Freeform Optics for Optical Payloads with Reduced Size and Weight
Phase II– Aug 27 2018
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Contract: 80NSSC18C0152

Performance Period: **30 May 2018 through 29 May 2020**

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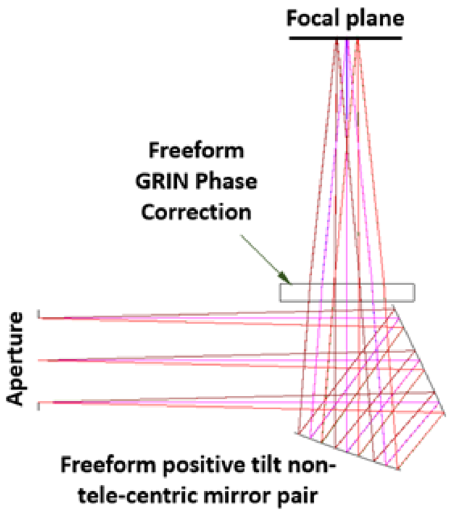
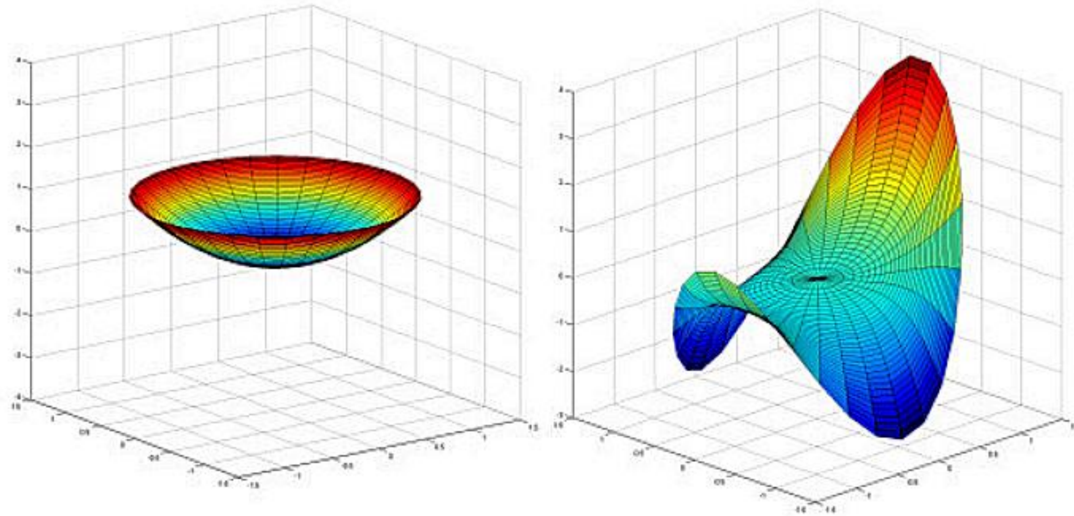
VOXTELNANO

Unmet Need: Correct Aberrations in Cubesat Optics



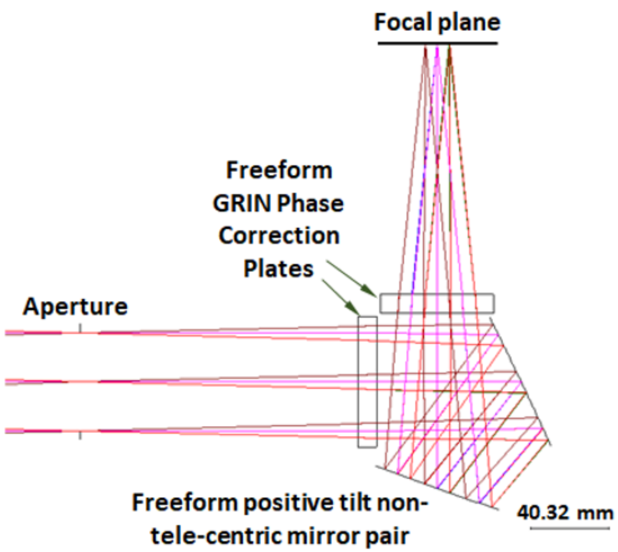
Typical two mirror optical path for small satellites; space is limited



A rotationally symmetric mirror (left) based optical path is not as space efficient as one based on a non-rotationally symmetric freeform mirror (right)

- **Compact high-quality optics in a cubesat volume requires freeform mirrors in order to realize necessary design degrees of freedom (DOF)**
- **Mfg and assy of freeform reflectors expensive and time consuming for each unit**
- **Process: measure assy aberrations, then correct with VIRGO freeform GRIN phase plates, custom delivered for each unit**
- **Results: *Vacuum, LEO, quality optics, lighter, smaller, in far less time at less cost***

