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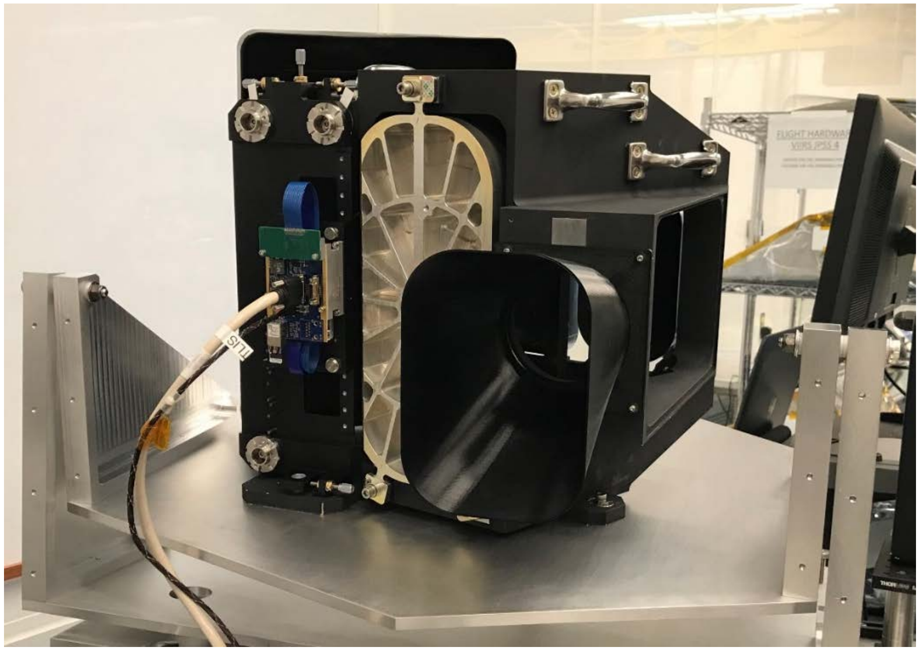

Advanced Technology Land Imaging Spectroradiometer (ATLIS)

Grant Number: NNX16AP64G/80NSSC18K0103

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2019 June 11

ATLIS is funded by NASA ESTO through the Sustainable Land Imaging-Technology Program Grant NNX16AP64G/80NSSC18K0103. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Aeronautics and Space Administration.

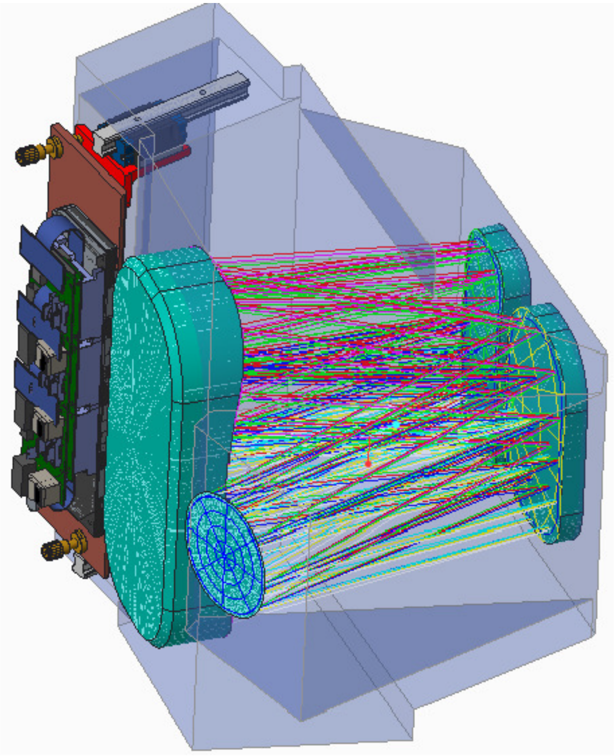
Acknowledgements

- Many thanks to the test team for their sustained efforts in characterizing performance of this system: Dr. Kushal Mehta, Dr. Joe Choi, Dr. Kyle Heideman, Mr. Alex Demos, Ms. Mignon Huang, Mr. Andrew Sararu
- Many thanks to NASA ESTO for funding this work

ATLIS-Prototype (ATLIS-P)

- SLI-T project involves designing, building, testing and demonstrating an Advanced Technology Land Imaging Spectroradiometer Prototype (ATLIS-P)
  - Interchangable spectral filters at 865 nm and 443 nm can be used to cover the entire FPA
  - VIIRS Integrated Filter Assembly (IFA) provides additional VNIR spectral bands
- Key elements of the technology demonstration include:
  - Wide FOV nearly telecentric Freeform Reflective Telescope with real entrance pupil
  - Production digital Si:PIN FPA based on the Raytheon space-qualified SB501 ROIC
  - ATLIS system engineered and optimized for SLI-T Reference Mission Architecture (RMA) requirements by means of integrated imager system performance models
- 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 Telescope imaging system meet RMA 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-T goals

