TFAWS Aerosciences/Aerothermal Paper Session

The SCIFLI Airborne Observation of Artemis 1 Ascent

1. **Kylel Scott, Hyun Jung Kim, Matthew Boyda, Carey Scott, Jennifer Inman**
(NASA Langley Research Center, Hampton, VA, USA)
2. **Robert Conn**
(Analytical Mechanics Associates (AMA), Hampton, VA, USA)
3. **Tait Pottebaum**
(Opto-Knowledge Systems, Inc. (OKSI), Torrance, CA, USA)
4. **Tony Casey,**
(KRATOS SRE, Birmingham, AL, USA)

Presented By

Kylel Scott

Thermal & Fluids Analysis Workshop
TFAWS 2023
August 21-25, 2023
NASA Goddard Space Flight Center
Greenbelt, MD

Presentation Outline

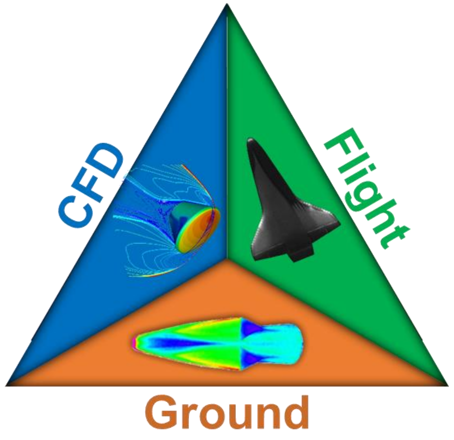
- Background
  - Collecting Flight Data
  - Scientifically Calibrated In-Flight Imagery (SCIFLI)
  - SCIFLI Airborne Multispectral Imager (SAMI)
  - Artemis 1 Ascent Observation
- Observation
  - Sensor Specifications and Imaging Objectives
  - FDA Evaluation Data Review
  - Post-Flight Radiometric Calibration
  - Temperature Extraction
  - Base Heatshield and 3D Mapping
- Conclusions
  - Lessons Learned
  - Summary

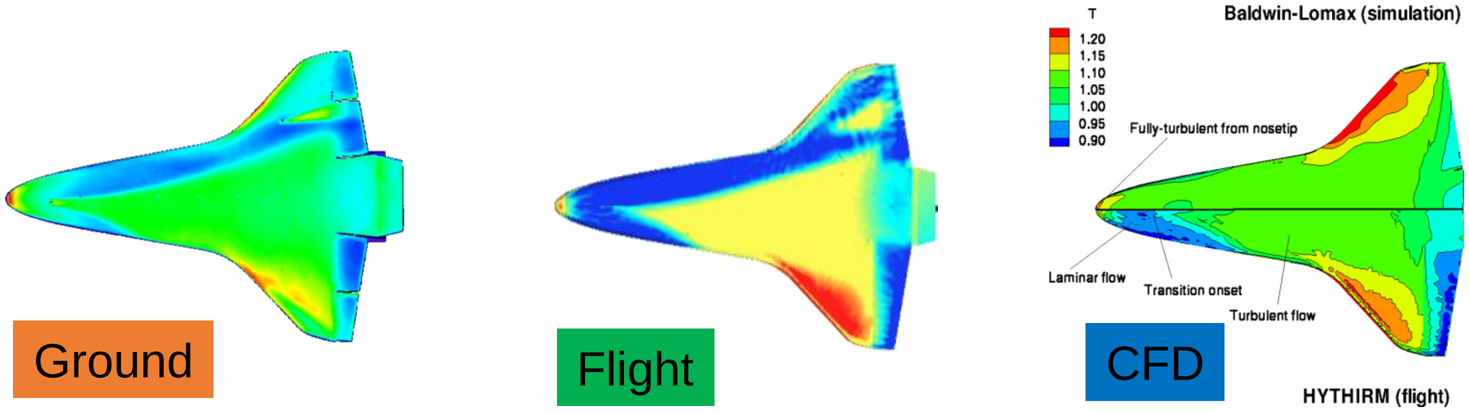
Presentation Outline

- Background
  - Collecting Flight Data
  - Scientifically Calibrated In-Flight Imagery (SCIFLI)
  - SCIFLI Airborne Multispectral Imager (SAMI)
  - Artemis 1 Ascent Observation
- Observation
  - Sensor Specifications and Imaging Objectives
  - FDA Evaluation Data Review
  - Post-Flight Radiometric Calibration
  - Temperature Extraction
  - Base Heatshield and 3D Mapping
- Conclusions
  - Lessons Learned
  - Summary

Background: *Collecting Flight Data*

Why **Flight Data**?





Observing flight conditions is essential

- Misunderstanding flight conditions can have tragic consequences, such as the Columbia accident, the catalyst for SCIFLI's creation.
- Vehicle conditions during mission events are key to understanding performance of engineering & technology designs

Flight conditions are difficult to document

- Ground testing and simulations cannot fully capture in-flight vehicle performance.
- Onboard instrumentation can be challenging in extreme environments and is limited to discrete locations
- In-flight measurements can be used to validate other tools and data collection techniques

Background: *Scientifically Calibrated In-Flight Imagery*

- SCIFLI's Approach

In-flight imaging aims to make spaceflight safer by collecting information about vehicles under real flight conditions.

Flight-Specific Observations

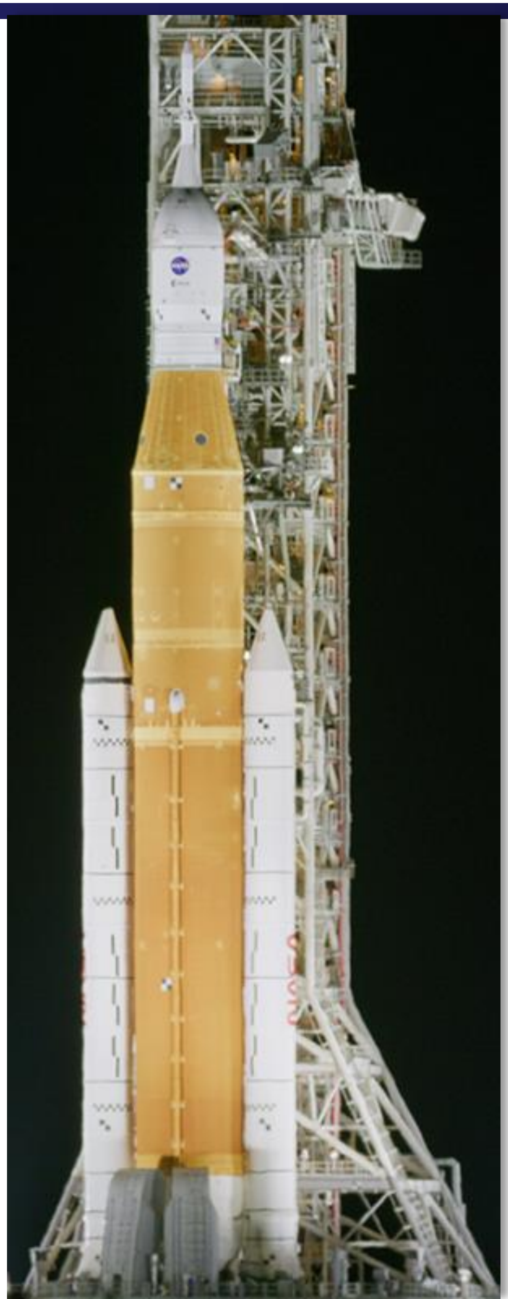
- High Altitude Plume Dynamics
- Parachute & Recovery Systems
- Engine Health Monitoring
- Boundary Layer Transition
- Booster Separation
- RCS Performance
- TPS Sizing

