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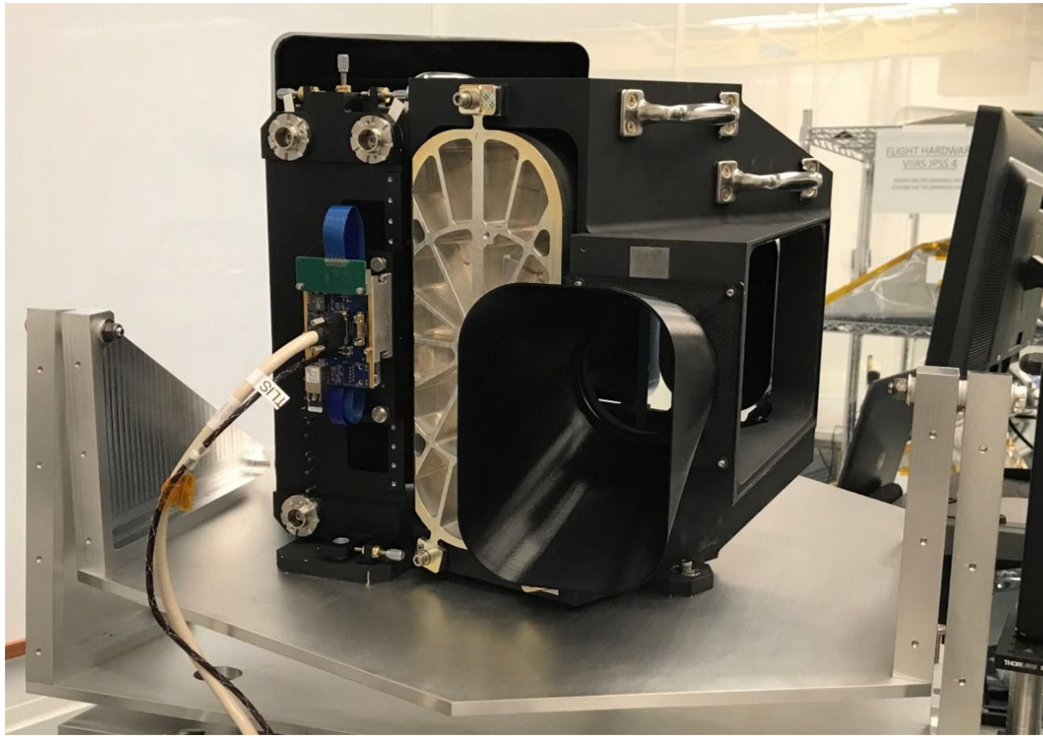

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Advanced Technology Land Imaging Spectroradiometer-Prototype (ATLIS-P) Advanced Technology Demonstration

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  - Principal Investigator: Dr. Jeff Puschell (retired)
  - Chief Engineer: John Schlaerth
  - Test Engineers: Dr. Joe Choi, Dr. Kushal Mehta, Dr. Kyle Heideman
  - Telescope Manufacturing: Dr. John Schaefer (retired)
  - Optical Design Lead: Lacy Cook (retired)
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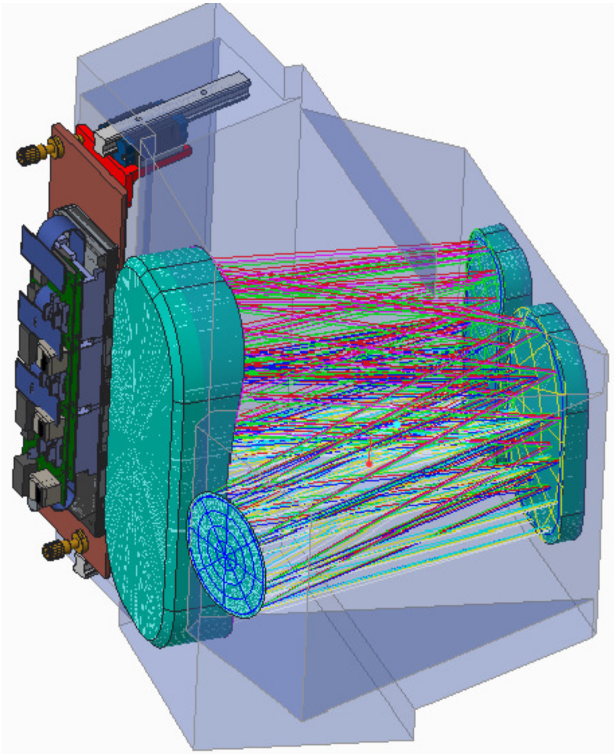
ATLIS-Prototype (ATLIS-P)