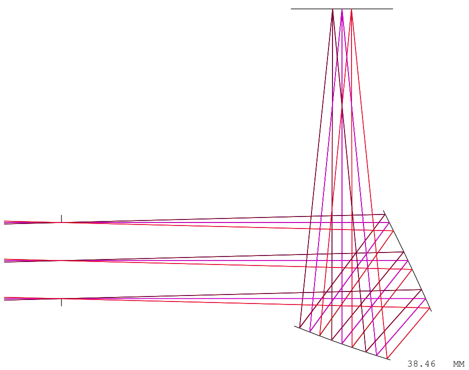
NASA Optical System Design



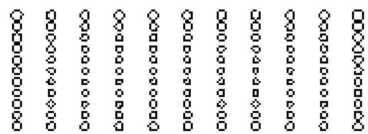
NASA optics path

- NASA's FF PP NT (freeform, positive/positive tilt, and non-telecentric) mirror design is the assumed baseline for our design
- We have from NASA a description for an initial design case with assembly and manufacturing errors
  - Described with Zernike Polynomials
- Now designing an optimal GRIN material and 3D free-form profiles, with new design tools, to correct the as-built aberrations
  - Because we are not at the pupil, optic path modifications affect each field differently
  - Need to select a single or dual corrector plate architecture

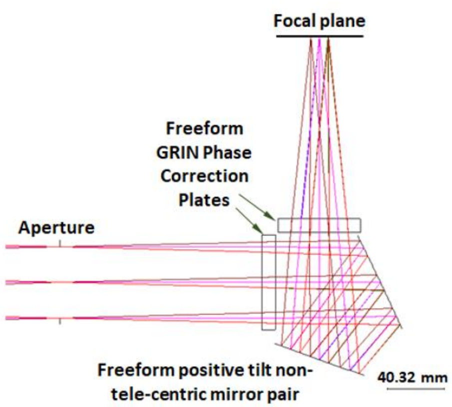
Phase I Optical Design Meets Objectives



RMS Spot Diameter	
Min Value	0.0186
Max Value	0.0331
Average Value	0.0239
Std Deviation	0.0036



FF PP NT NASA Design

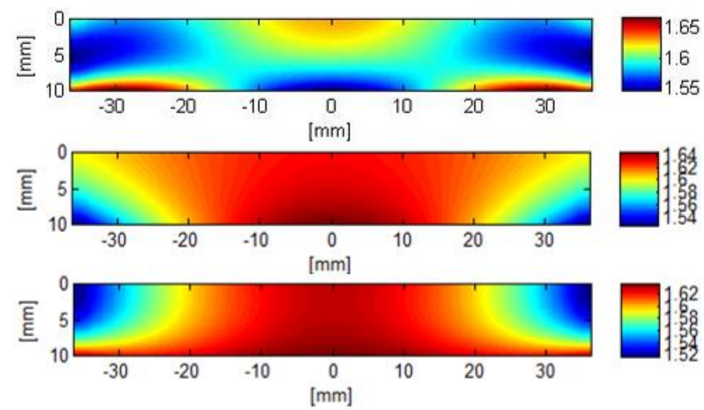


RMS Spot Diameter	
Min Value	0.0032
Max Value	0.0082
Average Value	0.0054
Std Deviation	0.0012

Field of focal sponts on the focal plane

Voxtel Design w/two FFG PCPs

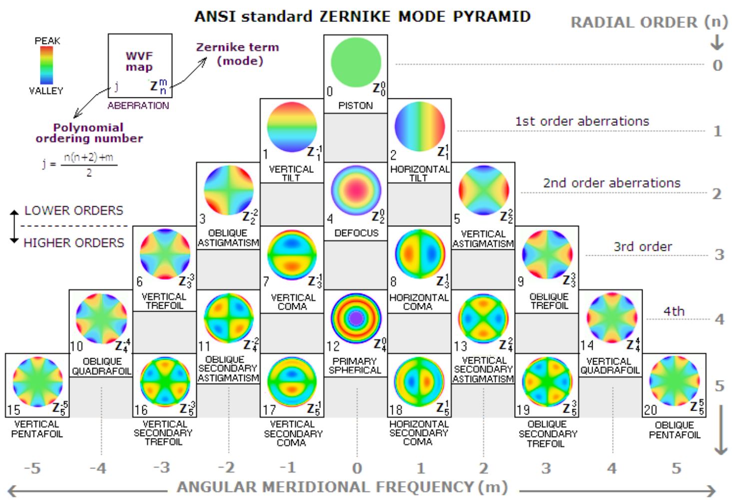
RMS Spot Diam. (mm)	Baseline	Field-Side GRIN	Aperture-Side GRIN	Both
Min	0.0186	0.0126	0.0068	**0.0032**
Max	0.0331	0.0191	0.0231	**0.0082**
Avg	0.0239	0.0147	0.0141	**0.0054**
Std Dev	0.0036	0.0016	0.0039	**0.0012**



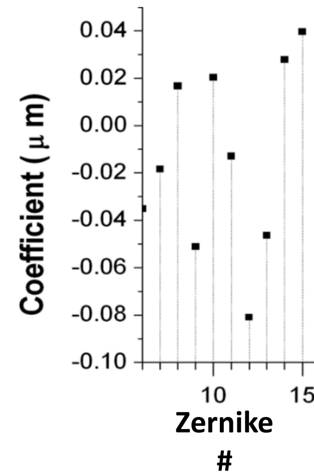
Summary table (above) and cross section Index maps for (top) aperture side alone, (middle) aperture side w/both, and (bottom) field side w/both FFG optics from Voxtel's Phase I research