ATLIS-P supports Sustainable Land Imaging (SLI) architectures

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- ATLIS-P supports future SLI architectures by providing a direct path to a disaggregated architecture using an ATLIS-like approach for the VISWIR and a separate instrument for the TIR – similar to the current architecture
  - Other work at Raytheon with WFOV emissive infrared refractive systems has already reduced risk for the emissive infrared element of this architecture – prompting us to develop the freeform Zernike polynomial described mirror reflective telescope for SLI-T
- ATLIS-P also supports a full spectrum instrument 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

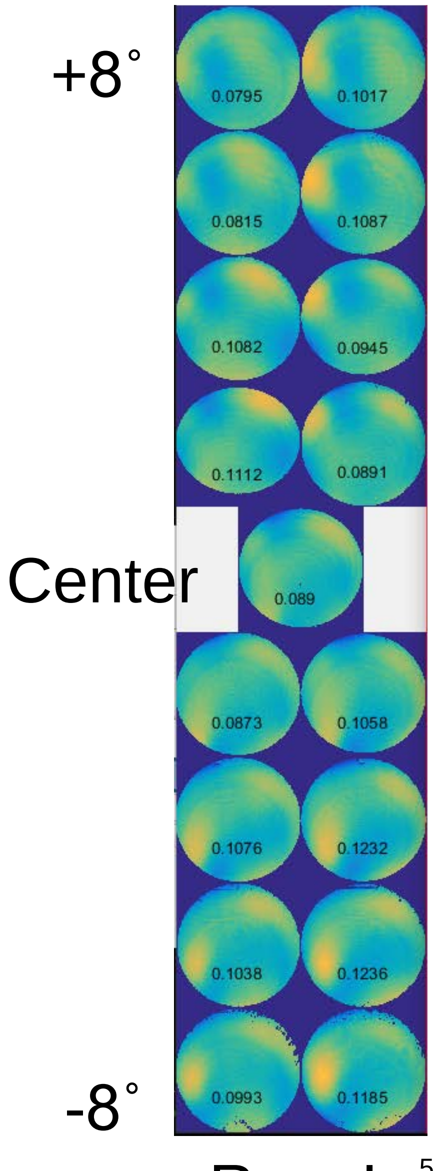
ATLIS-P telescope extends US industrial capabilities

- ATLIS-P telescope is the first Freeform Reflective Telescope (FFRT) manufactured by US industry
  - Earlier FFRTs developed by University of Rochester and TNO for Tropomi do not address SLI-T RMA requirements for aperture size and FOV
- 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

ATLIS-P telescope development reduces risk for future imaging and remote sensing systems

Measured telescope Wave Front Error (WFE) at initial alignment

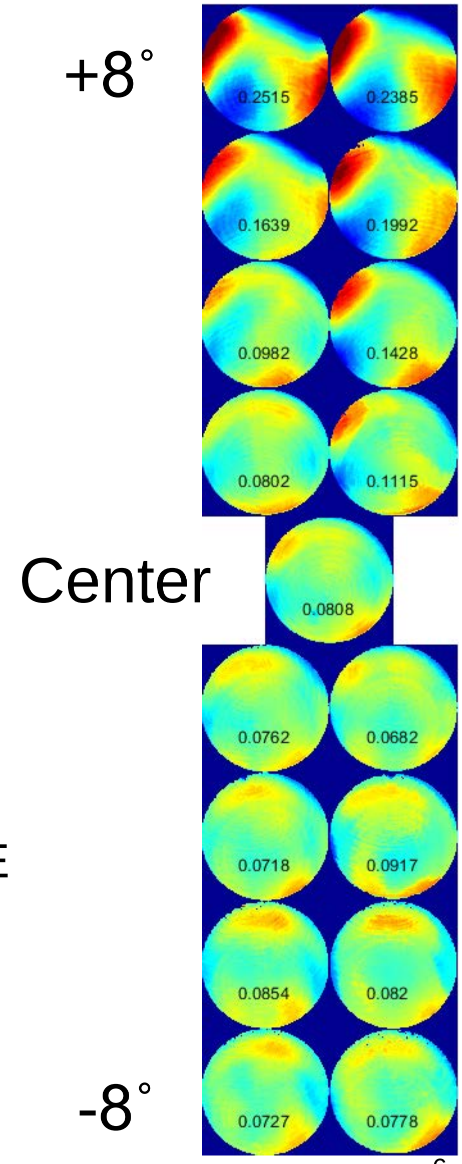
- During telescope alignment in early 2018 August, WFE was measured at 17 locations across ATLIS-P telescope field of view (FOV) using a Zygo laser interferometer
  - WFEs were measured repeatedly for trial telescope alignments to find optimum alignment across entire FOV
  - Measurement set shown at right is typical of what was measured before the mirrors were staked in place
- WFE is reported in fractional wavelength or wave of the He-Ne laser wavelength of 632.8 nm
- For the measurement set shown here, RMS WFE ranged from 0.0795 wave (50.31 nm) to 0.1236 wave (78.21 nm) with average RMS WFE of 0.1019 wave (64.49 nm)