Mitigates Risk of Data Loss

- Embedded Sensor Failure
- Trajectory Reconstruction
- Unrecoverable Data
- Vehicle Termination
- Telemetry Blackout
- Night Launch

Supplements Onboard Instrumentation

- Global vs Discrete Measurement
- Embedded Sensor Validation



Background: *SCIFLI Airborne Multispectral Imager*

SAMI
SCIFLI AIRBORNE MULTISPECTRAL IMAGER

A customizable & cost-effective aircraft-agnostic multispectral imaging testbed designed to collect plume and surface temperatures during Artemis I ascent.

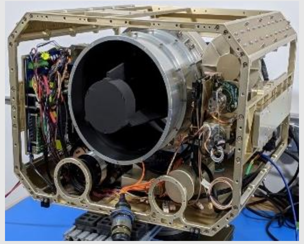
Key Capabilities

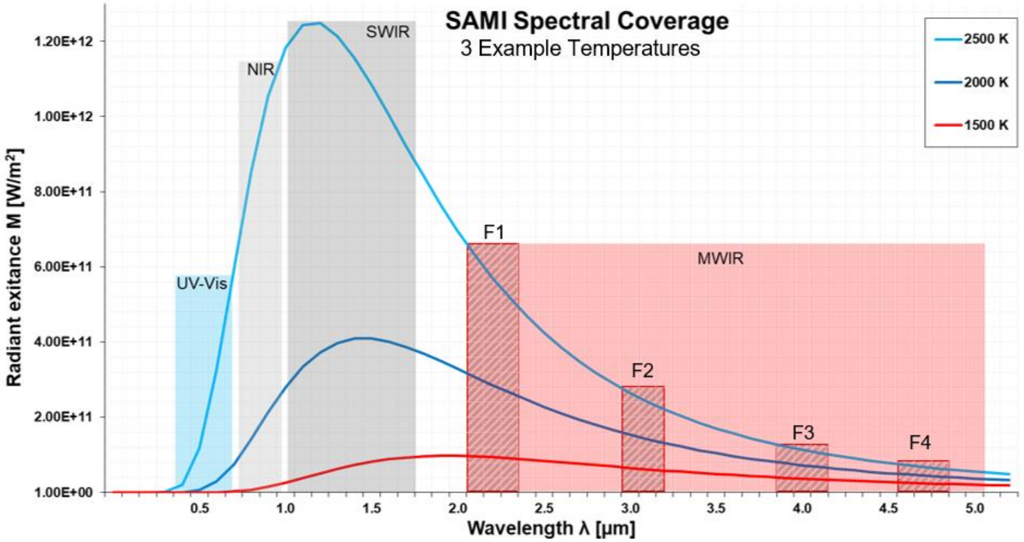
- Passive and active thermal control
- Integration within pre-existing platforms
- Multiple sensors (UV-VIS to MWIR)
- High image quality
- Semi-modular design to support mission adaptability

Mission Portfolio *to date*

NASA Artemis 1 Launch
SPACEX Starship Launch
SPACEX CRS-27 Return
NASA OSIRIS-REx Capsule Return (Sept '23)

SAMI WB-57 aircraft config.





SAMI G-IV Aircraft config. (in development M.A.R.S. and O.K.S.I.)

Background: *Artemis 1 Ascent Observation*

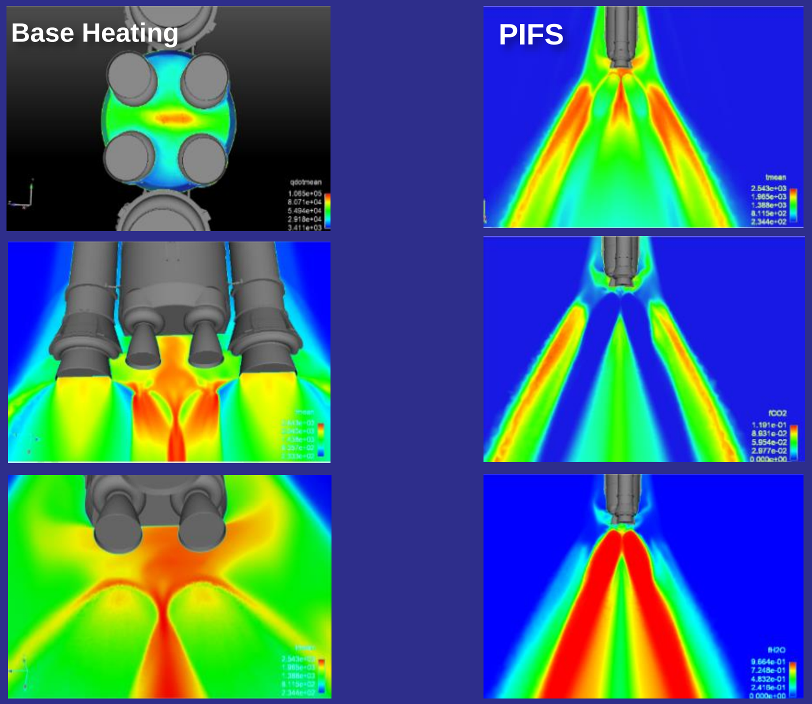
Feasibility Analysis:

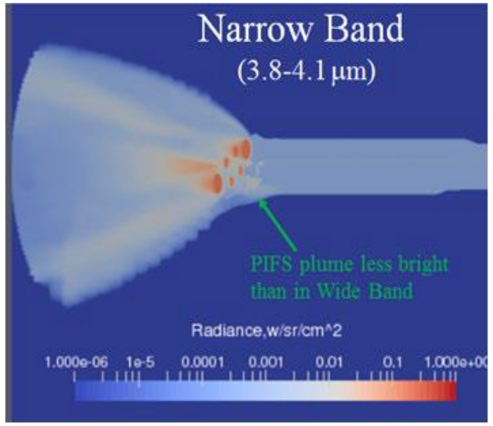
- Broadband (3-5 µm) MWIR for PIFS imaging; high temp surface data available at 2 µm
- **Multispectral Imaging**
  - simultaneous observation of plume ***and*** hardbody thermal signatures
  - high spatial resolution
  - Low uncertainty