- **NASA's optic system design for Phase I**
  - **Entrance Pupil Dia: 50 mm, FOV: 2.86° x 8.73°, Focal Length: 250 mm**
  - **λ = 587.56 nm**
- **Dual freeform GRIN (FFG) phase corrector plate (PCP) design is 1st Phase II target**

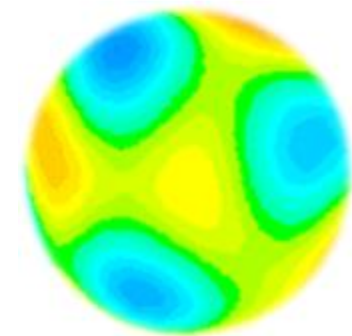
Phase II Optical Design Work



Zernike Polynomial Terms



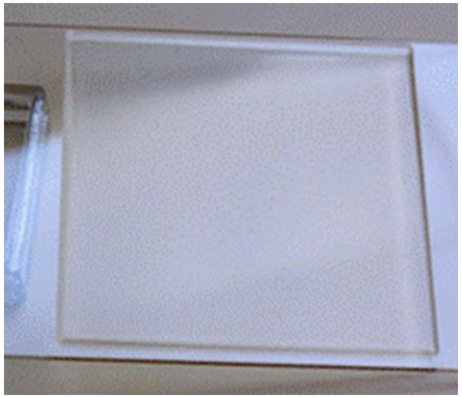
Term Combinations



Combined OPD correction plate

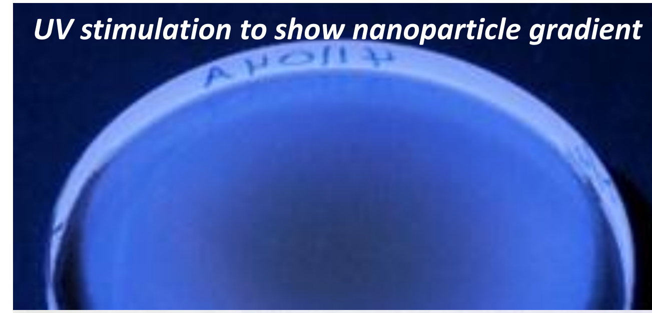
- **In Phase II we will**
  - **Explore using other freeform mirror coefficients, as only originals were varied in Phase I**
  - **Explore using spacing and angular tilts of freeform mirrors (fixed in Phase I)**
  - **Polychromatic performance tools are being created for Code V and implemented**
  - **Refractive index range (Δn), rate of index change variation across FFG PCP constrained by VIRGO**
  - **Printed area and volume constrained by cubesat optic path (e.g., 50 mm diameter)**
- **NASA Provides, for final design and interim experiments;**
  - **Assembly and alignment geometry tolerances and expected errors (test cases)**
  - **Freeform mirror aberrations (as Zernike polynomials)**
- **With this information, we will select type of PCP**
  - **Simple corrector, or with optical power**
  - **One or two phase corrector plates**

Fabricating Freeform Gradient (FFG) PCP w/VIRGO



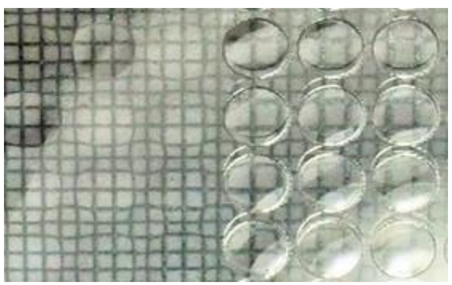
160 µm pitch, 32,400 lens array

0.5 mm Hex Pack Hogel Lens Array

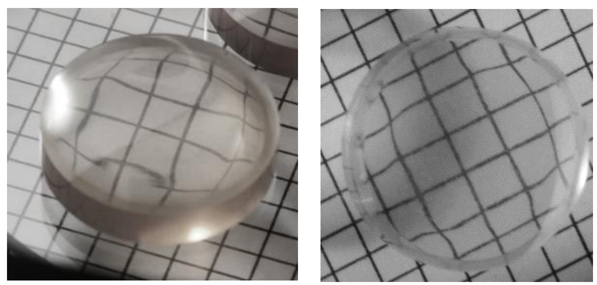


UV stimulation to show nanoparticle gradient

45 mm phase corrector plate (PCP) on an optic flat



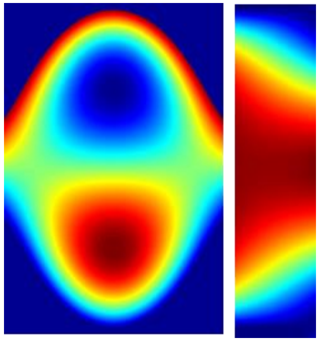
Plano 4 mm GRIN (left) & GRIN w/62 mm convex (right)



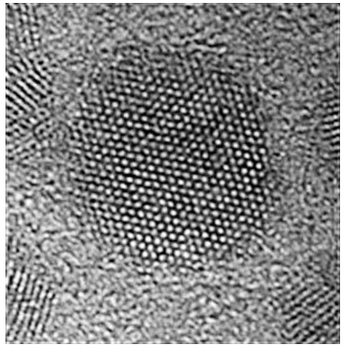
Freeform diamond-turned 12 mm f5, w/convex 200 mm radius

