MiniSpec: Miniaturized Imaging Spectrometer to Measure Vegetation Structure and Function

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Program: IIP/ICD-16

Problem to Solve

- Earth's vegetated provide food, fiber and habitat and operate as key components of the carbon, water and energy cycles. They function to remove CO_2 from the atmosphere and convert it to stored biomass (and oxygen) but are susceptible to changing climate.
- NASA has strong interest in detecting and predicting changes in vegetation productivity as described in their Strategic and Science plans.
- The 2017 Decadal Survey for Earth Sciences emphasizes 3D vegetation structure and physiological (function) change.
- Accurate measurements are limited at scales necessary to understand and mediate or adapt to these changes.
- Need compact instruments for deployment on agile S/C – i.e.Smallsats

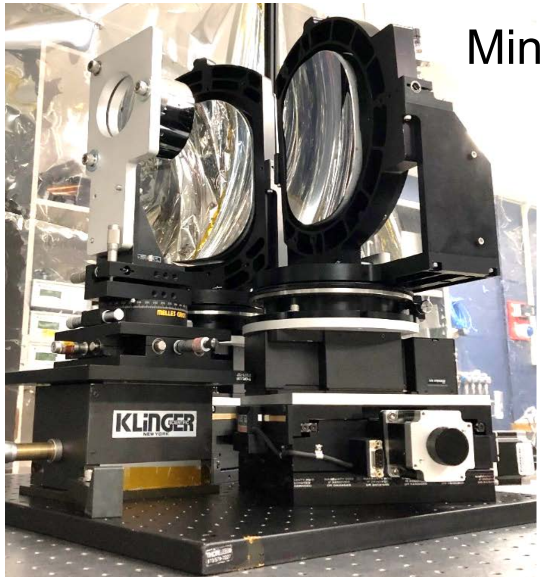
Solution

- Measurements are required at diurnal timescales and moderate resolution for light use efficiency (LUE) and pigments which are indicators of vegetation functioning. **SmallSat constellations with a compact imaging spectrometer can get these data**.
- Variable shadow fraction, however, limits the accuracy of this approach and currently used methods and concepts require complex sensors with multi-angle views to infer shadow fraction. Small **Hi-res imager using super resolution techniques can measure shadow fraction and 3D structure.**
- **This concept study designed an approach utilizing both instruments. The MiniSpec spectrometer concept will be emphasized here.**

Instruments

- Structure measurements (3D stereophotogrammetry):
  - **Mini3D** - Panchromatic visible imager developed by GSFC
  - 30 cm aperture
  - Mass 14kg
  - Power 17 W
  - 525 – 600nm wavelength with SNR 100
  - 1-2 m resolution
  - 30 km swaths targeted at tower flux sites
  - TRL 6
  - **MiniSpec** – Miniature VSWIR Spectrometer
  - 450 – 1700 nm,
  - 125, 10 nm spectral bands
  - 30 km swath contiguous over biomes
  - TRL 3/4
- Instrument avionics shared between the Mini3D and MiniSpec

Mini3D



MiniSpec

Technical

- Optical surfaces with "freeform" shapes enable future flight instrument designs
  - Larger fields of view
  - Faster f-numbers
  - Additional degrees of freedom allow the designer to reduce volume and eliminate surfaces from more traditional designs
- MiniSpec is a three mirror, high quality, state-of-the art, freeform spectrograph
- Objectives:
  - Show that a compact, wide field of view spectrograph is buildable using freeform optics
  - Complete fabrication to challenging surface error tolerances
  - Complete component-level acceptance testing
  - Complete system alignment (breadboard)
- Technology maturation -> reduces risk for a mission