PRELIMINARY RESULTS

Post-staking telescope alignment

- Telescope alignment drifted during staking
- Efforts to release telescope from staking damaged the telescope mirrors, resulting in high WFE near +8 deg cross track angle
  - Measurement set shown at right is the measured telescope WFE after telescope was released from staking and realigned
- For the measurement set shown here, RMS WFE ranged from 0.0682 wave (43.2 nm) to 0.2515 wave (159.1 nm) with average RMS WFE of 0.1172 wave (74.16 nm)
  - Average RMS WFE is close to what was measured before the telescope was damaged, but the highest WFE is ~2x higher than the maximum WFE measured before staking



ATLIS Performance Model (APM) verification is at the heart of this study

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- Measured performance of ATLIS-P was compared with predictions made by a detailed instrument system performance model that combines industry-standard analysis techniques for SNR, MTF and many other related parameters with measured ATLIS-P telescope, FPA, electronics and test equipment characteristics to predict measured ATLIS-P system performance
  - Differences between predictions and measured performance were investigated in detail to determine the source of any anomaly
- APM is derived from similar imaging spectroradiometer system performance models used at Raytheon to successfully predict performance of many recent instruments including VIIRS, JAMI and earlier Landsat instruments
- APM simulates the image and signal processing chain step-by-step to account for impact of all system elements on ATLIS data products, while accounting for all known sources of noise and signal degradation in predicting quality of sensor products
- Before ATLIS-P hardware was available, APM was tested by putting in design characteristics for existing systems like OLI and comparing performance predictions with measured performance – results looked good for predicted and measured MTF, SNR and RER slope

ATLIS-P performance characteristics for characterization and demonstration

- Spatial and temporal coverage
- Radiometric SNR
- Saturation radiance
- Relative Edge Response (RER)
- Edge Extents
- Pixel-to-pixel uniformity
- Radiometric stability

Spatial and temporal coverage, radiometric SNR, saturation radiance, RER and radiometric stability are discussed here

Spatial and temporal coverage (STC)

- **RMA requirements:** RMA 1.2.1 requires a maximum 16 day revisit time with a single system resulting in an 8 day revisit time with two systems in operation; **185 km wide cross track swath from a 705 km altitude**, corresponding to a **15 deg cross track FOV**. RMA pixel size for the solar reflectance bands measured by ATLIS-P is **15 m (RMA Table A.1) for the panchromatic band and 30 m for the multispectral bands** (RMA VISWIR-1100 and Table A.1).
- **Basic test approach and results:**
  - ATLIS-P is designed to have a 16 deg FOV cross track, to respond to RMA requirements
  - To get credit for meeting RMA STC requirements, radiometric sensitivity and image quality requirements need to be met across the entire ATLIS-P FOV
  - Radiometric sensitivity and image quality performance have been measured at 865 nm and 443 nm at several different locations across the FOV, including area with highest WFE
  - Measured SNR meets RMA requirements with margin using TDI and agrees well with APM predictions
  - Measured RER Slope meets RMA requirements, except in the high WFE part of the damaged telescope FOV

