MiniSpec: Miniaturized Imaging Spectrometer to Measure Vegetation Structure and Function

Presenter: Jon Ranson, PI
Team Members:
Joe Howard, Manal Khresei, Ray Ohl, Phil Dabney, Kurt Thome, Fred Huemmrich
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
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
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 (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


- Khreishi, M. (2019), Ultra-Precision Non-Contact Metrology for Optical Shop and Alignment Applications (Doctoral dissertation, College of Optical Sciences, the University of Arizona)


- 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

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. 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.