- SLI-T 2015 project involved designing, building, testing and demonstrating an Advanced Technology Land Imaging Spectroradiometer Prototype (ATLIS-P)
  - Interchangable spectral filters at 865 nm and 443 nm cover entire FPA
  - VIIRS Integrated Filter Assembly (IFA) provided additional VNIR bands
- Key elements of the technology demonstration include:
  - Wide FOV nearly telecentric Freeform Reflective Triplet (FFRT) telescope with real entrance pupil
  - Production digital Si:PIN FPA based on Raytheon space-qualified SB501
  - ATLIS system engineered and optimized for SLI-T 2015 Reference Mission Architecture (RMA) requirements using ATLIS Performance Model (APM), an integrated imager system performance model
  - Compact, end-to-end onboard calibration system
- ATLIS-P telescope and FPA design characteristics were selected to reduce cost, while enabling a valid demonstration of system performance

ATLIS-P Entrance Pupil Diameter (EPD): 8.74 cm



Basic question posed by ATLIS-P: Can a small aperture Freeform Reflective Triplet Telescope imaging system meet SLI-T RMA 2015 requirements?

ATLIS-P is a testbed for future NASA and Raytheon funded demonstrations of calibration, VNIR and SWIR focal plane technology and any other technologies that support NASA and USGS SLI goals

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ATLIS-P supports Sustainable Land Imaging (SLI) architectures

- ATLIS-P supports future SLI architectures by providing a direct path to a disaggregated architecture using an ATLIS-like approach for the VSWIR and a separate instrument for the TIR – similar to the current Landsat 8/9 architecture
  - Other work at Raytheon with WFOV emissive infrared refractive systems had already reduced risk for an emissive infrared element of this architecture similar to TIRS – prompting us to develop the freeform Zernike polynomial described three mirror reflective telescope for SLI-T
- ATLIS-P also supports full spectrum instruments by demonstrating a scalable design approach that could be built with the larger aperture size required to deliver high quality 60 m TIR pixels
  - Improved understanding of freeform telescope captured in ATLIS combined with improved system engineering tools improves technology readiness for a larger aperture ATLIS-like approach