ATLIS-P telescope WFE map projected into SNR/MTF measurement space

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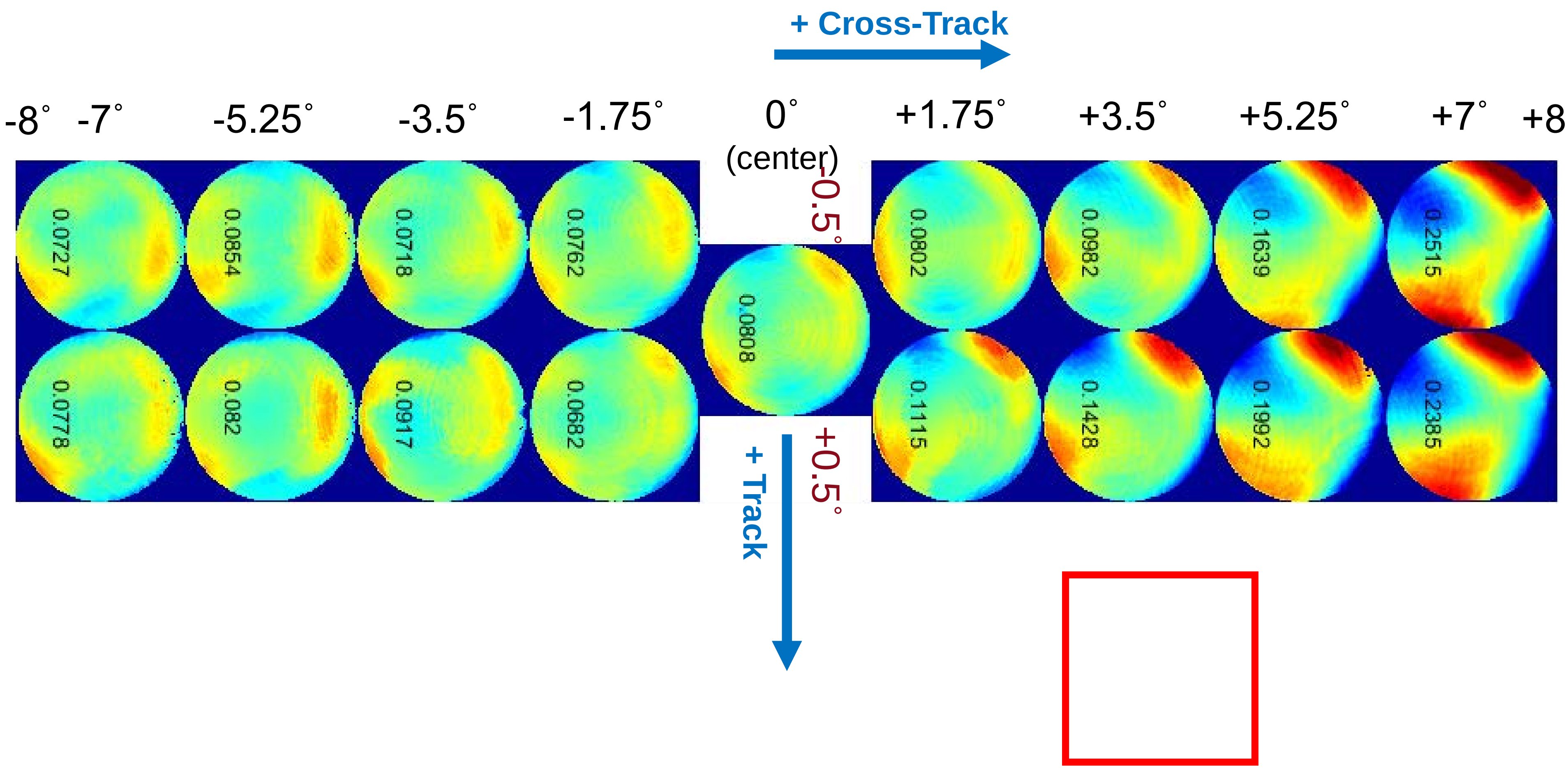

ATLIS-P FPA footprint (1.98º x 1.98º)

PRELIMINARY RESULTS

APM results show RER slope performance for smaller telescopes like ATLIS-P is more sensitive to WFE and de-focus than for larger telescopes

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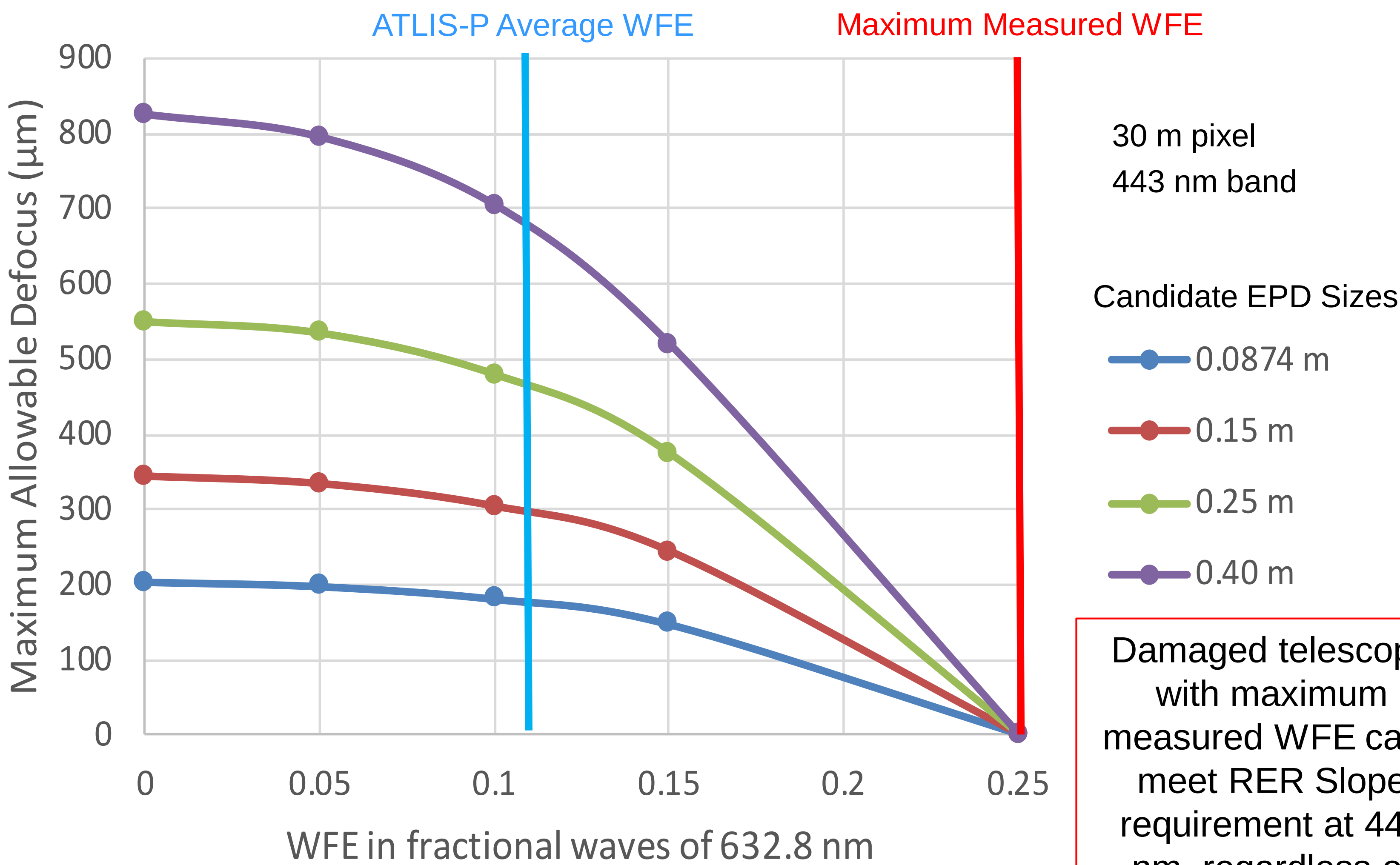