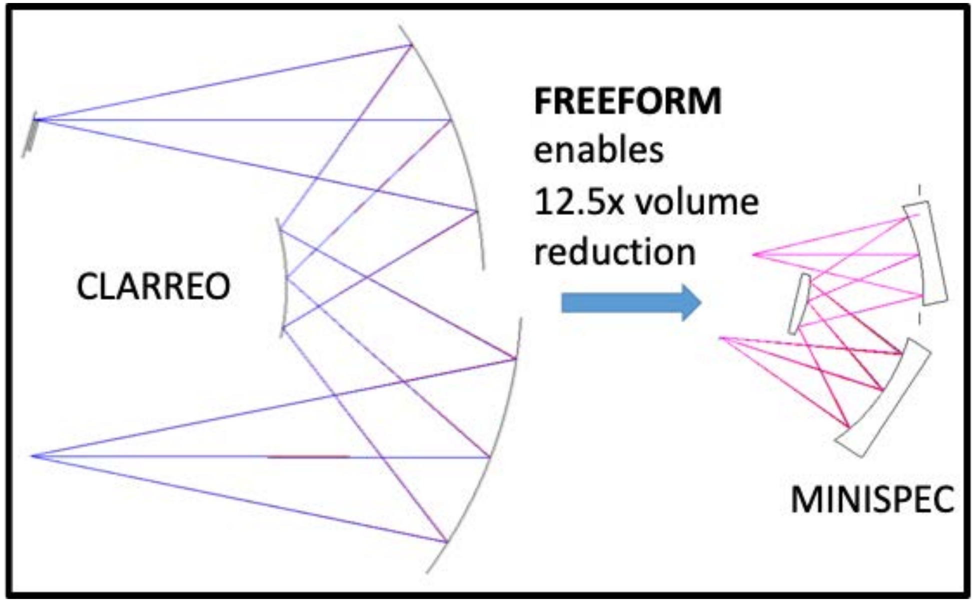
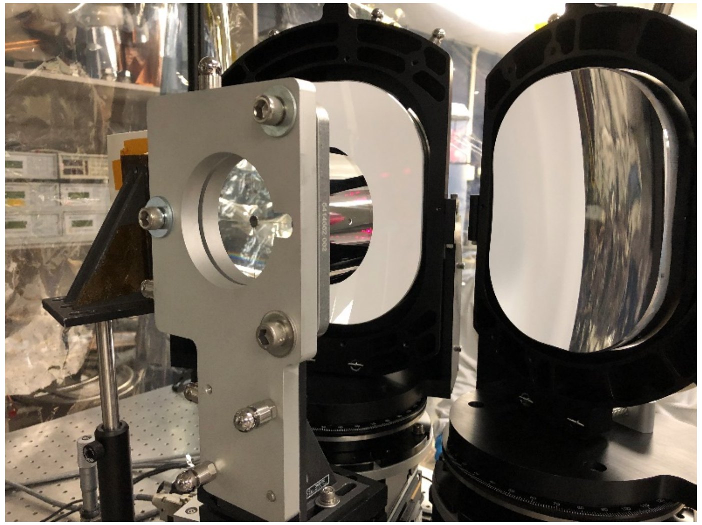


Illustration of the volume reduction enabled by freeform optical surfaces



Photograph of the aligned MiniSpec breadboard

Innovations

- Fabrication (Corning)
  - Fabricated freeform mirrors from aluminum to tight tolerances at a cost point that is do-able for a SmallSat mission (Corning Specialty Materials, Keene, NH)
  - Fabricated a large, convex, freeform grating with a variable blaze angle to tight tolerances
- Component-level testing (GSFC Optic Branch)
  - For freeform surfaces, standard test techniques are not feasible under SmallSat financial constraints
  - Used a novel, state-of-the-art, non-contact, coordinate measuring machine (CMM) to test and align freeform optical surfaces, resulting in a new test technique, data reduction algorithms, and a GUI software product applicable to a broad range of GSFC programs
- System-level alignment (GSFC Optics Branch)
  - Built a breadboard that decouples alignment degrees of freedom
  - Relied on component-level calibration from CMM
  - Used laser radar to align the surfaces in 6 DoF; fast & deterministic

Fabrication

- Corning Specialty Materials, Keene, NH
- Delivered in mid-calendar 2019
- Met figure and roughness specifications with margin --- “beautiful optics”
- Example data from O1:

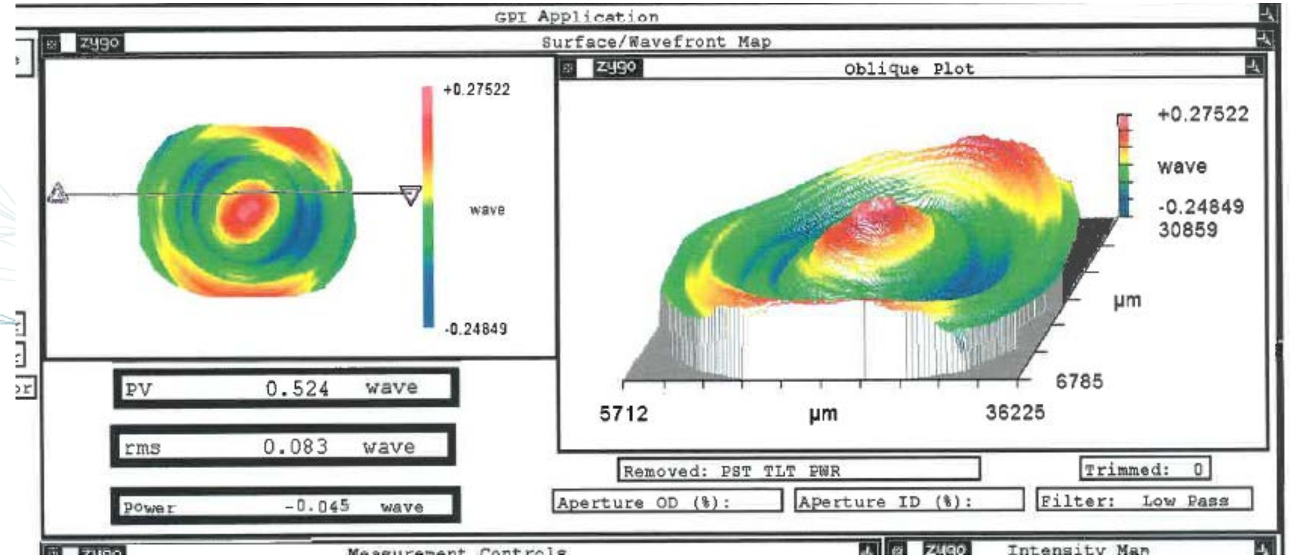


Image showing surface figure error map for O1 mirror, 0.083λ RMS (tolerance <0.2λ)