- **Volumetric Index of Refraction Gradient Optics (VIRGO) process in development**
- **In earlier NASA work (Contract NNX14CG41P) we fabricated PCP on optic flats**
- **FFG PCP's are to be printed on 1/10th wave fused silicon or glass substrate**
- **Optical ink will be optimized for this application (minimizing 2nd order dispersion)**

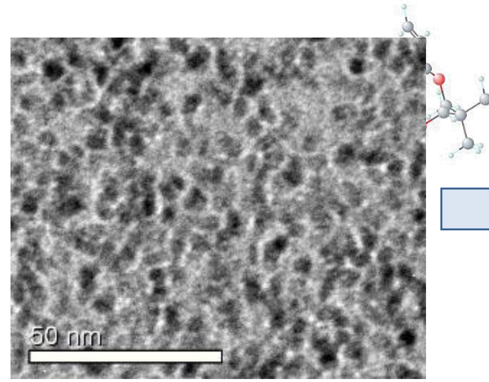
Additive Manufacture of Freeform GRIN Optics



Freeform GRIN Design

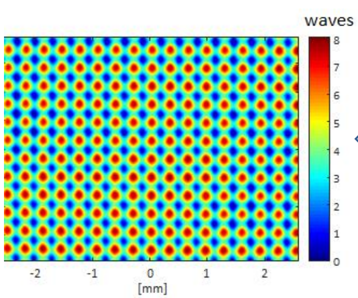


On-demand Nanoparticle Filler Synthesis

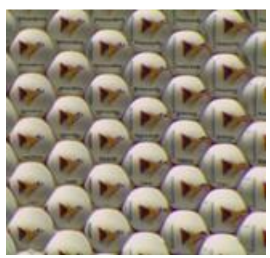


On-demand Nanocomposite Ink Formulation

Print Head Load

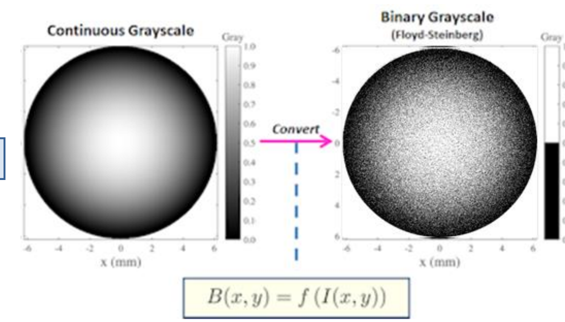


Metrology



3D & Freeform GRIN Optics

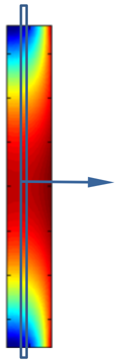
High-throughput Inkjet Fabrication



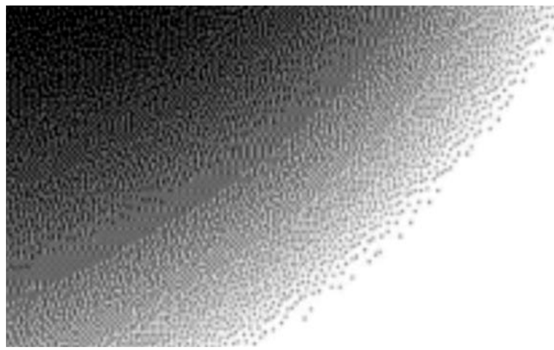
Multi-level Print Diffusion Masks

- **24-hour design and build cycle time**

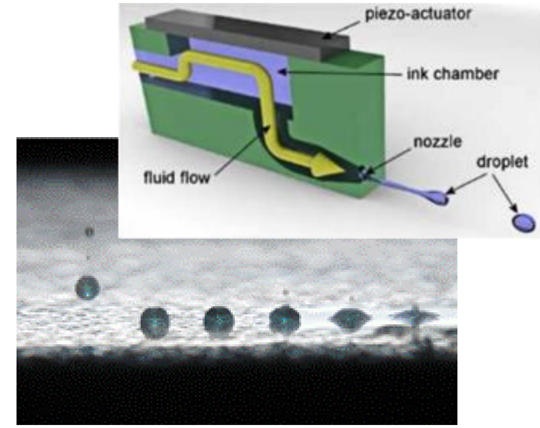
VIRGO Ink Jet Print Fabrication Process



3D Freeform GRIN Design (FFG PCP)



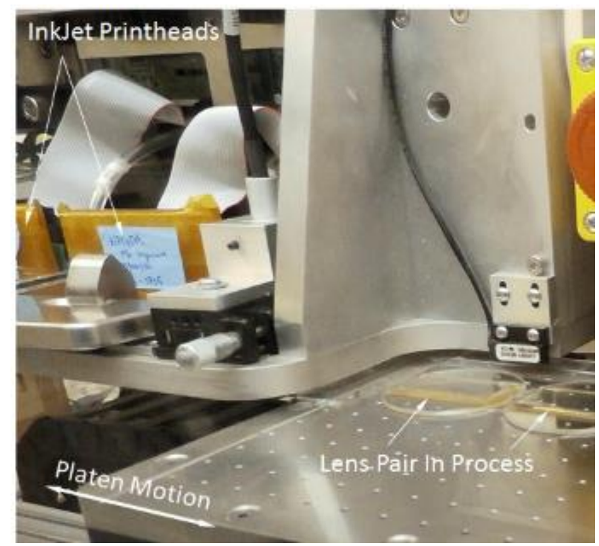
Conversion from continuous to voxelated bitmap for printing



