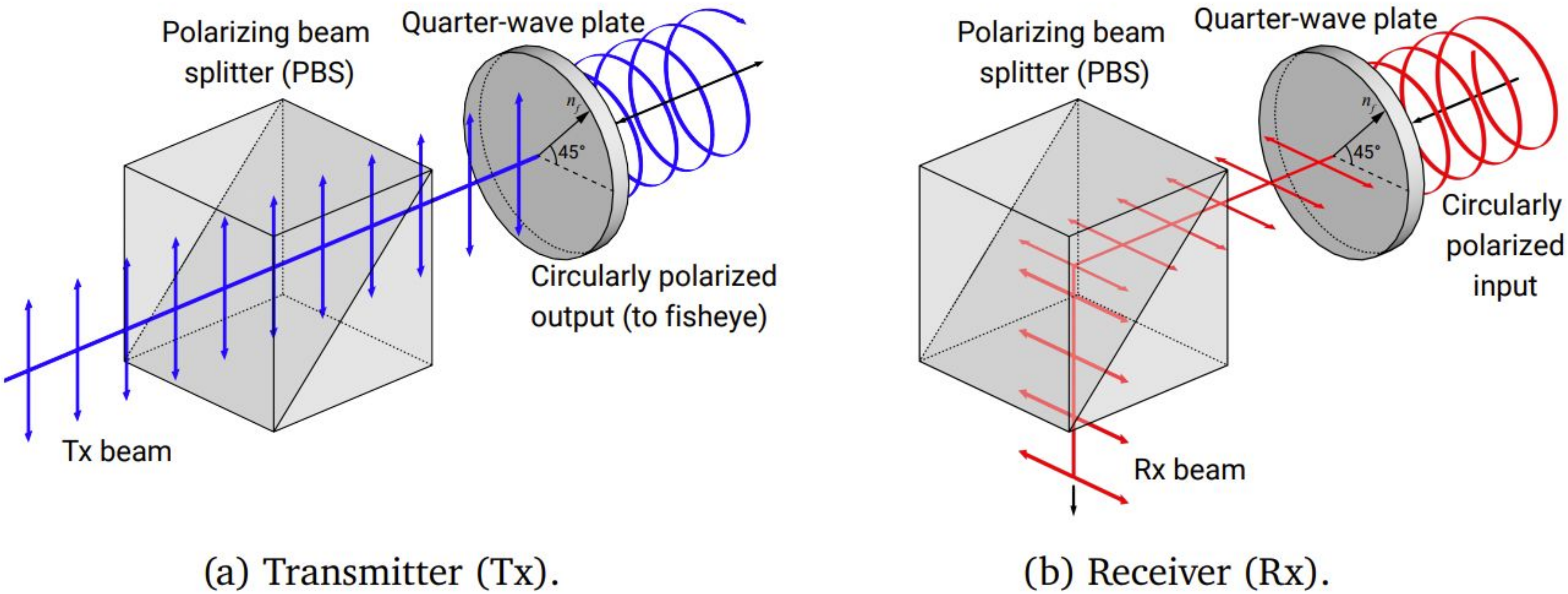
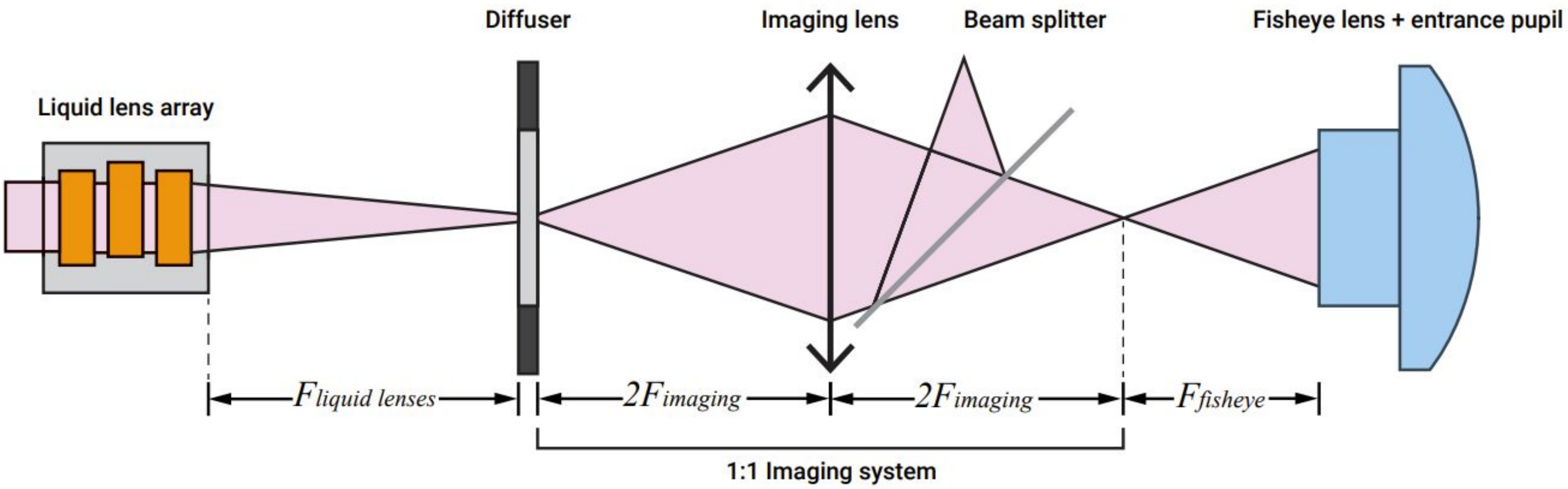