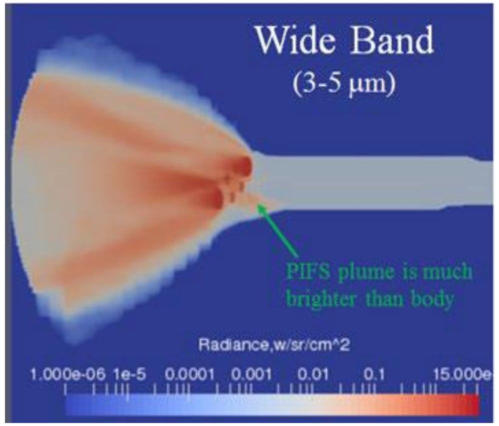
<u>Technical Challenges</u>

- Large temperature range between regions of interest
- Emissivity variation with temperature and view angle
- Hot plume gas obscuring regions of interest
- Hot plume gas causing radiative heating

CFD Solutions for Mach 4 (110 kft) Plume Structure







Goal: Collect calibrated temperature images of the base region of SLS core stage and exhaust plume dynamics during boost phase.

- Use calibrated multispectral imagery to conduct surface temperature retrieval for base heat shield (BHS) and aft region of SLS core stage.

Best Effort **–** Observe plume recirculation phenomena or Plume Induced Flow Separation (PIFS).

Best Effort **–** Observe Booster and Core Stage separation dynamics.

Presentation Outline

- Background
  - Collecting Flight Data
  - Scientifically Calibrated In-Flight Imagery (SCIFLI)
  - SCIFLI Airborne Multispectral Imager (SAMI)
  - Artemis 1 Ascent Observation
- **Observation**
  - Sensor Specifications and Imaging Objectives
  - FDA Evaluation Data Review
  - Post-Flight Radiometric Calibration
  - Temperature Extraction
  - Base Heatshield and 3D Mapping
- Conclusions
  - Lessons Learned
  - Summary

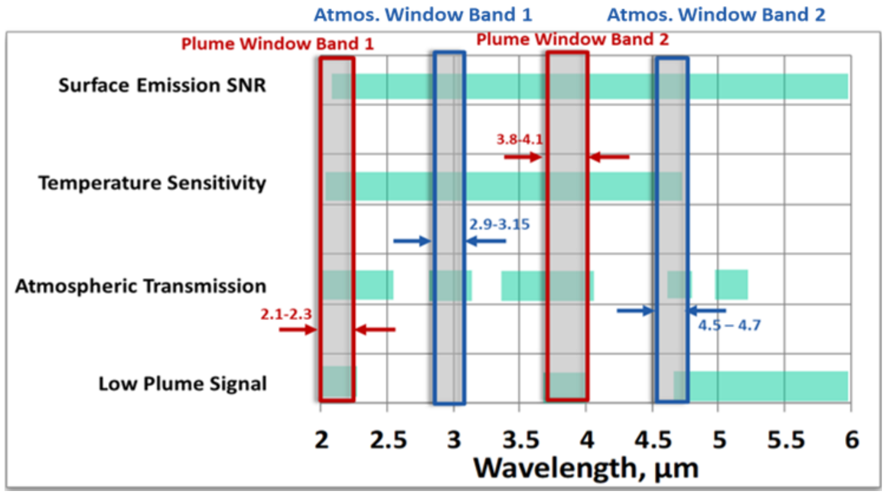
Observation: *Sensor Specifications and Imaging Objectives*

SAMI was deployed for multispectral coverage of Artemis 1 SLS launch. The system is designed to acquire scientific data of several physical and aerothermal events of interest during SLS Ascent and was configured to cover Visible through Mid-Wave Infrared wavelengths of interest for the observation.

SAMI Sensor Specifications

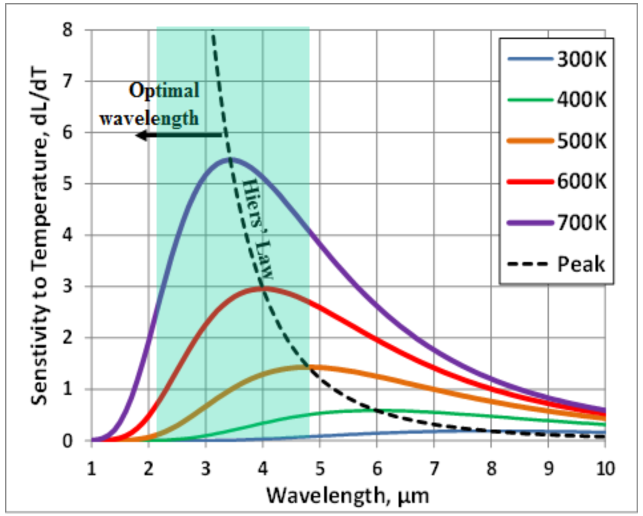
Channel	Spectral Range	Sensor Type	H pix	V pix	Pixel Pitch (μm)	IFOV (μRad)	Frame rate (fps)	Bit depth
MWIR	2 – 5 μm	nBn	1280	1024	12	7.38	120	16
SWIR	900 – 1700 nm	InGaAs	1280	1024	12.5	7.69	60	12
NIR	370 – 1100 nm	sCMOS	2650	2160	6.5	4.00	100	16
UV-Vis	310 – 750 nm	CMOS	1936	1216	5.86	3.60	50.8	12
WFOV-MWIR	3 – 5 μm	InSb	640	512	15	54.5 – 789	30	14
WFOV-Vis	300 - 1100 nm	CCD	1280	960	3.75	15.6 – 312	33.3	14