Droplets on Substrate

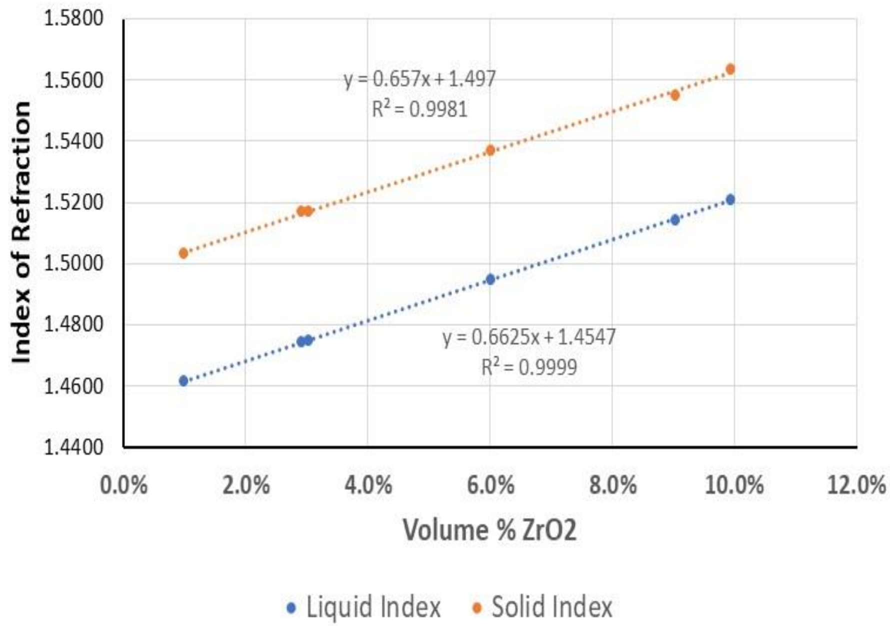
Fabrication process

- Design parameter(s) chosen
- 3D GRIN profiles selected based on optimization
- Nanofiller concentration profiles developed based on:
  - Nanoparticle diffusion
  - Number of inks used
    - Binary or multi-level optical index levels (grey scale)
    - Multiple spectral characteristics (Abbe number)
- Error diffusion halftone algorithm used to convert design to binary or multi-level bitmaps