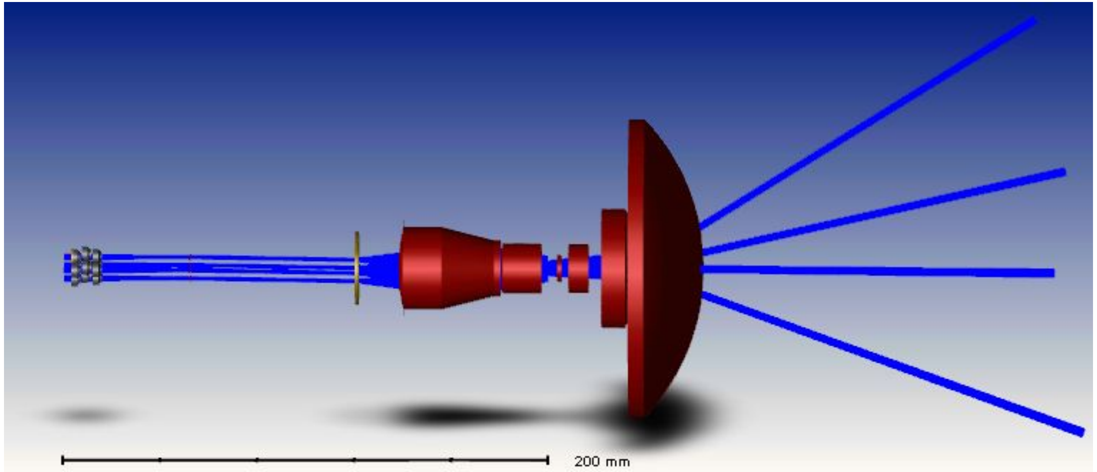
Diagram of how polarizing beam splitters and quarter-wave plates can be used as to separate transmit and receive paths, similar to three-port optical circulators (Shreeyam Kacker, MIT)

Transceiver Design (3/3)



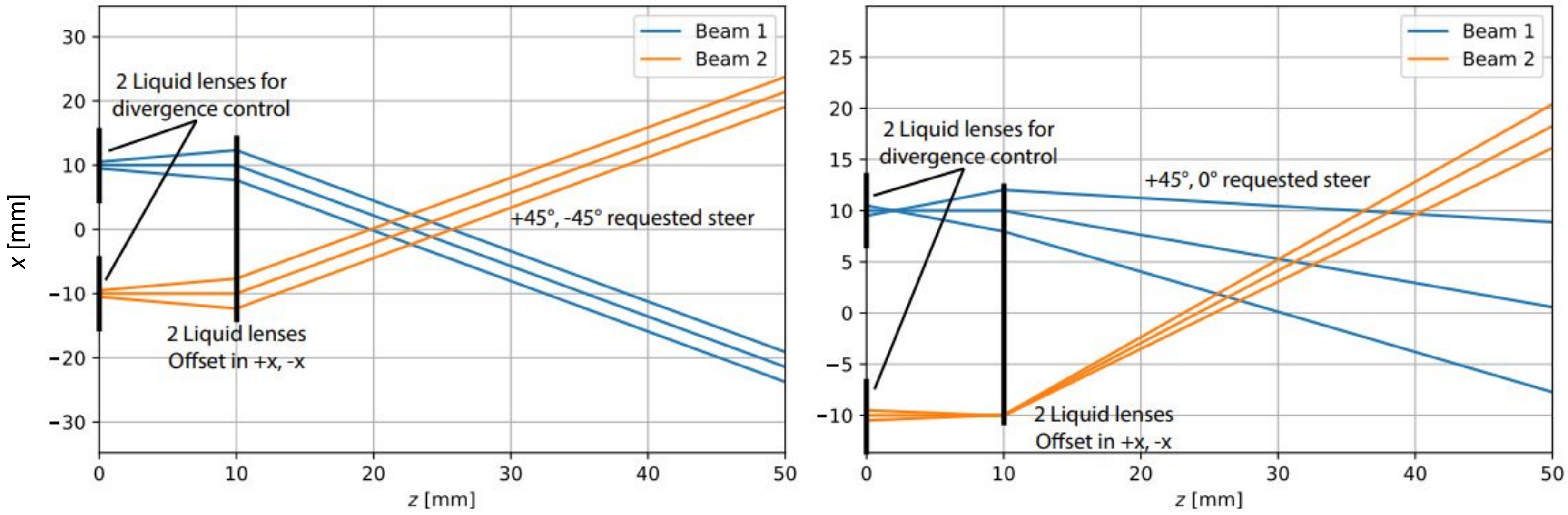
One-to-one imaging system allowing diffuser in transmit path without affecting receive path (Shreeyam Kacker, MIT)