Damaged telescope with maximum measured WFE can't meet RER Slope requirement at 443 nm, regardless of EPD

PRELIMINARY RESULTS

Does the ATLIS-P telescope meet RMA requirements across the entire FOV?

- As manufactured, following the damage that occurred during the alignment and staking process, the ATLIS-P telescope does not meet RER slope requirements across the entire FOV
  - However, lessons learned from building this first of a kind hardware element are expected to avoid similar manufacturing problems in the future
  - WFE across FOV before staking met RMA requirements with detectors optimized for MTF/RER Slope performance - closer to expectations of how a flight version of this telescope would perform
- ATLIS-P with the SB501T FPA meets RMA VISWIR requirements in all spectral bands, except in the Panchromatic band, where the design falls short in RER Slope, assuming the highest measured WFE (78.21 nm) for the telescope before damage and a relatively high de-focus of 50 µm
  - SB501T FPA with 100% fill factor square detectors has higher impact on MTF/RER Slope than alternative detector designs – as expected
  - With rectangular or embedded (<100% fill) square detectors, ATLIS-P design meets RER Slope requirements in all VISWIR bands with selected WFE and de-focus, according to APM predictions

Predicted performance of ATLIS-P like system versus RMA requirements

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WFE: 78.21 nm

De-Focus: 50 µm

SB501 FPA detector samples with 11.9 m GSD resampled to required pixel size

Band Reference	Band Name	Center Wavelength	Bandwidth	Resolution	Minimum Edge Slope	Maximum Edge Slope	Predicted Cross Track RER Slope	Predicted Along Track RER Slope	Required SNR @ L_{typ}	Predicted SNR @ Ltyp	TDI
		nm	nm	m	m^{-1}	m^{-1}	m^{-1}	m^{-1}	-	-	-
1	Coastal Aerosol	443	20	30	0.027	0.033	0.031	0.031	130	265	16
2	Blue	482	65	30	0.027	0.033	0.031	0.031	130	457	4
3	Green	562	75	30	0.027	0.033	0.032	0.031	100	421	4
4	Red	655	50	30	0.027	0.033	0.031	0.031	90	328	4
5	NIR	865	40	30	0.027	0.033	0.031	0.032	90	203	4
6	SWIR1	1610	100	30	0.027	0.033	0.031	0.032	100	274	4
7	SWIR2	2200	200	30	0.027	0.033	0.032	0.032	100	309	4
8	Panchromatic	590	180	15	0.054	0.067	0.049	0.048	80	150	8
9	Cirrus	1375	30	30	0.027	0.033	0.031	0.031	50	171	8

ATLIS-P falls short of meeting RER Slope requirements in the Pan band – but, design can be optimized for RER Slope using rectangular or embedded square detectors to meet RMA requirements in all bands

PRELIMINARY RESULTS

Radiometric SNR

- **RMA requirements:** RMA SNR requirements at typical and high spectral radiances are largely based on the Landsat 8 requirements, as listed in the table below, which is RMA Table A.10.