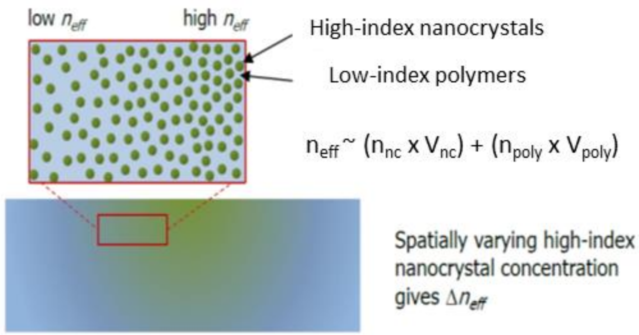


Custom R&D Multi-head Ink Jet Print Platform

Index Increases w/Nanocrystal Load



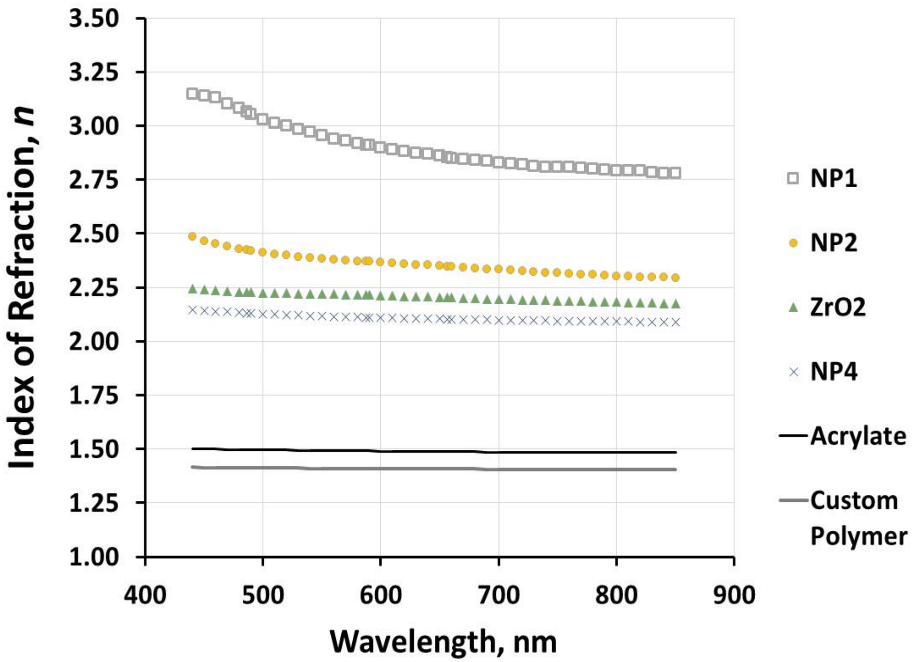
Index Linearity vs Nanoparticle Fill



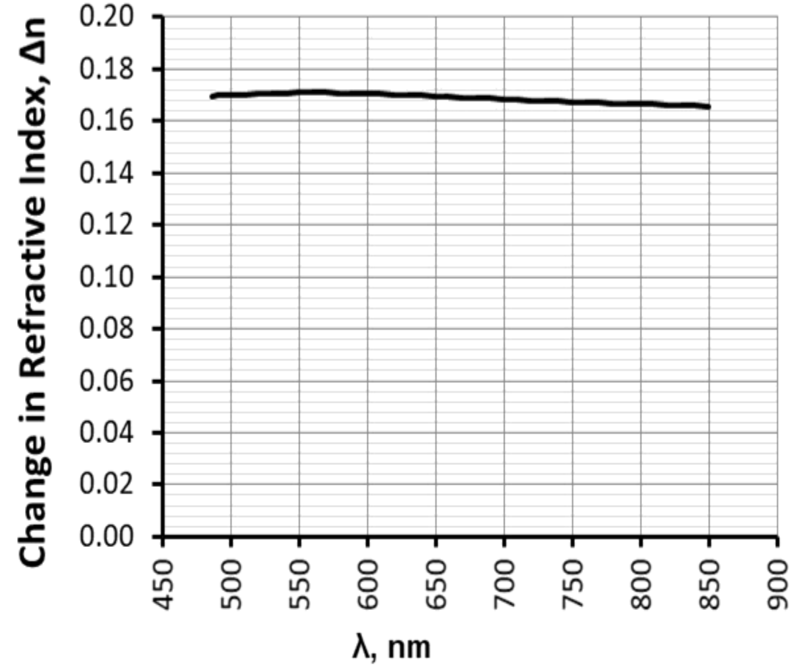
Non-scattering, well-dispersed nanofiller concentrations create index gradients

- **We combine liquid monomer with nanoparticles (NP) such as ZrO_2 for optical ink**
- **As NP loading increases, index increases; relationship is locally linear**
  - **Index measured with our abbe refractometer (repeatable to 4 decimals), and with a Woollam M44 Spectroscopic Ellipsometer for wide spectrum measurements**
- **NPs are distributed throughout body of optic to create gradient refractive index**
- **Liquid nanocomposites are polymerized (cured to a hard state) layer by layer**

Nanocomposite Optical Ink Design



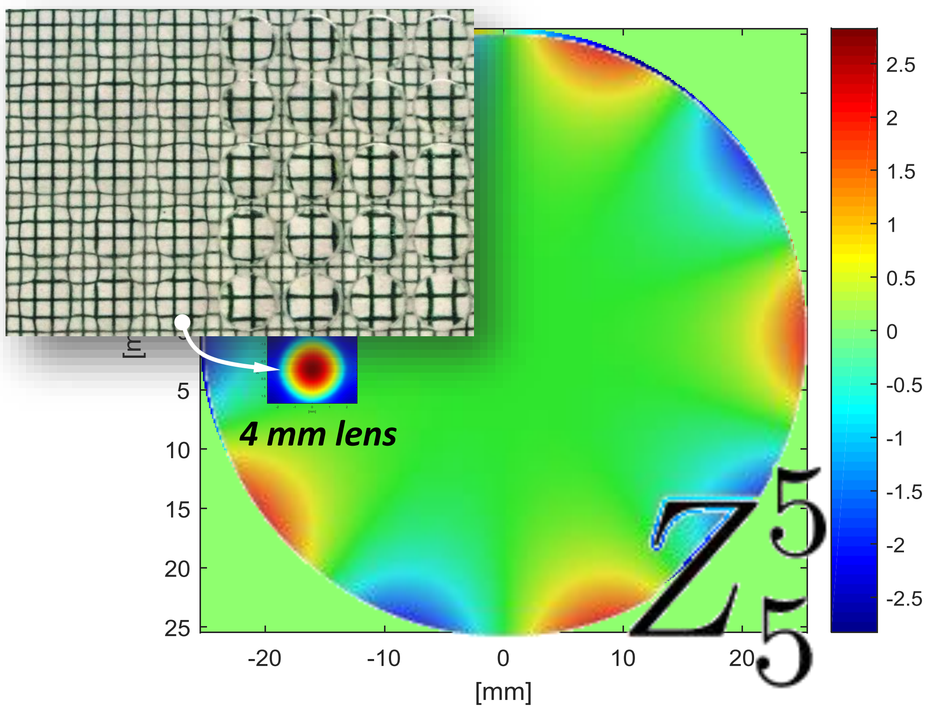
Index vs Wavelength (dispersion) for Ink Components