Optimal Wavebands to Meet All Imaging Objectives



SAMI Filter Wheel Bands for MWIR Channel

Estimated Temperature Ranges During SLS Observation



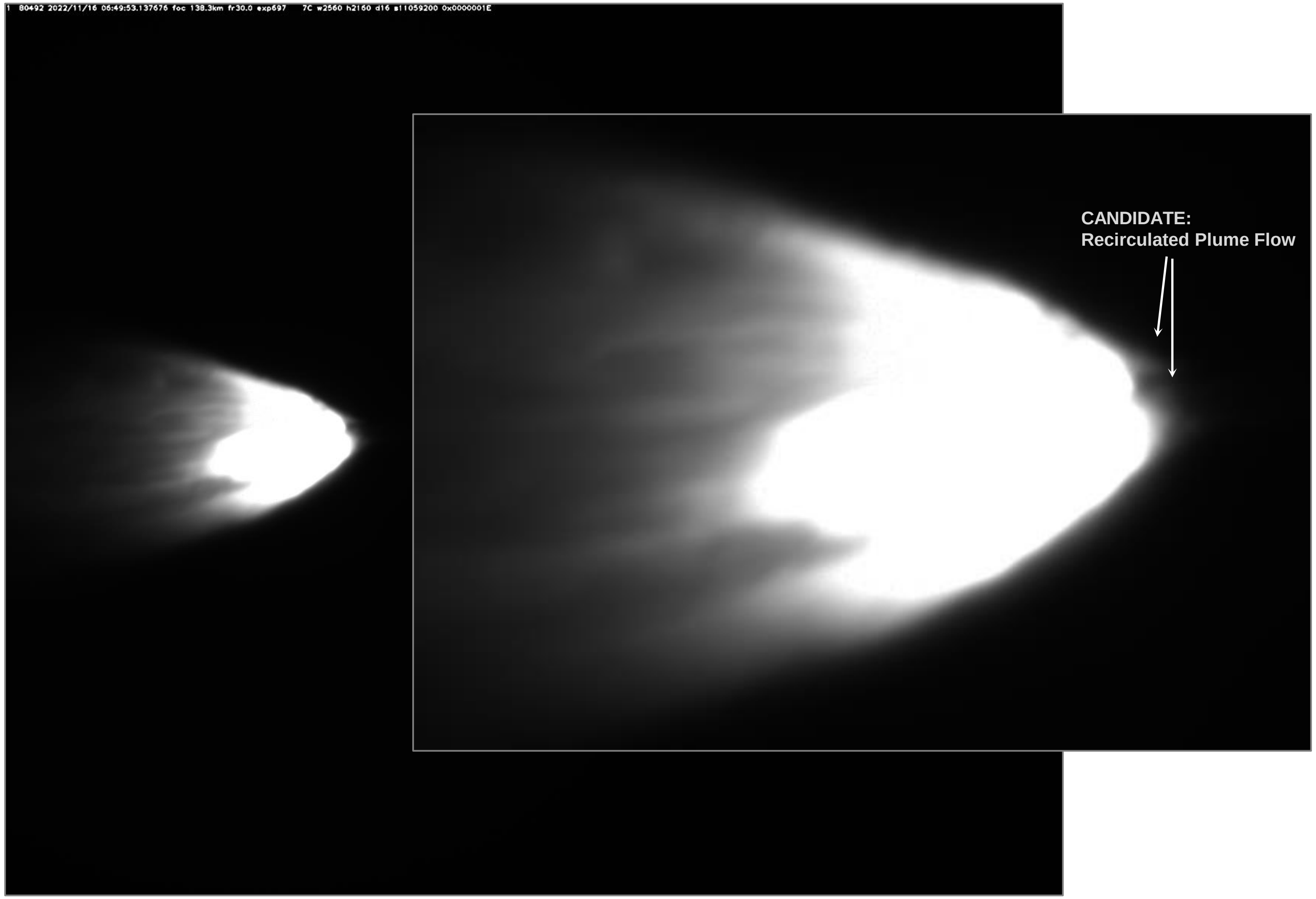
SCIFLI Contributions to Artemis-1 Flight Test Objectives

FTO-STE-AT-01 FDAs	Airborne Imagery Contributions
FDA-STE-AT-1.1 Ascent Aerothermal	Core Stage surface temperatures
FDA-STE-AT-1.2 Plume Radiation Heating	Exhaust plume radiation (thermal signature characterization, shape, size)
FDA-STE-AT-1.3 Plume Convection Heating	Core Stage and Booster surface temperatures
FDA-STE-AT-1.4 Plume Induced Flow Separation (PIFS) Heating	Core Stage and Booster plume recirculation
FDA-STE-AT-1.5 Plume Impingement – (Booster Separation)	Booster Separation Motors (BSM) activations, general plume direction/spray