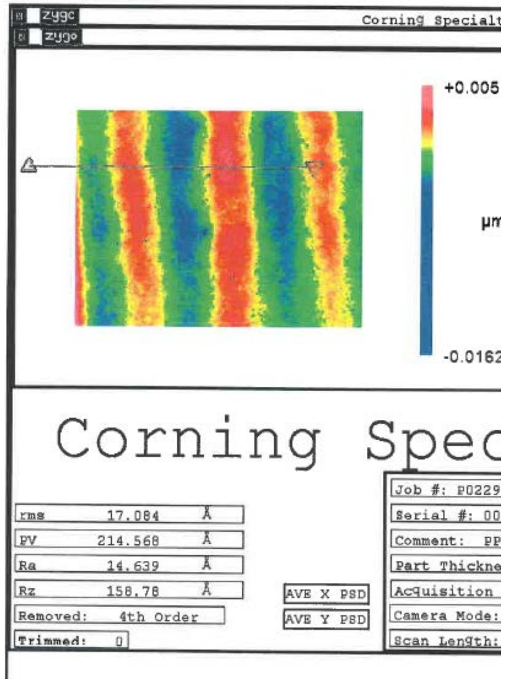
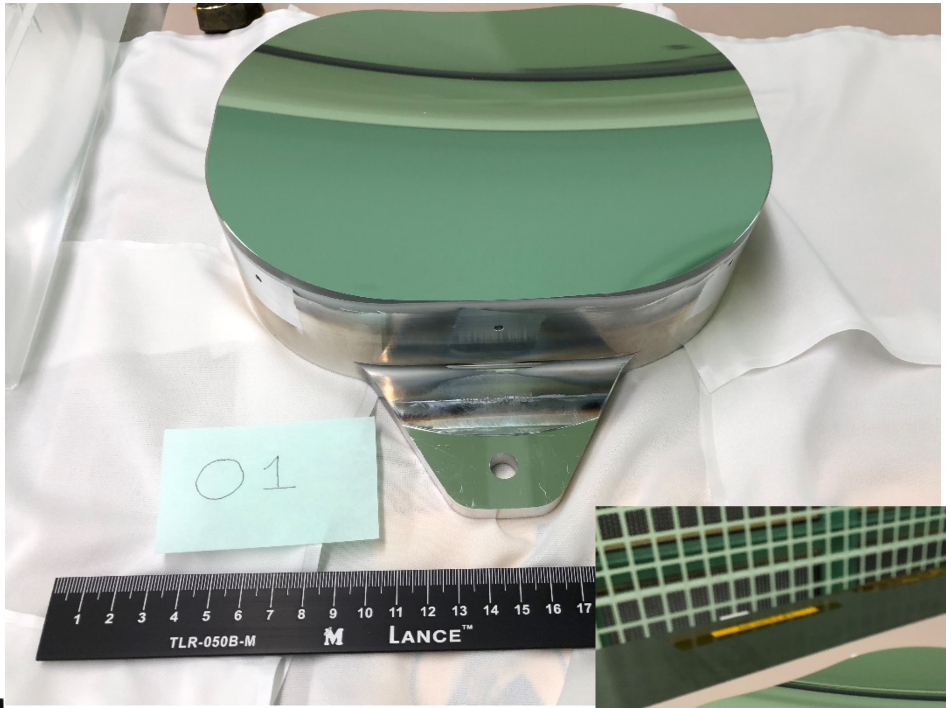
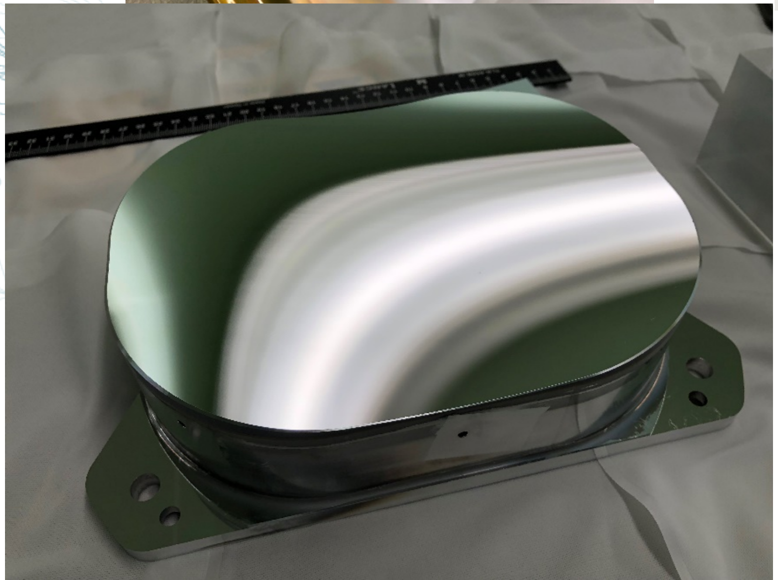
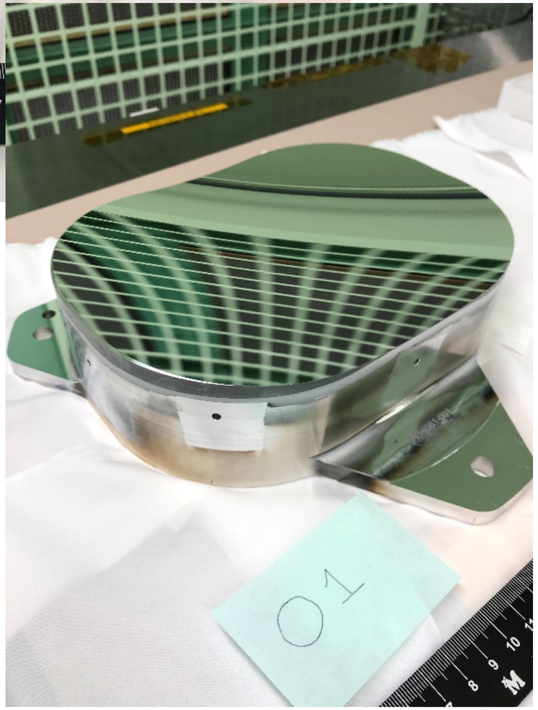