ATLIS-P telescope extends US industrial capabilities

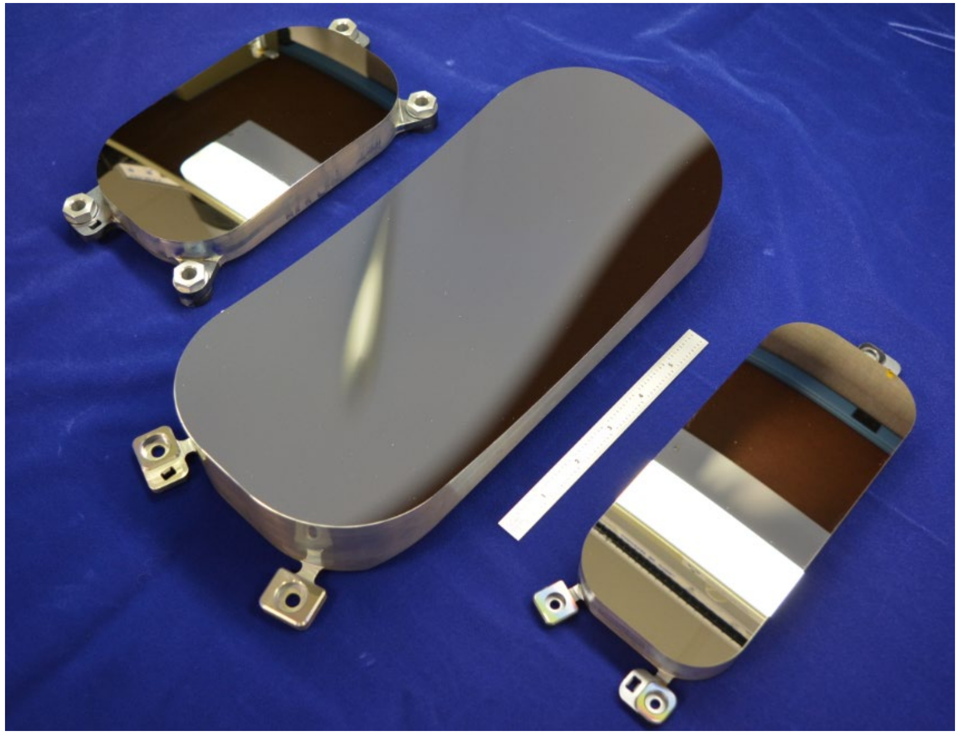
- ATLIS-P telescope is the first Freeform Reflective Triplet (FFRT) telescope manufactured by US industry and the first known FFRT for the VNIR
  – Earlier telescopes with all free form mirrors developed by University of Rochester and TNO for Tropomi among others are not RTs and do not address SLI-T RMA requirements for aperture size, FOV and IFOV
- New freeform metrology methods were created and demonstrated with successful Magnetorheological (MRF) figure correction
- Lessons learned include:
  – Freeform mirrors require more processing time to achieve figure
  – Freeform Zernike mirror alignment sensitivities differ from rotationally symmetric aspheres, requiring models that account for Zernike sensitivities

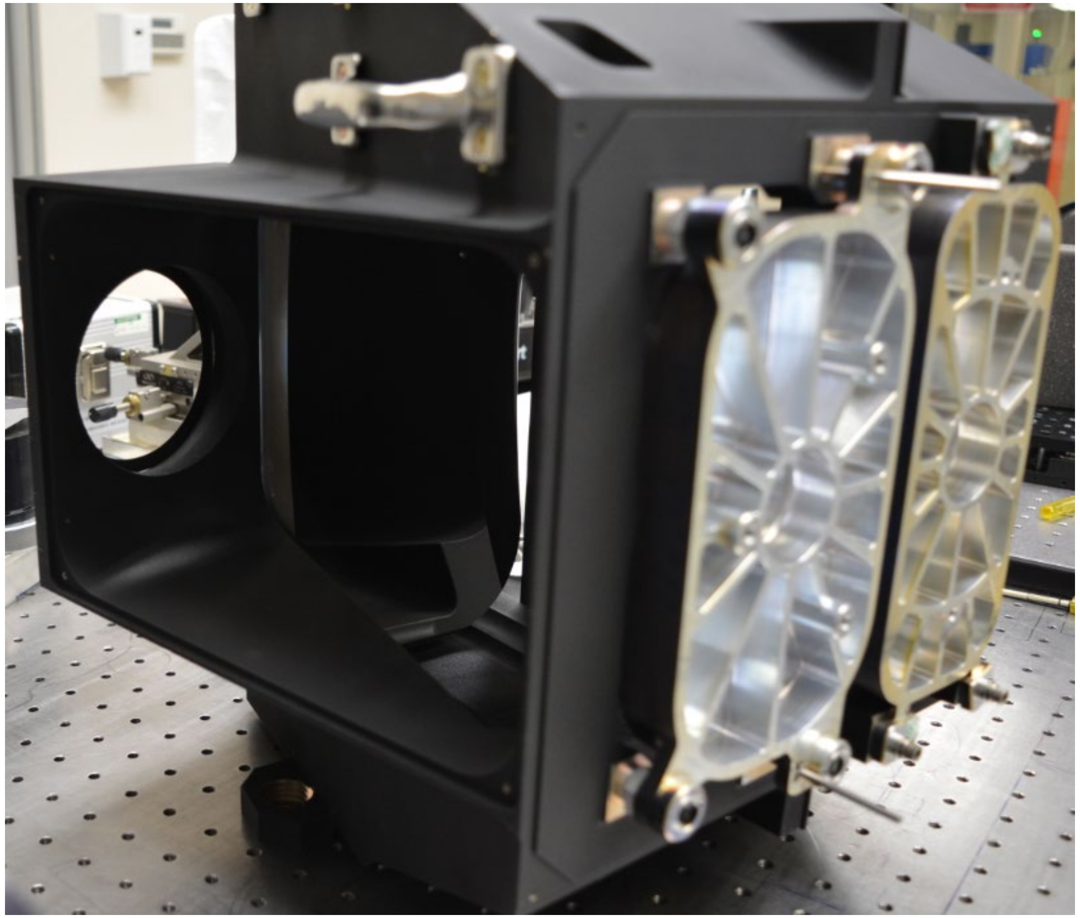
Thanks to NASA's investment in this technology, ATLIS-P reduced risk and inspired design and fabrication of multiple FFRTs for a wide variety of Earth observation systems