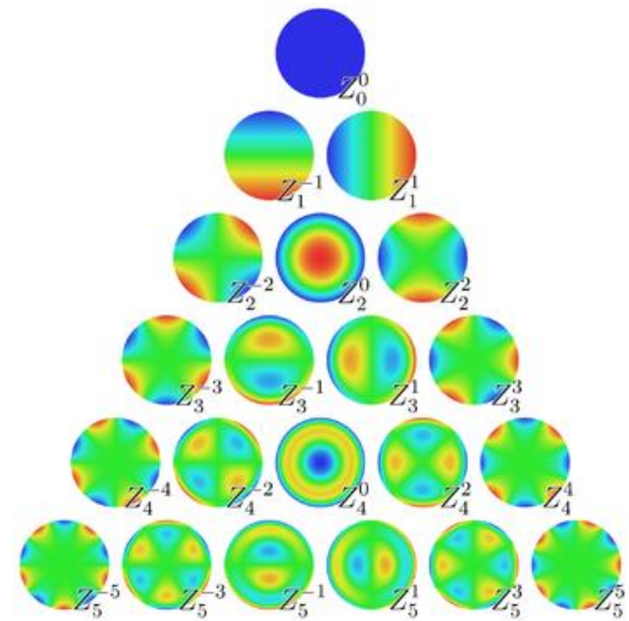
2 NP ink design minimizes dispersion

- **Index change between high and low index optical inks can vary with wavelength, which produces all the normal chromatic aberrations**
- **Dispersion and partial dispersion of Δn over the spectrum is controlled by balancing NP dispersion in the formulation of high and low index ink**
- **Balance of optical power (total *Δn*), partial dispersion, and chemical complexity**
- **Voxtel's custom fluoropolymer improves stability and optical power**

VIRGO Resolution Can Map 21 Zernike Polynomials



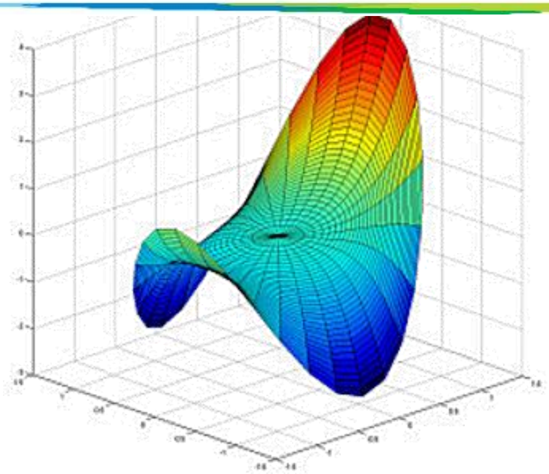
Zernike (5,5) w/successful 4 mm Voxtel GRIN lens, inset



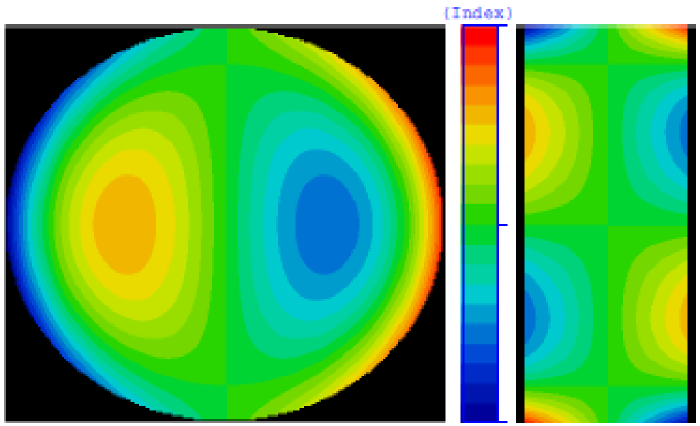
The first 21 Zernike polynomials

- **Comparison of Zernike polynomial (5,5) to measured phase image of VIRGO printed 4 mm plano GRIN lens (scaled to the 50mm Zernike aperture)**
- **Demonstrates that we can achieve the Zernike polynomial phase variation requirements, which vary slowly across a 50 mm aperture relative to 4 mm lens GRIN**
- **Demonstration accomplished on both research and production process**

New Design Tools



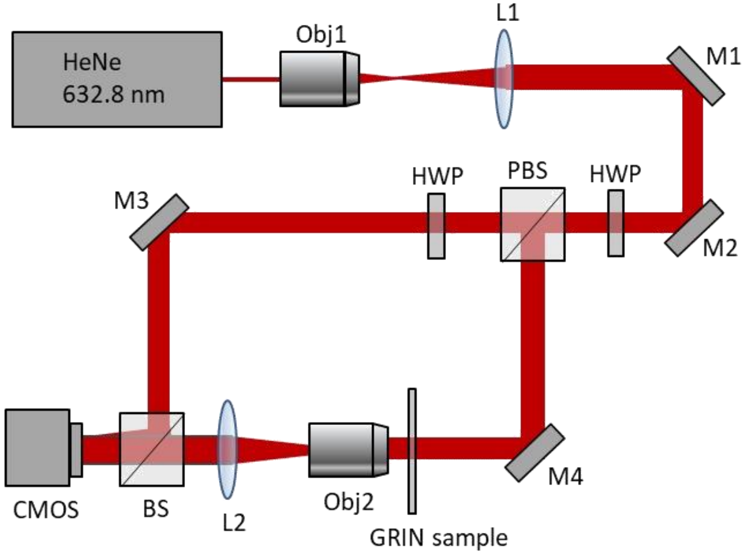
A non-rotationally symmetric freeform mirror with polychromatic light