Multicast (1/2)



- Four beam multicast with four sets of three Corning lenses.
  - In this design, Corning lenses are selected for compactness
  - Three lens optical train not able to focus multiple laser spots to independently controlled locations
    - Attempted with differing wavelengths and more lenses in the optical train

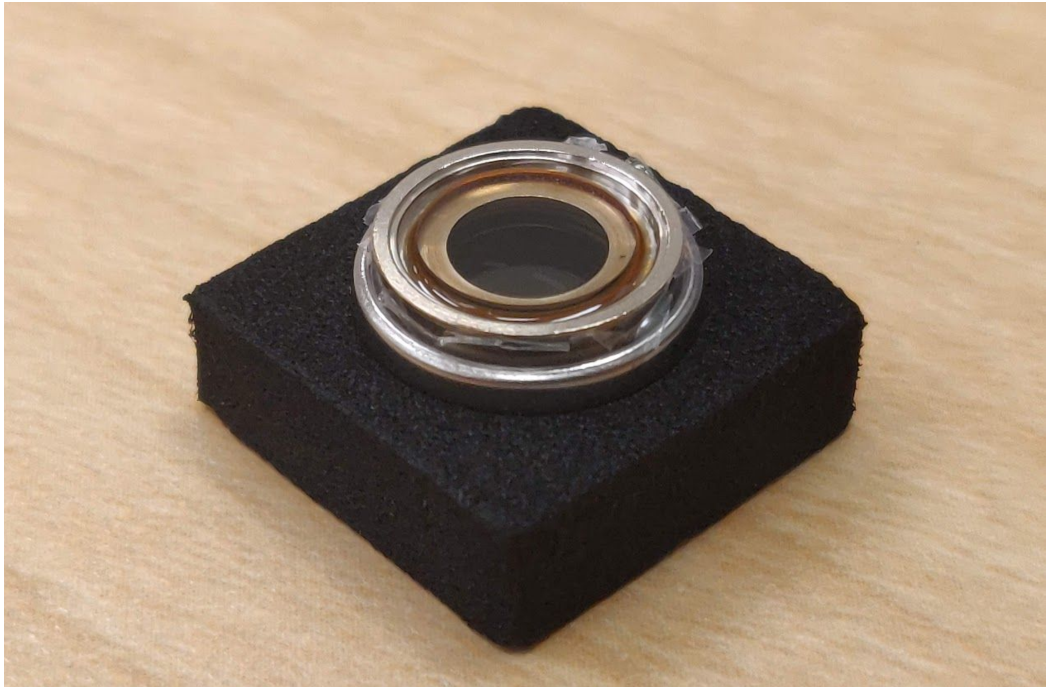
Multicast (2/2)



(a) Symmetric steering. (b) Asymmetric steering.

Multicast simulation steering two beams with four lenses, with symmetric and asymmetric steering cases shown.

1550 nm prototype lenses



Conclusions

- Liquid lenses shown to be a promising technology for space applications, particularly nonmechanical beam steering
- Power handling capabilities much better than expected at 2.25 W
- Potential for multicast using a single optical train (paper in prep.)
- Beacon divergence is a limiting factor on crosslinks, control with liquid lenses can improve this capability
- Lens components brought up to TRL 5-6 during project

Future Work

- Evaluate potential of integrated beaconing using divergence control with nutation
- Finalize mathematical formulation for multi-beam steering through a single train of liquid lenses

Publications and Research Products

[1] F. Fogle, O. Cierny, P. do Vale Pereira, W. Kammerer, and K. Cahoy, *“Miniature Optical Steerable Antenna for Intersatellite Communications Liquid Lens Characterization,”* IEEE Aerospace Conference, 2020.

[2] F. Fogle, SM Thesis (2020) *Liquid lens beam steering and environmental testing for the miniature optical steered antenna for inter-satellite communication*.

[3] US Patent No. 10,826,609 B2. *Liquid-lens based optical steering system for free-space laser communication.*

[4] S. Kacker, O. Cierny, J. Boyer, and K. Cahoy, *Link Analysis for a Liquid Lens Beam Steering System, the Miniature Optical Steered Antenna for Intersatellite Communication (MOSAIC)*, SPIE Photonics West (2021).

[5] S. Kacker, SM Thesis (2022), *Optical Performance and Prototyping of a Liquid Lens Laser Communications Transceiver.* Available: starlab.mit.edu

[6] S. Kacker, K. Cahoy, *Optical Performance of Commercial Liquid Lens Assemblies in Microgravity*, pending submission.

STAR lab
Space Telecommunications Astronomy Radiation

Thank you!

Questions?

mosaic-nasa@mit.edu