Free form optics can reduce optical aberration and minimize instrument size and mass for wide FOV systems

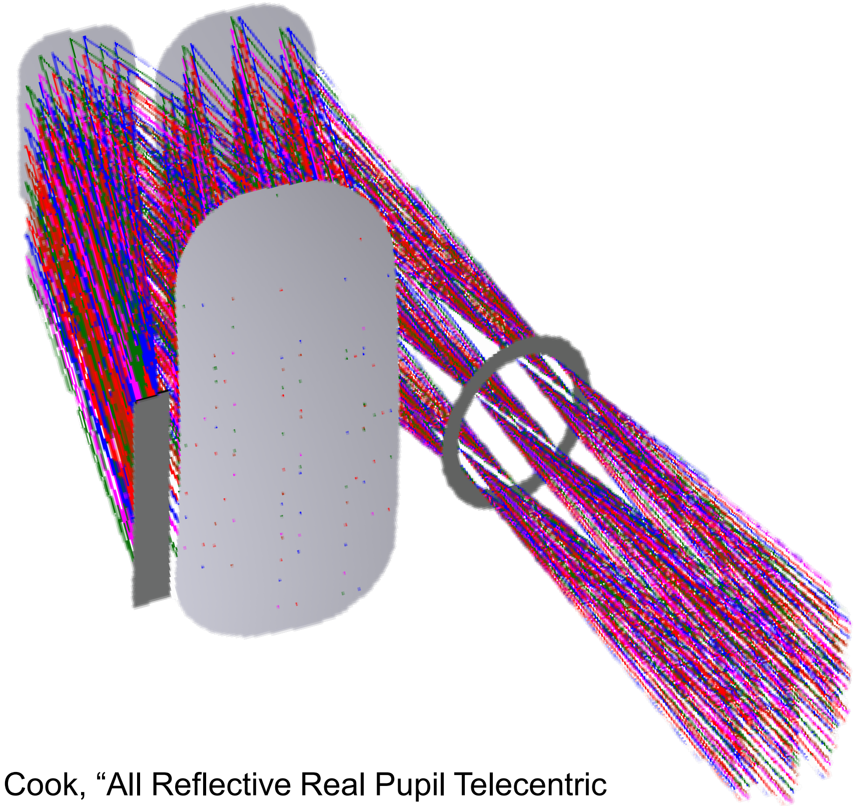
- Free form optical elements have shapes that are not manufactured using standard spherical or aspherical manufacturing techniques
  - ✓ Require new generation of optics manufacturing machines that can be programmed to create a shape defined by other mathematical functions such as Zernike polynomials or even discrete element arrays that are produced by optimizing figures of merit at the optical system level
- These abstract surface shapes can be designed and manufactured to minimize aberration across wide fields of view with fast optics (low f/numbers) to achieve image quality performance and etendue more typical of larger systems in a smaller package than legacy systems