Band Number	Band	SNR Requirements	
		At LTypical*	At LHigh*
1	Coastal Aerosol **"443 nm"**	130	290
2	Blue	130	360
3	Green	100	390
4	Red	90	340
5	NIR **"865 nm"**	90	460
6	SWIR 1	100	540
7	SWIR2	100	510
8	Panchromatic	80	230
9	Cirrus	50	N/A

Table provided courtesy of the NASA Goddard Space Flight Center and Raytheon Company.

Comparison of predicted and measured SNR at 865 nm

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	Nominal spectral radiance at 860.34 nm: 13.73 W m^{-2} sr^{-1} μm^{-1}			Nominal spectral radiance at 860.34 nm: 147.08 W m^{-2} sr^{-1} μm^{-1}			Nominal spectral radiance at 860.34 nm: 173.79 W m^{-2} sr^{-1} μm^{-1}		
Integration time (ms)	**Predicted SNR**	**Measured SNR**	**Ratio**	**Predicted SNR**	**Measured SNR**	**Ratio**	**Predicted SNR**	**Measured SNR**	**Ratio**
0.44	13.9	13.7	0.98	104	106	1.02	117	121	1.03
1.75	48.1	46.0	0.96	252	254	1.01	277	282	1.02
3.50	83.5	79.1	0.95	372	371	1.00	407	408	1.00

PRELIMINARY RESULTS

Comparison of predicted and measured SNR at 443 nm

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	Nominal spectral radiance at 441.02 nm: 38.60 W m^{-2} sr^{-1} μm^{-1}			Nominal spectral radiance at 441.02 nm: 183.52 W m^{-2} sr^{-1} μm^{-1}			Nominal spectral radiance at 441.02 nm: 216.77 W m^{-2} sr^{-1} μm^{-1}		
Integration time (ms)	**Predicted SNR**	**Measured SNR**	**Ratio**	**Predicted SNR**	**Measured SNR**	**Ratio**	**Predicted SNR**	**Measured SNR**	**Ratio**
0.44	9.3	9.6	1.04	39.0	40.0	1.03	45.0	46	1.03
1.75	33.4	33.4	1.00	115	116	1.01	129	131	1.01
3.50	59.9	59.1	0.99	184	182	0.99	201	202	1.00

PRELIMINARY RESULTS

Saturation radiance

- **RMA requirements:** ATLIS-P shall be able to measure saturation radiances in routine observation without saturating the ROIC. RMA saturation radiances are the same as the maximum or high spectral radiances.
- Unfortunately, the ATLIS-P laboratory spherical integrating sphere (SIS) calibration source is unable to illuminate ATLIS-P at the saturation radiance
- However, characteristics of the ATLIS-P instrument are well understood and characterized well enough to be able to predict whether the instrument saturates when observing saturation radiances
- Table on the following page shows that ATLIS-P does not saturate at maximum spectral radiance, for single detector sample integration times
  - Maximum well capacity is more than enough to avoid saturation in ATLIS-P for integration times compatible with SNR and RER requirements
  - Measured well capacity is 22% higher than nominal well capacity of 240ke-

ATLIS-P does not saturate at maximum spectral radiance

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Center Wavelength (nm)	Spectral Bandwidth (nm)	L_{max} (W m^{-2} sr^{-1} μm^{-1})	Maximum Integration Time without Saturation (s)	Signal PEs from L_{max}	ROIC Well Capacity (SB501 for VISWIR)	Saturated (Y/N)
443	20	555	1.69E-03	5.75E+04	2.40E+05	N
482	65	581	1.69E-03	2.18E+05	2.40E+05	N
562	75	544	1.41E-03	2.40E+05	2.40E+05	N
590	180	88.5	2.89E-04	1.20E+05	2.40E+05	N
655	50	462	1.69E-03	1.97E+05	2.40E+05	N
865	40	281	1.69E-03	1.31E+05	2.40E+05	N
1375	30	88.5	1.69E-03	4.70E+04	2.40E+05	N
1610	100	71.3	1.69E-03	1.48E+05	2.40E+05	N
2200	200	24.3	1.69E-03	1.38E+05	2.40E+05	N

PRELIMINARY RESULTS

Relative Edge Response (RER)

- **RMA requirements:** The table below (RMA Table A.4) lists the VISWIR band RMA requirements for minimum RER slope along with nominal GSD and maximum half edge extent