Image showing surface microroughness error map for O1 mirror, 1.7nm RMS (tolerance <2.5nm)

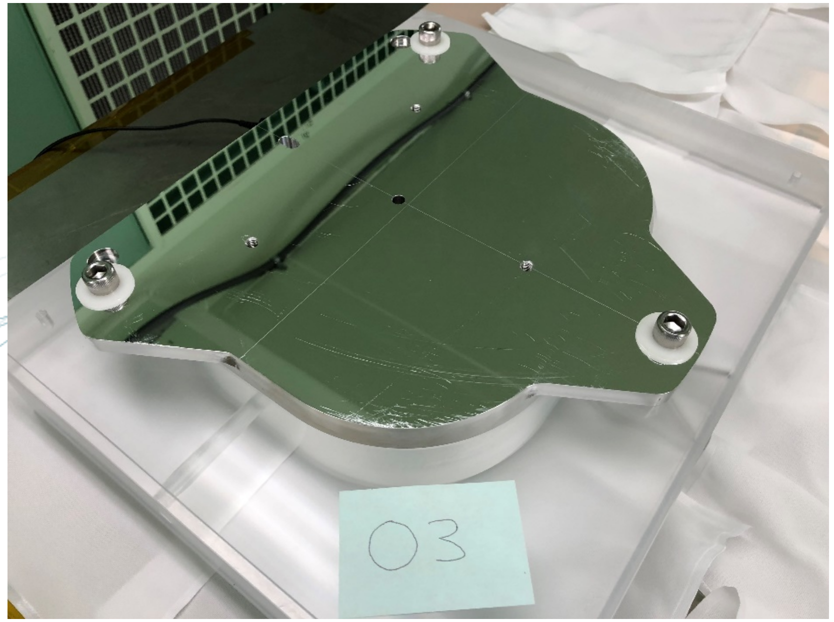
O1 mirror

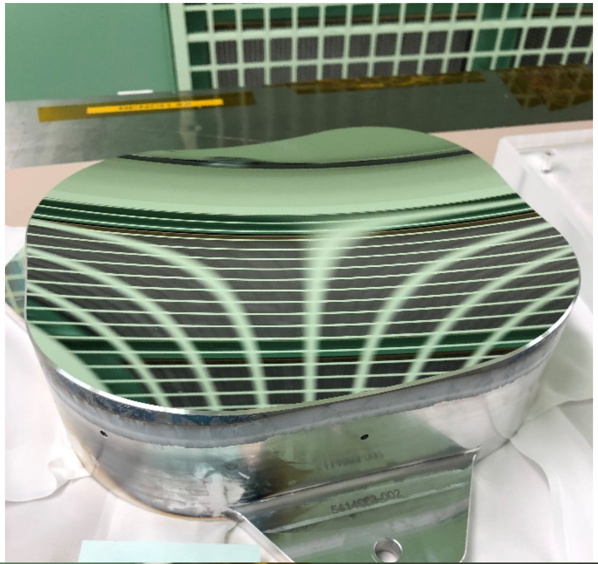


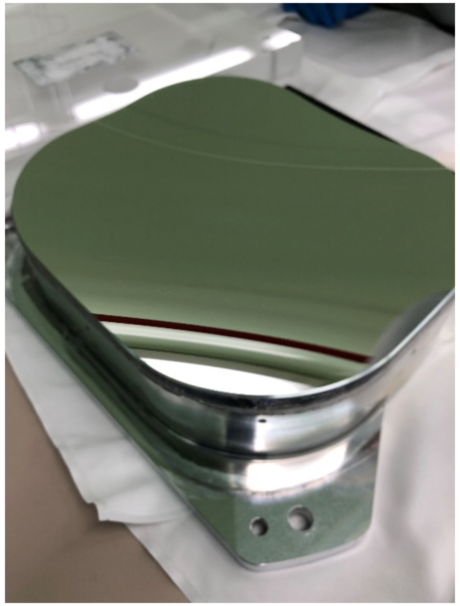


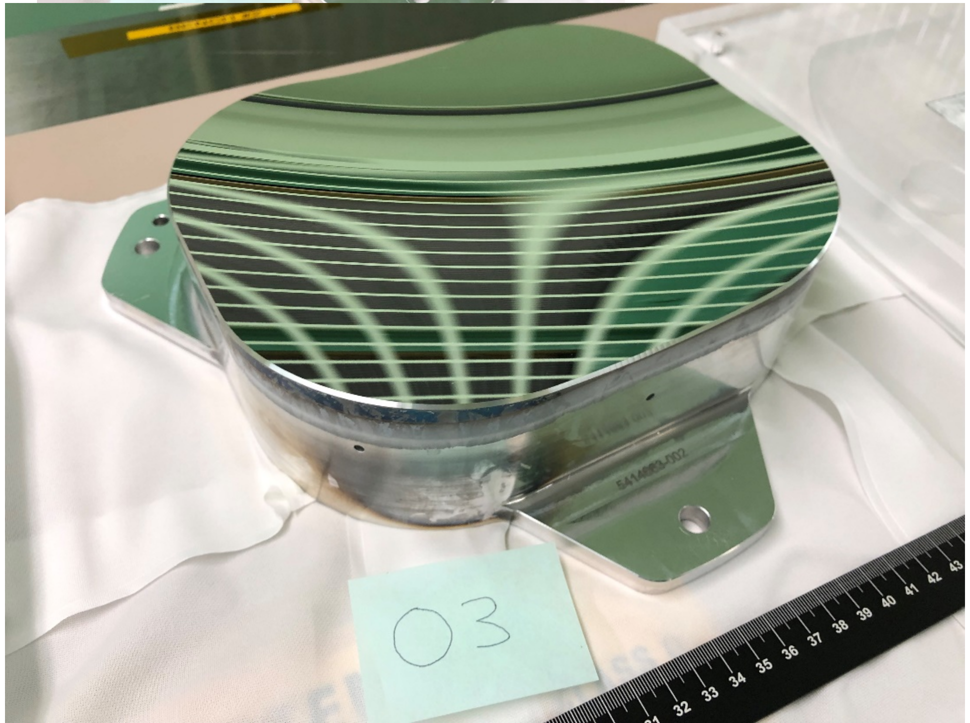


O3 mirror

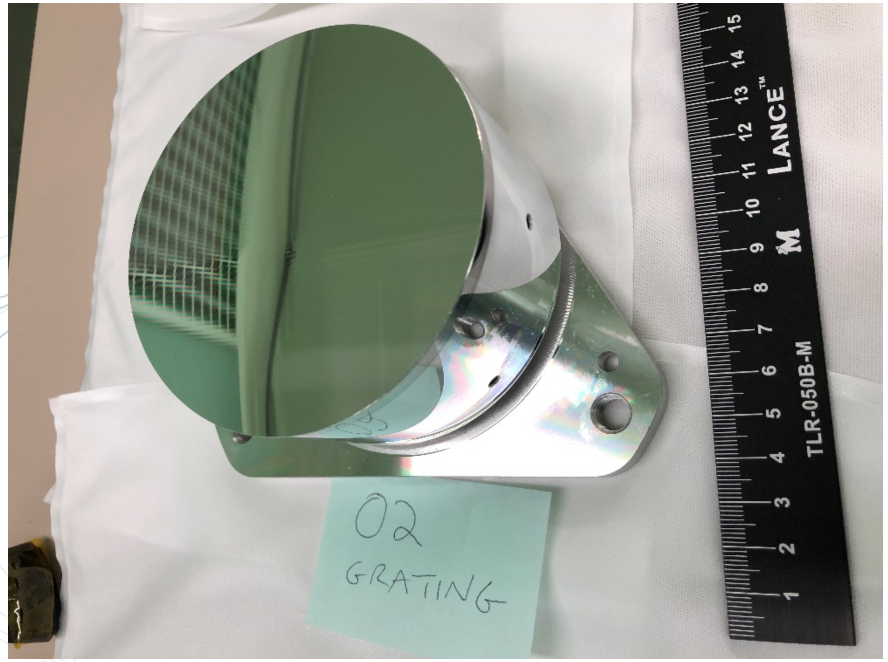


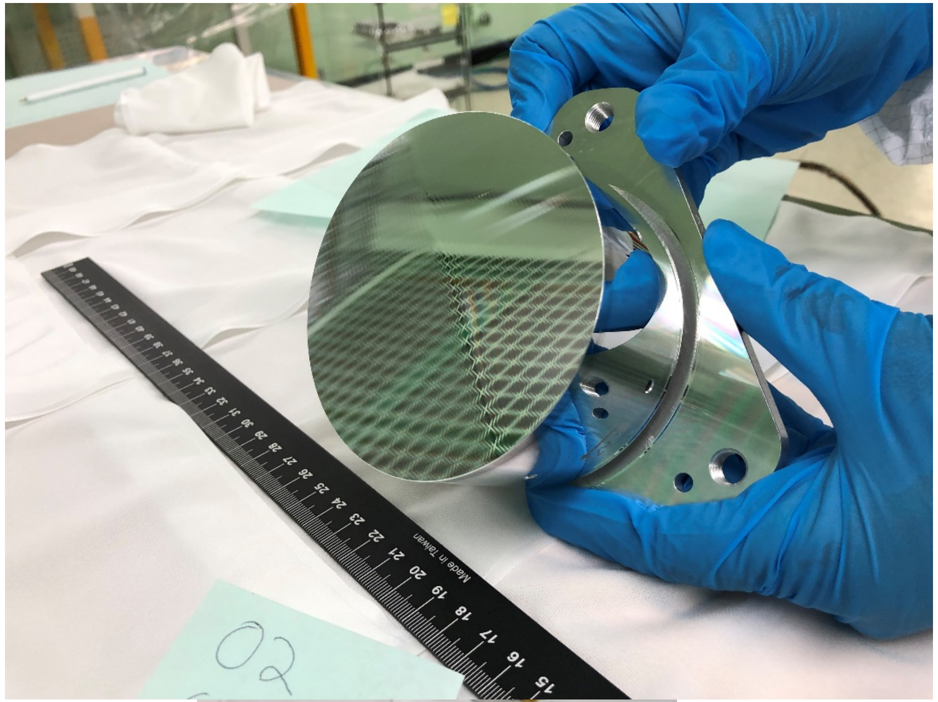


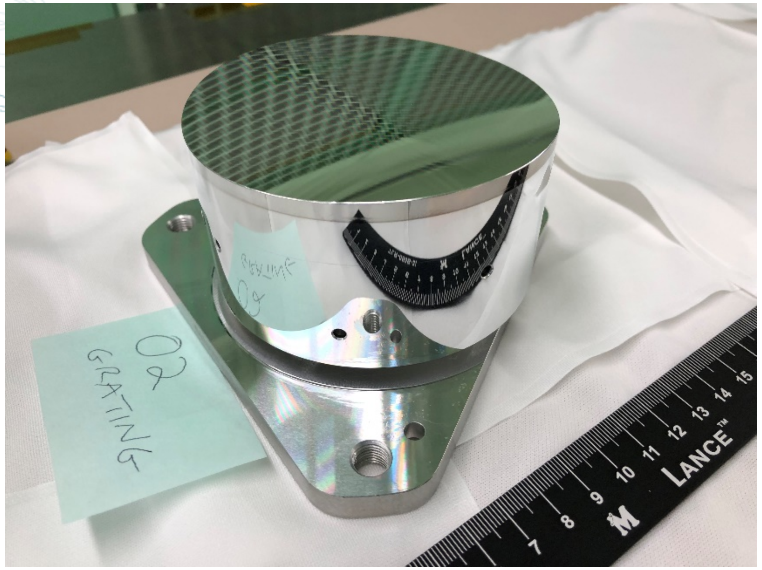




O2 grating

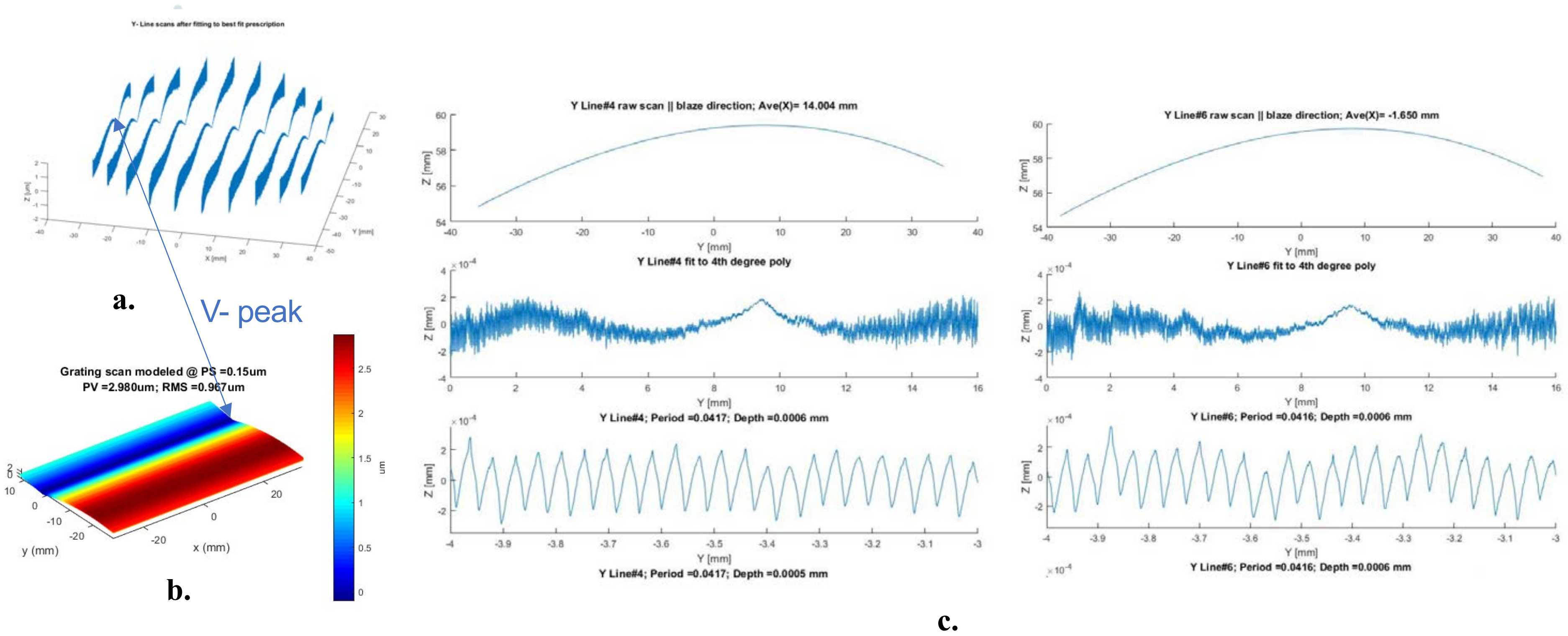

O2
GRATING
LANCE™
TLR-050B-M


O2
Made in Taiwan


O2
GRATING
LANCE™


O2
GRATING

O2 grating (Corning) profile “V-peak” feature



a. 3D or isometric view of grating profiles after removal of prescription. b. False-color, 3D plot also showing magnitude of V-peak feature. c. Plots of selected scans showing overall prescription/form (top), residual profile after subtraction (middle), and enlargement more clearly showing the grooves and blaze (bottom).

Next Steps / Contributions

Next Steps

- Further characterization of O2 grating when center reopens
  - Possible free form grating testbed
- Physical optics modeling w/ U of Arizona
- Future proposals for MiniSpec telescope and detector development

Contributions

- Improved fabrication techniques at Corning
- Improved metrology and data reduction techniques for freeform optics, including producing a software GUI to ease data reduction
- Construction of a state-of-the-art freeform spectrograph breadboard using large, high quality freeform mirrors and a freeform grating
- 2 related STTRs (OptiPro and UNC Charlotte)