Three mirror WFOV ATLIS-P Free Form Reflective Triplet Telescope





ATLIS-P telescope achieved low WFE performance needed for high performance small satellite imagers



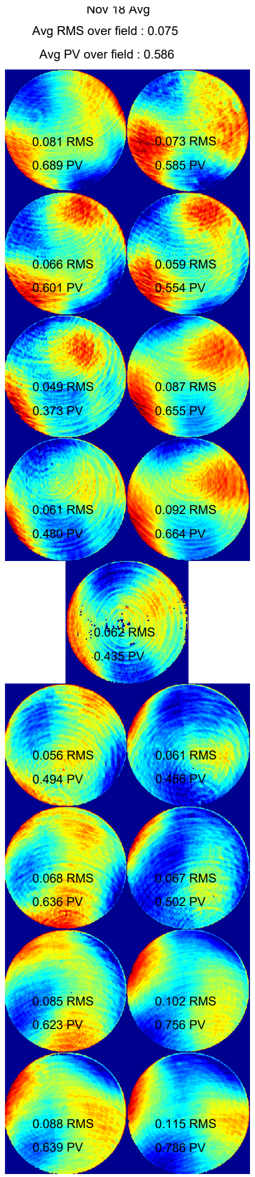
Reference: Lacy Cook, “All Reflective Real Pupil Telecentric Imager”, US Patent 8,714,760 (2014)

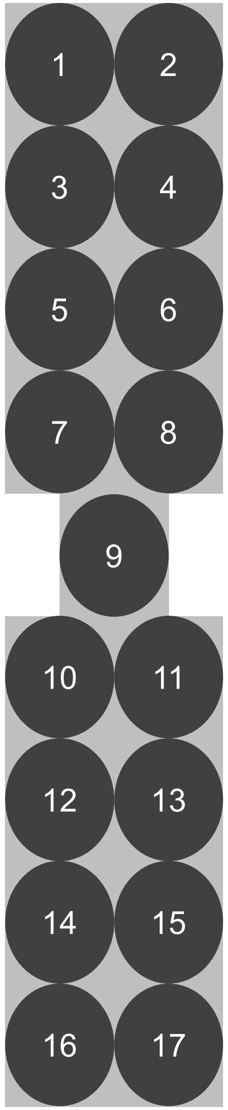
- Circular, external, real entrance pupil enables accurate calibration with smaller sources than alternative designs
- Nearly telecentric design with maximum angle over FOV of 1.21 mrad
- Image AOI: 22.56°
- FOV: 1 x 16 deg^2
- EFL: 48 cm (f/5.492 with EPD of 8.74 cm)
- Diffraction limited at 660 nm
- Design residual (waves at 632.8 nm)
  - ✓ Average RMS WFE: 0.016
  - ✓ Maximum RMS WFE: 0.029
- Measured average WFE across full FOV of 0.075 wave

ATLIS-P telescope fabricated by Raytheon in Texas and integrated in California achieved excellent WFE across full FOV

- **General Purpose Optics (GPO) lab using 43 cm, 632.8 nm Zygo interferometer**
- **Average of five measurements with piston, tilt and power removed**
- **Average RMS WFE across 17 tooling ball positions is 0.075 wave**
- **Maximum RMS WFE is 0.115 wave**

Tooling Ball #	RMS WFE (waves)	PV WFE (waves)	Power (waves)
1	0.081	0.689	-1.259
2	0.073	0.585	-1.298
3	0.066	0.601	-1.422
4	0.059	0.554	-1.430
5	0.049	0.373	-1.608
6	0.087	0.655	-1.636
7	0.061	0.480	-1.858
8	0.092	0.664	-1.827
9	0.062	0.495	-2.007
10	0.056	0.494	-2.092
11	0.061	0.486	-2.050
12	0.068	0.636	-2.205
13	0.067	0.502	-2.189
14	0.085	0.623	-2.318
15	0.102	0.756	-2.281
16	0.088	0.639	-2.444
17	0.115	0.786	-2.533