***FDA**: Flight Data Analysis*
***FTO**: Flight Test Objective*

Observation: *FDA Evaluation Data Review*

SAMI NIR

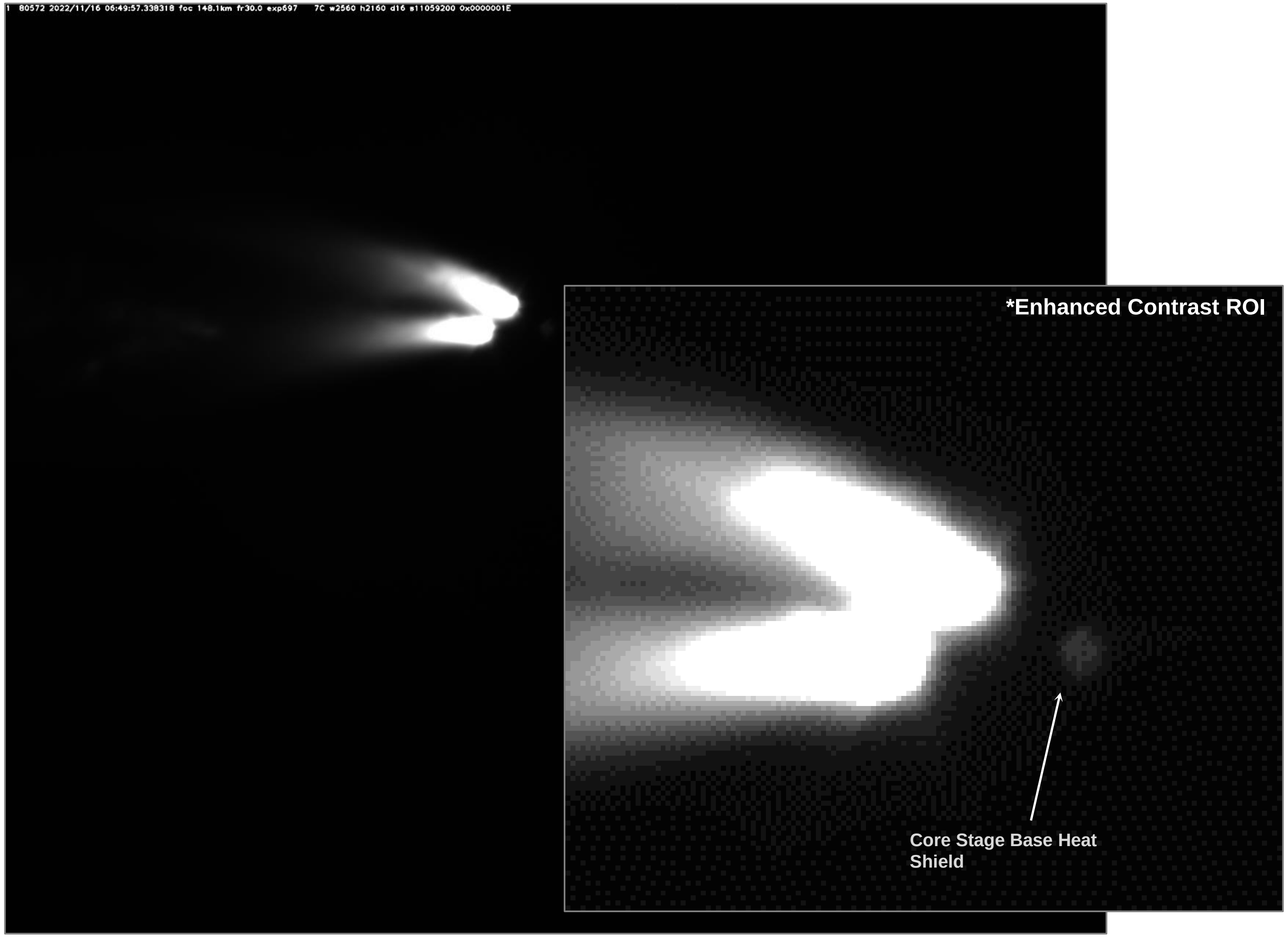


SCIFLI Contributions to Artemis-1 Flight Test Objectives

FTO-STE-AT-01 FDAs	Airborne Imagery Contributions
FDA-STE-AT-1.1 Ascent Aerothermal	Core Stage surface temperatures
FDA-STE-AT-1.2 Plume Radiation Heating	Exhaust plume radiation (thermal signature characterization, shape, size)
FDA-STE-AT-1.3 Plume Convection Heating	Core Stage and Booster surface temperatures
FDA-STE-AT-1.4 Plume Induced Flow Separation (PIFS) Heating	Core Stage and Booster plume recirculation
FDA-STE-AT-1.5 Plume Impingement – (Booster Separation)	Booster Separation Motors (BSM) activations, general plume direction/spray

Observation: *FDA Evaluation Data Review*

SAMI NIR

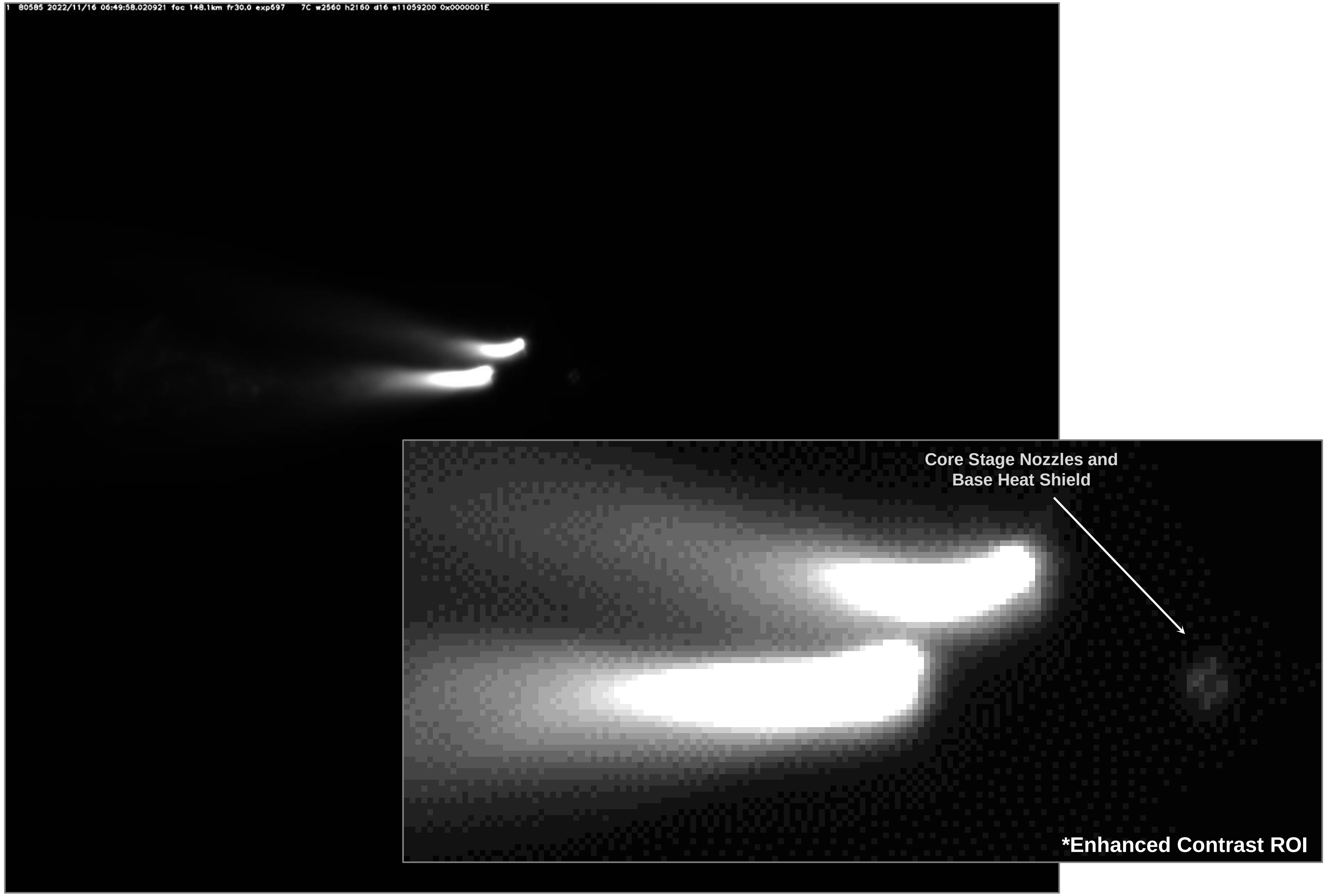


SCIFLI Contributions to Artemis-1 Flight Test Objectives

FTO-STE-AT-01 FDAs	Airborne Imagery Contributions
FDA-STE-AT-1.1 Ascent Aerothermal	Core Stage surface temperatures
FDA-STE-AT-1.2 Plume Radiation Heating	Exhaust plume radiation (thermal signature characterization, shape, size)
FDA-STE-AT-1.3 Plume Convection Heating	Core Stage and Booster surface temperatures
FDA-STE-AT-1.4 Plume Induced Flow Separation (PIFS) Heating	Core Stage and Booster plume recirculation
FDA-STE-AT-1.5 Plume Impingement – (Booster Separation)	Booster Separation Motors (BSM) activations, general plume direction/spray

Observation: *FDA Evaluation Data Review*

SAMI NIR



SCIFLI Contributions to Artemis-1 Flight Test Objectives

FTO-STE-AT-01 FDAs	Airborne Imagery Contributions
FDA-STE-AT-1.1 Ascent Aerothermal	Core Stage surface temperatures
FDA-STE-AT-1.2 Plume Radiation Heating	Exhaust plume radiation (thermal signature characterization, shape, size)
FDA-STE-AT-1.3 Plume Convection Heating	Core Stage and Booster surface temperatures
FDA-STE-AT-1.4 Plume Induced Flow Separation (PIFS) Heating	Core Stage and Booster plume recirculation
FDA-STE-AT-1.5 Plume Impingement – (Booster Separation)	Booster Separation Motors (BSM) activations, general plume direction/spray