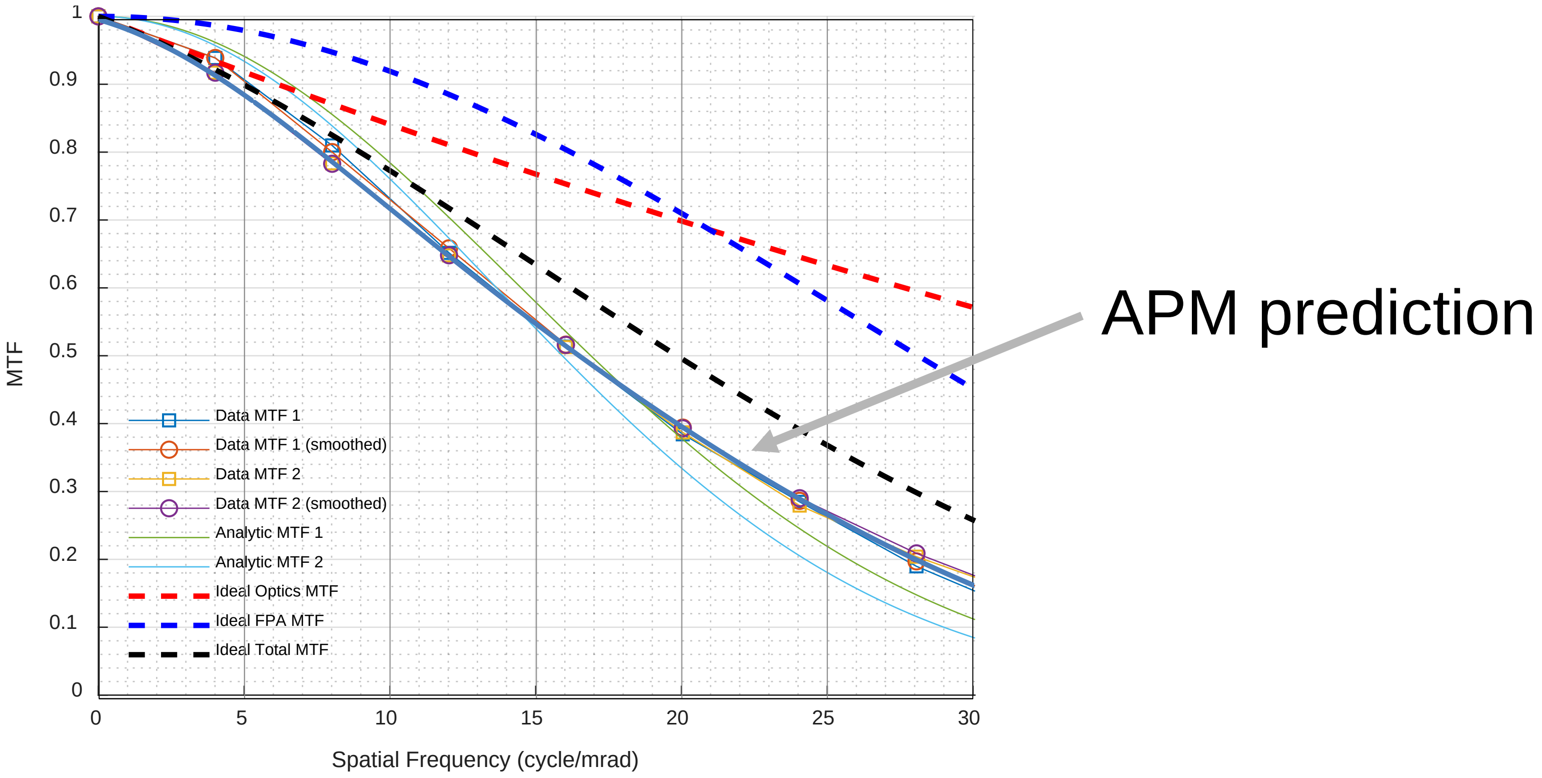
Table 10. RMA VISWIR nominal GSD, minimum RER slope and maximum half edge

Band Number	Band	Nominal GSD (m)	Minimum Edge Slope	Maximum Half Edge Extent (M)
1	Coastal Aerosol	30	.027/m	23.0
2	Blue	30	027/m	23.0
3	Green	30	027/m	23.0
4	Red	30	027/m	23.5
5	NIR	30	027/m	24.0
6	SWIR 1	30	027/m	28.0
7	SWIR 2	30	027/m	29.0
8	Panchromatic	15	027/m	14.0
9	Cirrus	30	027/m	27.0

Table provided courtesy of the NASA Goddard Space Flight Center and Raytheon Company.

- RER and MTF were determined from direct measurement of the edge response
- Results shown here are for single detector samples, corresponding to 11.9 m GSD from 705 km altitude with a nominal minimum RER of 0.069/m

Comparison of measured MTF data at 865 nm with model prediction



PRELIMINARY RESULTS

RER Slope and MTF measurements are preliminary results

- Analysis of RER Slope and MTF continues, with improvements being made to dark frame subtraction, NUC and removal of noisy data
- Large amount of data (10 FOV positions at two wavelengths with two slit orientations and two edges, each with 500 frames) requires automated processing, which can mask problems with individual measurements
- Measurement error bars are large, at this stage of analysis