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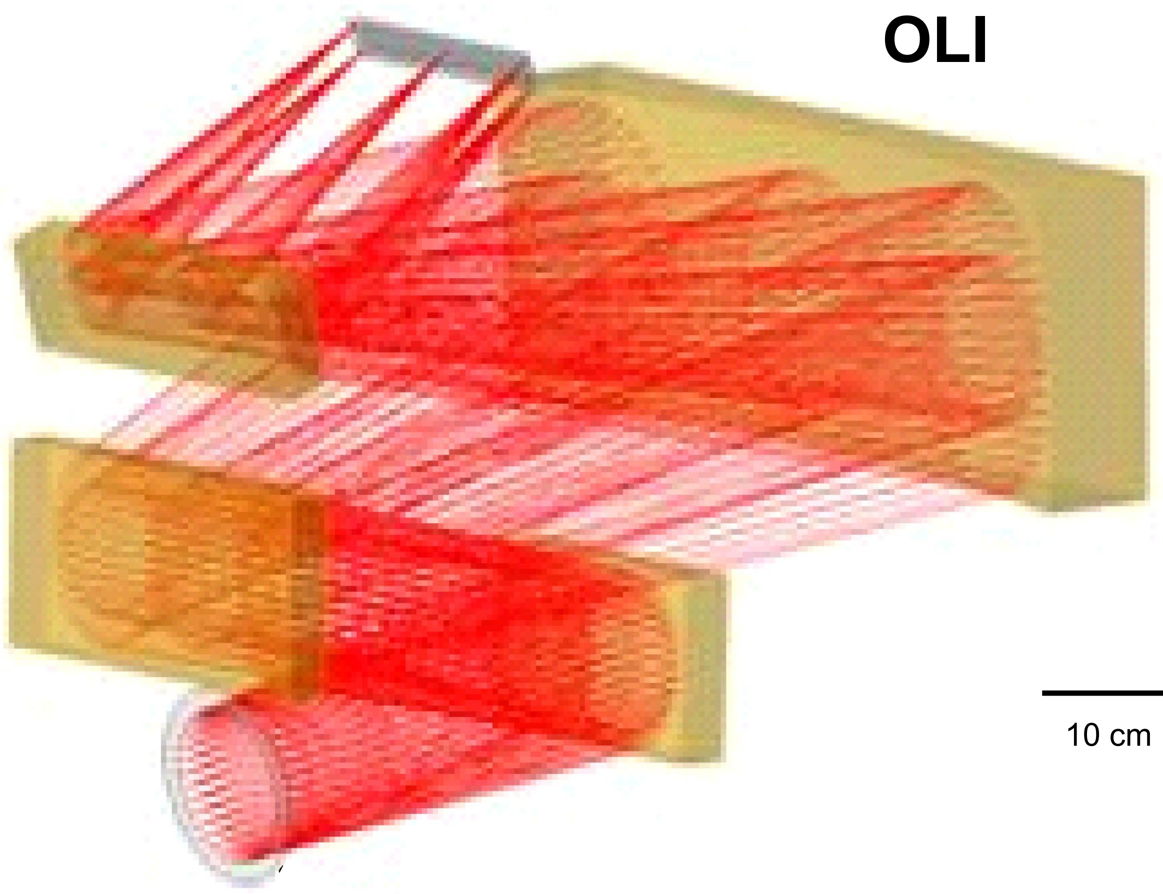
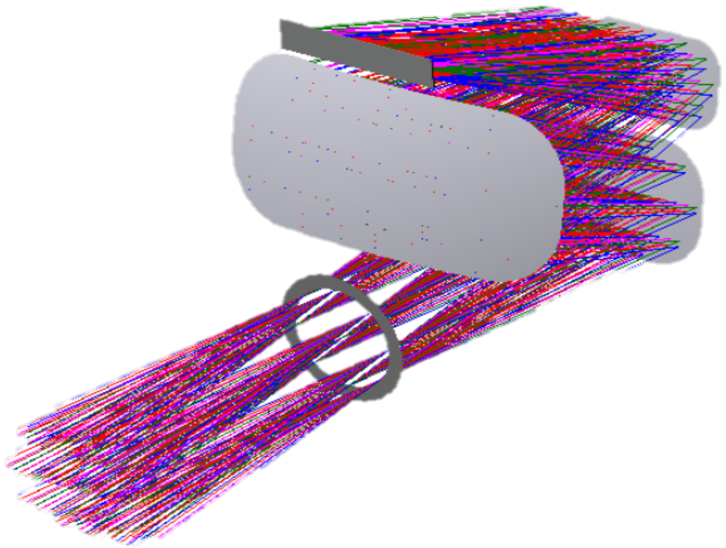
ATLIS-P meets L8/L9 VSWIR requirements using free form reflective triplet that is 75% smaller in volume than OLI telescope