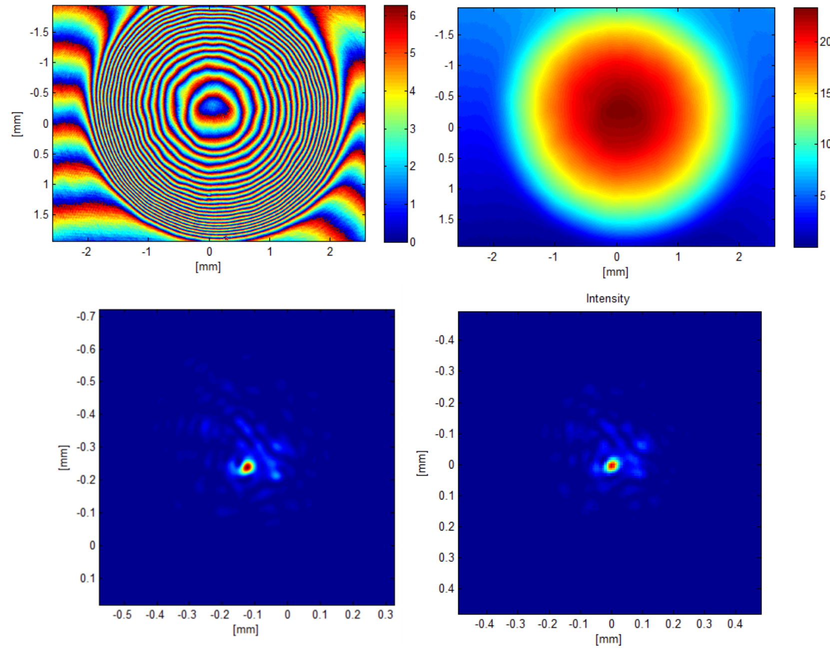
A non-rotationally symmetric freeform GRIN with 587.56 light

- **Dr. Julie Bentley, working with UR graduate students, is creating a non-rotationally symmetric GRIN optimization tool for this program**
  - **Integrates with CODE V as TFGRIN module**
  - **Free-form patterns, based on Zernicke polynomials in x,y plane and Legendre in z-axis**
  - **Will be polychromatic**
  - **Orthogonal and Improved *Δn* control during optimization**
- **Axial dependence can cancel out some aberrations or modify their field dependence**
- **Use stack of phase plates (corresponding to printed layers), integrate effect**
- **Currently monochromatic, already demonstrates otherwise unobtainable results**
  - **Because it is orthogonally modeled, we can add one aberration w/o additional aberrations**
  - **Requires higher order Legendre polynomials in z axis**

Digital Holographic Microscope for n(x,y,z) Detail



Digital Holographic Microscope (DHM)



Digitally Propagated ***Measured***

DHM radians and wave lens measurement, resultant expected focus, and actual focus

- **Digital holographic microscopy (DHM) allows for the extraction of both amplitude and phase information**
- **Quantitative mapping of phase delay through the sample**
- **Has been shown to accurately predict optical performance**

Phase II Program Technical Objectives

Goals	Measurable Objective Metrics	Approach (How)
A. Enhance or Develop Optical Inks Capable of Achieving NASA Requirements	• 0.4 to 3 µm • > 90% transmission • Δn of 0.12, $\Delta P_{d,f} < 0.000001$ • $f/df > 500$ • $dn/dT < 10 \times 10^{-6}$/K • CTE < 20×10^{-6} m/(m K)	• Use both fluoropolymer and acrylate based optical inks (e.g. VBX No. 8 3NP) • Use SiO_2 nanoparticles in low-index inks
B. Design phase-corrector plates that meet NASA Requirements	• > 80% smaller psf, 4x FOV uniformity • 5th order Zernike polynomials • 30 waves max correction • 25% reduction in optic size	• Use Zernike polynomials for optical system aberrations & mount design from NASA
C. Fabricate phase-corrector plates that meet NASA Requirements	• ½ wave accuracy • Include system assembly mounting features • impact energy > 0.5 kJ/m^2	• Use Voxtel custom-designed printers • Print flat optics and polish as necessary (Struers RotoPol-35 polisher)
D. Characterize phase-corrector plates that meet NASA Requirements	• ¼ wave characterization accuracy • Compare with design intent	Use Voxtel, UO, UR, OSU optic toolset • Digital Holographic Microscope • Zygo profilometer • BYK Gardner haze-gard plus
E. Achieve environmental performance necessary for NASA mission	• 100 temp cycle haze increase < 2% • High vacuum, < 1% TML • Cryogenic, 120 K • Δn of 0.12, T% > 90%, $P_{d,f} < 0.001\%$, impact energy > 0.1 kJ/m^2 at vacuum, cryogenic operating points	• Model mechanical system on COMSOL • ATAMI Instron Mechanical Tester • Voxtel dewars • UO CAMCOR Vacuum chambers
F. Achieve radiation performance that meets NASA Requirements	• Radiation per plan • 1E12 p/cm^2 @ 0.1 MeV protons • 10E9 p/cm^2 @ 1.5 MeV protons • 5E12 e/cm^2 @ 0.1 MeV electrons • 2E9 e/cm^2 @ 1.5 MeV electrons	• Perform radiation tests throughout program using NASA Radiation Effects Test Facility • Quarterly tests