Observation: *Temperature Extraction Candidate Selection*

- Candidates from the raw imagery were selected and assessed for radiometric quality during the initial review of the Post-flight data assessment
- Imaging of the base heatshield in the **NIR** was determined to have **high SNR**, spatial resolution, and **minimal motion blur** during the time of interest (post-SRB Separation)

cam1_1668581399_080607.tiff

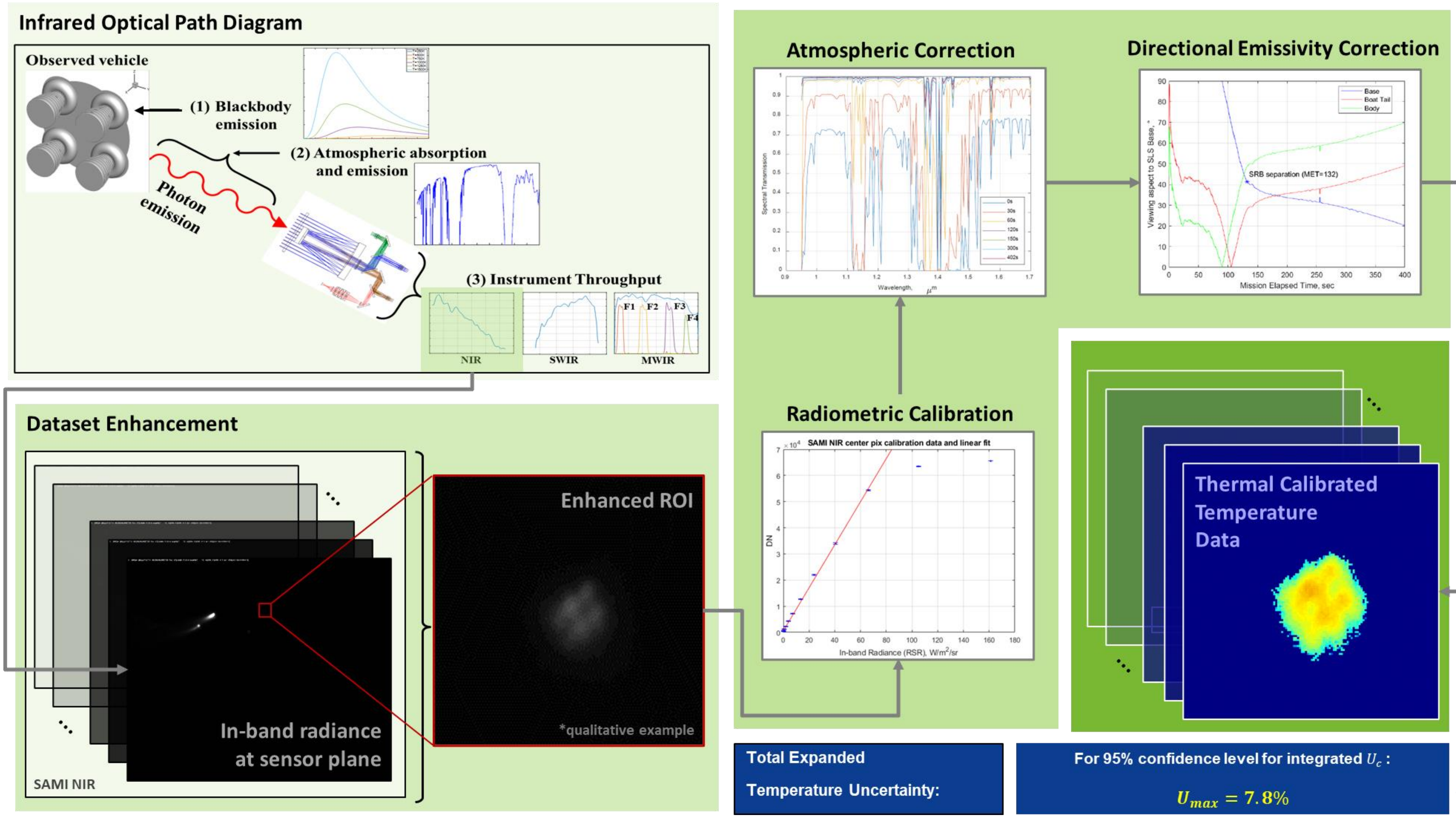
SAMI_Cam3: MWIR

cam3_1668581399_018686.tiff

SAMI_Cam2: SWIR

cam2_060886.tiff

Observation: *Data Acquisition to Temperature Images*



Total Expanded Temperature Uncertainty:

For 95% confidence level for integrated U_c :

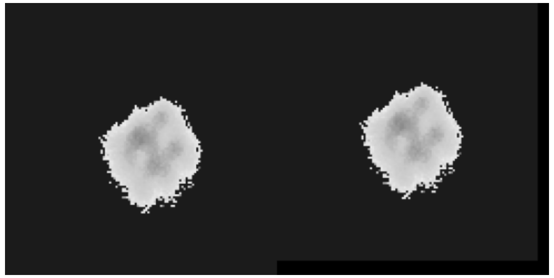
$U_{max} = 7.8\%$

Observation: *Base Heat Shield 3D Mapping*

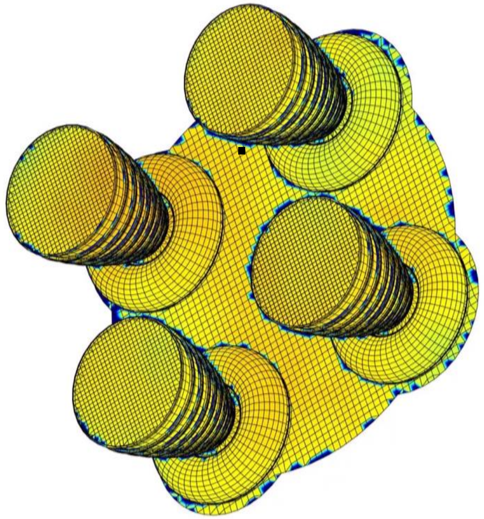
- **WB-57 acquired approx. 43 seconds of useable NIR thermal data.**
- These data were corrected for:

☑ Atmospheric path length
☑ View angle to BHS w.r.t. aircraft gimbal orientation
☑ Emissivity of the BHS material

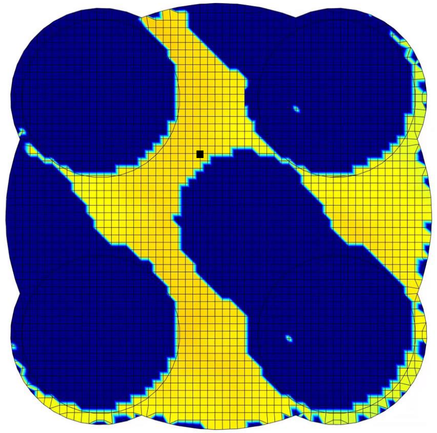
View from WB-57 in flight.