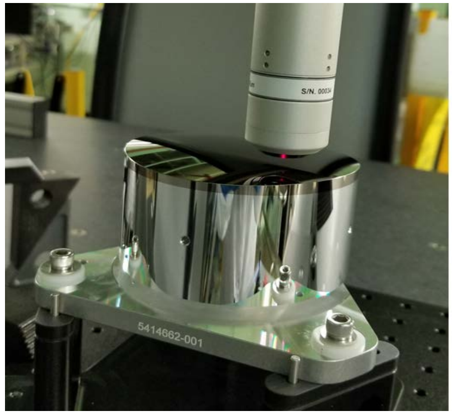
Publications and Presentations

- Czaja, W., Murphy, J.M. and Weinberg, D., 2018. Superresolution of Noisy Remotely Sensed Images Through Directional Representations. *IEEE Geoscience and Remote Sensing Letters*, *15*(12), pp.1837-1841.
- Mareboyana, Manohar, and Jaqueline Le Moigne. , 2018. "Super-resolution of remote sensing images using edge-directed radial basis functions." *Signal processing, sensor/information fusion, and target recognition XXVII*. Vol. 10646. International Society for Optics and Photonics, 2018.
- Mandl, Dan, Jon Ranson, Betsy Middleton, Fred Huemmrich, Phil Dabney and Jacqueline LeMoigne. 2018. Structure and Function of Ecosystems – a Smallsat Compliment to SBG. AGU Fall Meeting, Washington, DC. Advancing Global Surface Biology and Geology Science with Visible to Short-Wavelength Infrared Imaging Spectroscopy and Thermal Infrared Measurements Posters :GC13F-1900
- Goldblum, M., Fowl, L. and Czaja, W., 2019, May. Sheared multi-scale weight sharing for multi-spectral super resolution. In *Algorithms, Technologies, and Applications for Multispectral and Hyperspectral Imagery XXV* (Vol. 10986, p. 109860X). International Society for Optics and Photonics.
- Ranson, Jon, Fred Huemmrich, Phil Dabney Betsy Middleton, Dan Mandl and Jacqueline LeMoigne Attachments. 2018, Smallsat Constellations for Future Diurnal Observations of Terrestrial Ecosystems Structure and Function . AGU Fall Meeting, Washington DC. B44A: Centennial: Earth Observation Capabilities and Future Needs II Final Paper Number: B44A-11, Abstract ID: 412943
- Khreishi, M. (2019), Ultra-Precision Non-Contact Metrology for Optical Shop and Alignment Applications (Doctoral dissertation, College of Optical Sciences, the University of Arizona)
- Khreishi, M., Ohl, R., Howard, J., and Papa, J., Surface Characterization and Instrument Alignment for Freeform Space Applications Using Precision Coordinate Measuring Machine, OSA Freeform Optics, 10 June 2019 (invited talk)
- A New Method for Characterization of Diffraction Gratings using Scans GSC-18484-1: (Feb 2020)
- M. Khreishi, et al., “Precision, Non-Contact Metrology for Optical Shop Applications”, eNTR 1553898186
- M. Khreishi et al., “Instrument System Alignment using an Optical Coordinate Measuring Machine, Optical Engineering (in prep)”

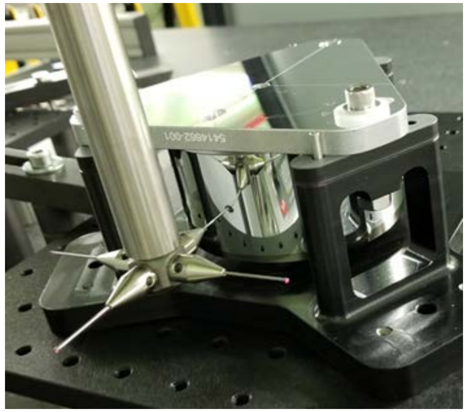
Back Up Slides

Component metrology

- Developed new techniques and data analysis approaches for measuring optics with “freeform” prescriptions
- Used a coordinate measuring machine (CMM) equipped with a non-contact, optical probe
  - Scanned the optical surface with an accuracy of tens of nanometers RMS
  - Measured features on the sides and reverse of the optic
  - Found the best-fit, as-built prescription for the surface
  - Established its absolute, 6 degree of freedom (DoF) pose with respect to mounting features and other references on the sides and rear
- Produced a graphical user interface (GUI) to allow any users to apply these techniques.
- Measurements of the components agreed well with other approaches, like interferometry performed by Corning
- Measurements also enable easier alignment to form an operating, optical instrument
- Also used a scanning white light interferometer (SWLI) to check the mid-spatial frequency error and microroughness



a.



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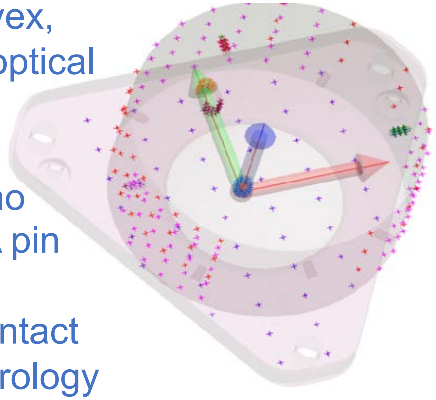

c.

a. Photograph of the much simpler setup showing the optical surface of a convex, freeform mirror under test using the optical head and the coordinate measuring machine (a mirror-like version of the grating in the MiniSpec design; i.e., no grating rulings, a practice part). b. A pin hole feature on the side of the optic undergoing measurement using a contact probe on the same machine. c. Metrology software showing various measured points and the coordinate system of the optic, with a CAD representation shown as semi-transparent.