Reference: Figoski et al. SPIE 7452, 74520T (2009)

ATLIS-P test results combined with model predictions confirm this innovative imager meets SLIT-15 RMA performance requirements

- Spatial and temporal coverage – performance across full FOV meets RMA requirements, enabling credit for spatial and temporal coverage
- Radiometric SNR – measurements agree with predictions to within 5%
- Saturation radiance – no saturation for maximum spectral radiance in all bands
- Relative Edge Response (RER) – meets requirements across the full field of view, except in the PAN band, which can be met with low fill detectors
- Edge Extent – measurements and predictions meet edge extent requirements
- Pixel-to-pixel uniformity – 0.1% or better following non-uniformity correction
- Radiometric stability - 0.0997±0.184% meaning each pixel varied by less than 0.1% over both short duration (one minute collects over 99 mins/day) and over 16 days, meeting both parts of the RMA radiometric stability requirement

In ATLIS-P, we examined key elements required for implementing small imaging systems that meet RMA 2015 requirements

- Low aberration all-reflective WFOV telescopes for pushbroom imagers
  - Free form designs enable better correction of aberrations across wide FOV than legacy designs – advanced manufacturing techniques fabricated mirrors successfully
  - However, to realize and maintain this performance, improved metrology methods are needed to integrate FPAs with the optical system – innovative techniques enabled quick and consistent low WFE telescope alignment, but FPA integration remained uncertain
  - More work is needed to establish that small WFOV telescopes maintain required focus and WFE over full range of operating conditions, following launch
- Digital FPAs with higher spatial frequency sampling than legacy systems to improve MTF and software Time Delay and Integration (TDI) to improve SNR
  - ATLIS-P verified that higher spatial frequency sampling improves system MTF and that software TDI improves SNR to required RMA 2015 performance
  - Analysis showed that low fill detectors and resampling (versus aggregation) provide additional system MTF improvements needed for successful small land imaging systems
- Compact onboard calibration source
  - Improved full spectrum calibration technology enables reducing size of legacy sources by ~90%
  - ATLIS-P demonstrated proof of concept for a source to be more fully developed on IRIS

Summary

- New and emerging optical, focal plane and calibration technology enables much smaller land imagers than current systems
- ATLIS-P achieved performance required to meet SLI-T RMA 2015 requirements - advanced key technology from TRL 3 to TRL 5
- Lessons learned in ATLIS-P telescope build and test reduce risk for future imaging system developments
- Overall comparison between measurements and model predictions looks good
- ATLIS-P supports both disaggregated architectures and full spectrum single instrument land imaging systems
- Key ATLIS-P technology benefits many other NASA Earth Science missions, especially those involving small satellite systems

Thanks to NASA ESTO for this investment in advanced land imager technology!