Comparison of 443 nm MTF/RER Slope measurements with model predictions

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Effective Wavelength (nm)	Track Angle (deg)	Cross Track Angle	Estimated WFE (nm)	De-focus (µm)	Measured MTF at Detector Nyquist	Predicted MTF at Detector Nyquist	Measured RER Slope (m^{-1})	Predicted RER Slope (m^{-1})
441.4	-0.50	-1.00	47.74	20	0.232	0.250	0.062	0.070
	-0.50	1.00	56.10	20	0.231	0.216	0.060	0.068
	-0.50	6.00	131.49	20	0.138	0.021	0.045	0.049
	0.00	0.00	51.13	20	0.250	0.236	0.067	0.069
	0.00	7.00	146.38	20	0.146	0.010	0.042	0.048
	0.50	-1.00	46.85	20	0.244	0.253	0.062	0.071
	0.50	1.00	59.58	20	0.180	0.202	0.056	0.067
	0.50	6.00	133.97	20	0.163	0.019	0.050	0.049
	0.50	8.00	154.33	20	0.143	0.007	0.040	0.047
				MTF Standard Deviation	0.031	RER Standard Deviation	0.030	

- WFEs estimated from 2D interpolation of measurements with damaged telescope
- De-focus estimated from highest MTF measurements and applied across FOV
- For MTF, (Predicted MTF - Measured MTF)/StdDev = -1.849 (measurements not consistent with high WFE MTF predictions and with 865 nm measurements)
- For RER Slope, (Predicted RER – Measured RER)/StdDev = 0.197

PRELIMINARY RESULTS

Comparison of 865 nm MTF/RER Slope measurements with model predictions

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Effective Wavelength (nm)	Track Angle (deg)	Cross Track Angle	Estimated WFE (nm)	De-focus (µm)	Measured MTF at Detector Nyquist	Predicted MTF at Detector Nyquist	Measured RER Slope (m^{-1})	Predicted RER Slope (m^{-1})
863.1	-0.50	-1.00	47.74	20	0.233	0.253	0.058	0.068
	-0.50	1.00	56.10	20	0.233	0.241	0.060	0.067
	-0.50	6.00	131.49	20	0.135	0.114	0.036	0.058
	-0.50	8.00	155.74	20	0.100	0.079	0.036	0.055
	0.50	-1.00	46.85	20	0.162	0.254	0.051	0.068
	0.50	1.00	59.58	20	0.161	0.236	0.053	0.067
	0.50	6.00	133.97	20	0.167	0.110	0.049	0.058
	0.50	8.00	154.33	20	0.103	0.081	0.032	0.055
				MTF Standard Deviation	0.032	RER Standard Deviation	0.047	

- WFEs estimated from 2D interpolation of measurements with damaged telescope
- De-focus estimated from 443 nm assessment
- For MTF, (Predicted MTF - Measured MTF)/StdDev = 0.288
- For RER Slope, (Predicted RER – Measured RER)/StdDev = 0.321
- Overall trends in 865 nm measurements agree with expectations for high WFE

Radiometric stability

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- **RMA requirements:** The table below (Table 9 from the RMA) summarizes ATLIS radiometric stability requirements.

Radiometric Stability	
Identifier	**Requirements Description**
VSWIR-1214 Radiometric Stability	For Bands 1-8, over any time period up to 16 days, after radiometric correction, with one set of gain coefficients that were determined prior to the 16 day period, the scene averaged VSWIR image data for radiometrically constant targets with radiances greater than or equal to L-typical shall not vary by more than plus or minus 1% (95% or 2 sigma confidence interval) of measured radiance.
VSWIR-1217 Radiometric Stability	Over any time period up to 60 seconds, after radiometric correction, the scene-averaged VSWIR image data for radiometrically constant targets with radiances greater than or equal to L-typical shall not vary by more than plus or minus 0.5% (95% or 2 sigma confidence interval) of measured radiance.

Table provided courtesy of the NASA Goddard Space Flight Center and Raytheon Company.

Radiometric stability results

- Radiometric stability testing over a period of 16 days
- Test and analysis focused on percent difference of a detector sample from the mean of 60 frames with one frame collected per second over one minute
- Percent difference was found to be 0.0997±0.184% meaning each pixel varied by less than 0.1% over both short duration (one minute collects over 99 min/day) and over 16 days, meeting both parts of the RMA radiometric stability requirement
  - Source stability was monitored by sensors and control systems inside the source

Closing remarks

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- New and emerging optical and focal plane technology enables much smaller land imagers than current systems
- ATLIS-P telescope achieved performance required to meet SLI-T requirements, before being damaged in alignment staking
- 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, except for MTF at 443 nm in FOV regions with high measured WFE after telescope damage – analysis continues
- ATLIS-P supports both a disaggregated architecture and a full spectrum instrument
- Key ATLIS-P technology benefits many other NASA Earth Science missions, especially those involving small satellite systems

Thanks to NASA ESTO for supporting this project!