Stabilization of BHS data post-SRB separation

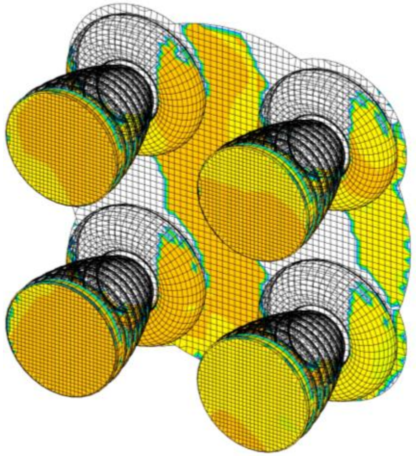


View normal to BHS



Notes:

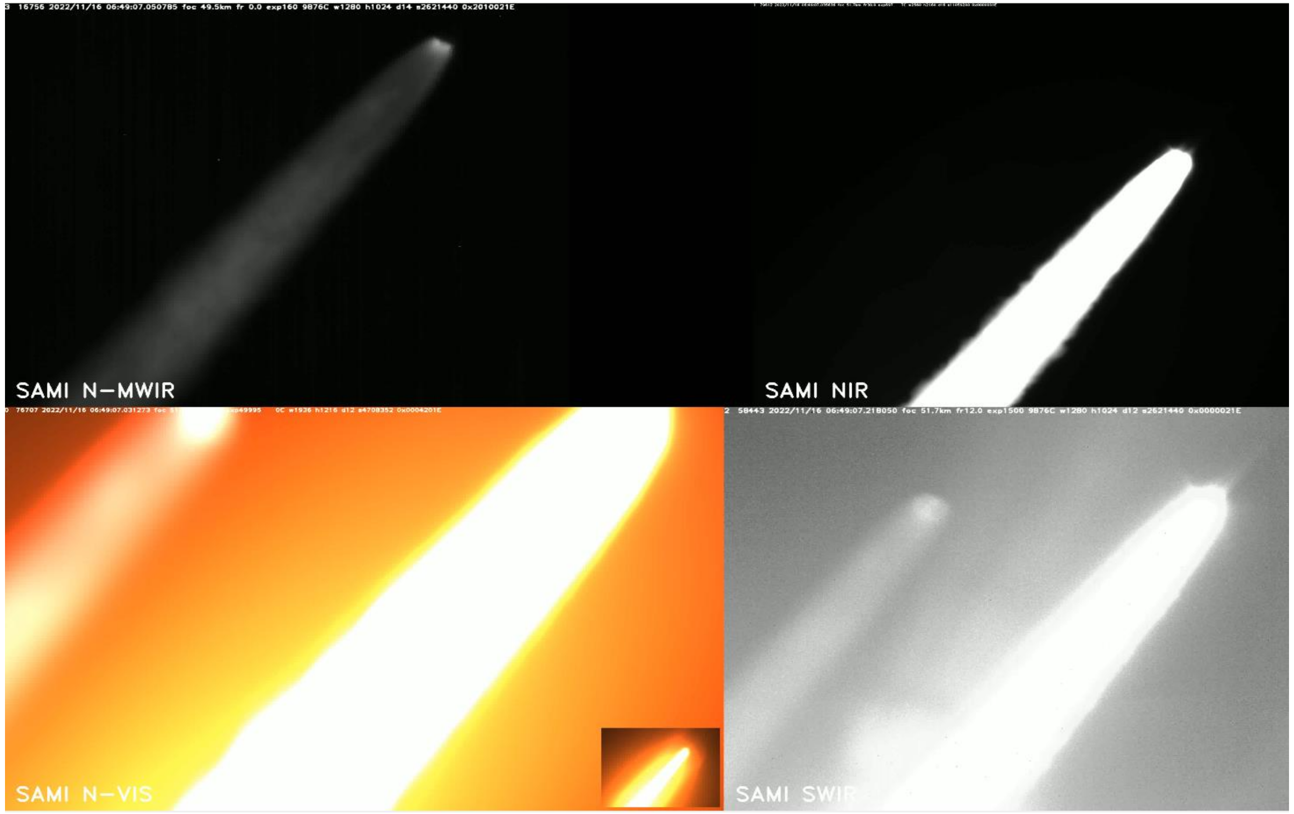
- Nozzles and blankets are **excluded** in this calculation.
- Alignment between the temperature image and the mesh is carried out manually with only 3 parameters free – horizontal and vertical translation of the image, and roll rotation (about the body axis) of the SLS base mesh.
- The bright nozzles provide the main reference points for this alignment, as they are bright in the imagery and are distinct in the mesh. It is assumed that the bright features of the images correspond to the exit planes of the nozzles.
- Roll alignment has an ambiguity of n*90°, where n=1,2,3, as we have no way to distinguish between the different nozzles. Roll was found to be nearly constant over the period of interest. For times after about MET = 159.32s, the alignment becomes more challenging.



Depiction of nozzle occlusion on BHS data collection

Presentation Outline

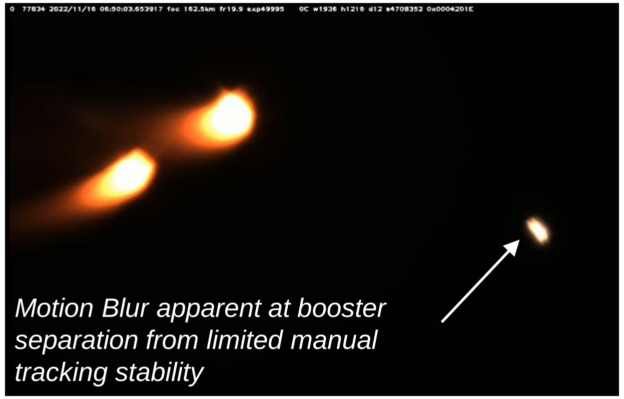
- Background
  - Collecting Flight Data
  - Scientifically Calibrated In-Flight Imagery (SCIFLI)
  - SCIFLI Airborne Multispectral Imager (SAMI)
  - Artemis 1 Ascent Observation
- Observation
  - Sensor Specifications and Imaging Objectives
  - FDA Evaluation Data Review
  - Post-Flight Radiometric Calibration
  - Temperature Extraction
  - Base Heatshield and 3D Mapping
- Conclusions
  - Lessons Learned
  - Summary

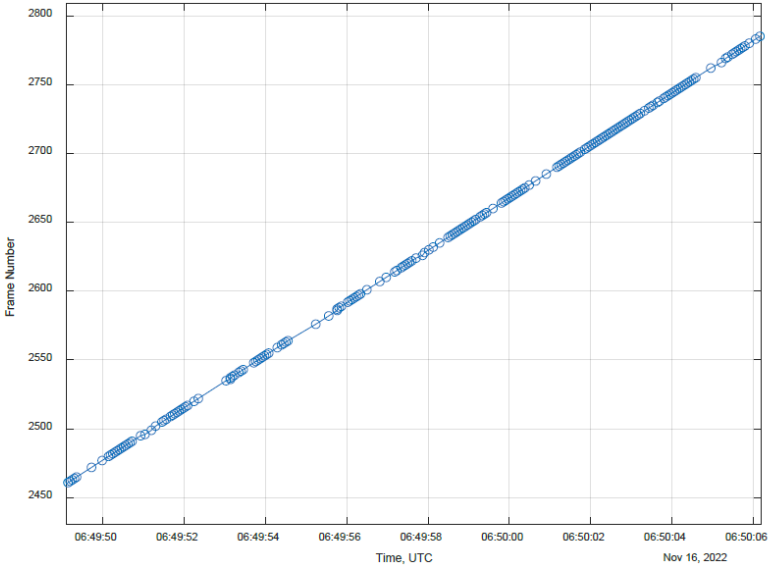


Conclusions: *Lessons Learned*

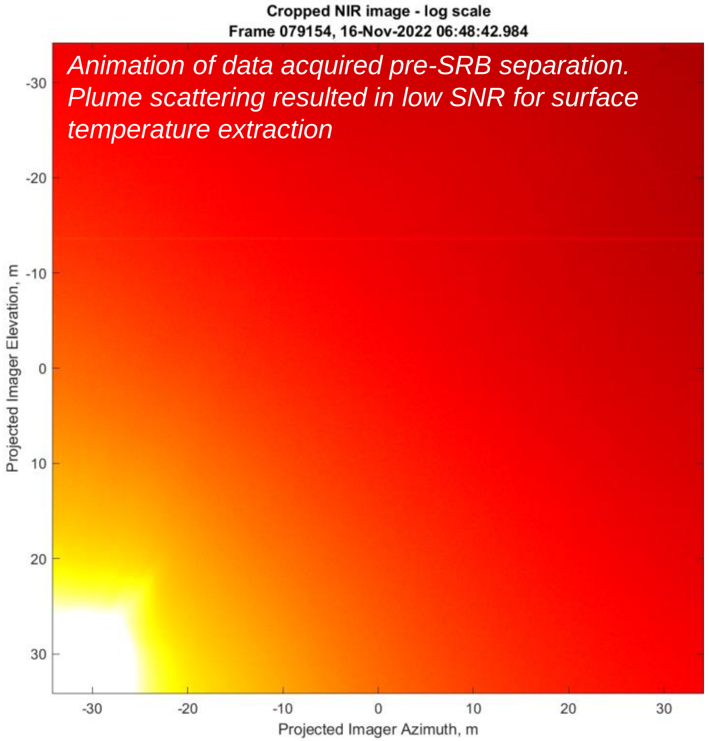
- Several factors influenced the imaging performance and data quality during the observation
  - Night observation and scattering
  - Non-optimal sensor settings resulted in substandard imagery in some wavebands
  - Inconsistent frame buffer writing
- Moving Forward
  - Software updates to SAMI DAC
  - Updated radiometric modeling into preliminary mission planning for finetuning of sensor settings (integration time)
  - Preliminary mission modeling to include mission-day condition case studies


SAMI Near FOV Visible camera overexposed frame during tower clear


Motion Blur apparent at booster separation from limited manual tracking stability



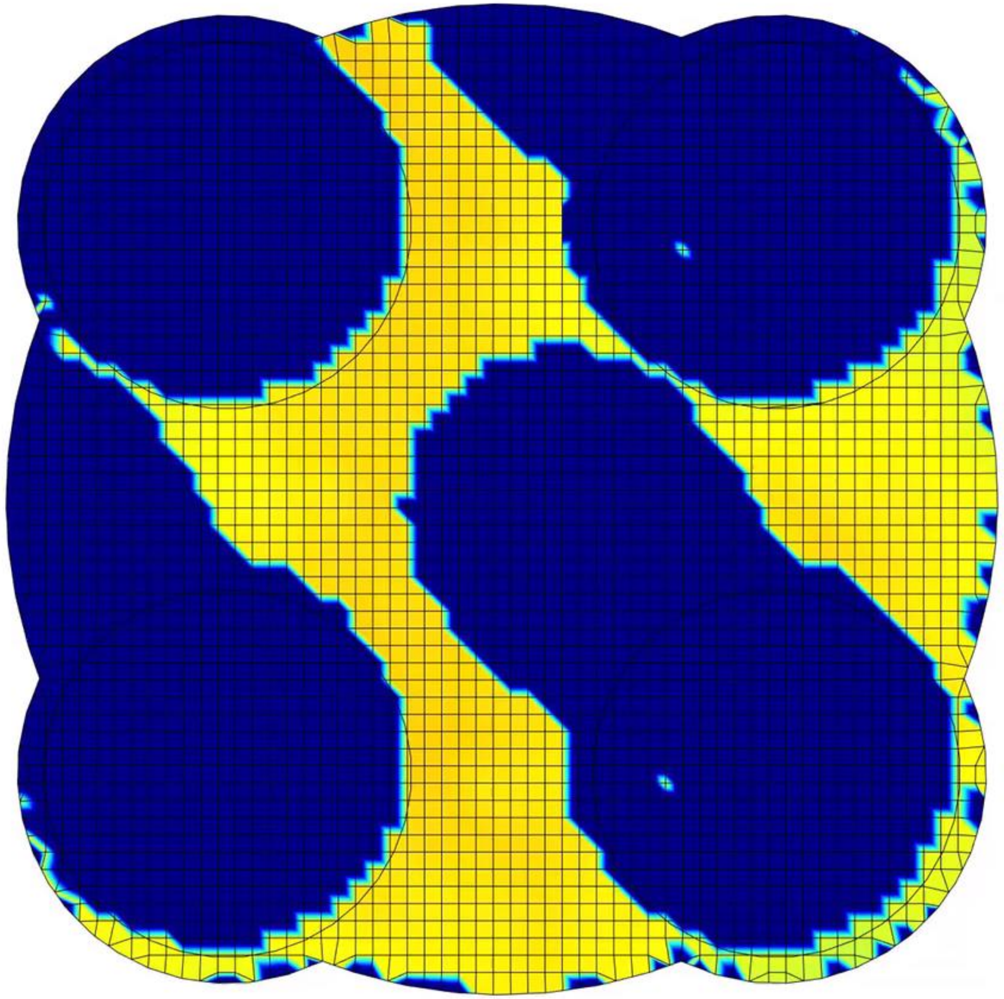
Frame number vs. UTC time for SAMI SWIR camera



Animation of data acquired pre-SRB separation. Plume scattering resulted in low SNR for surface temperature extraction

Conclusions: *Summary*

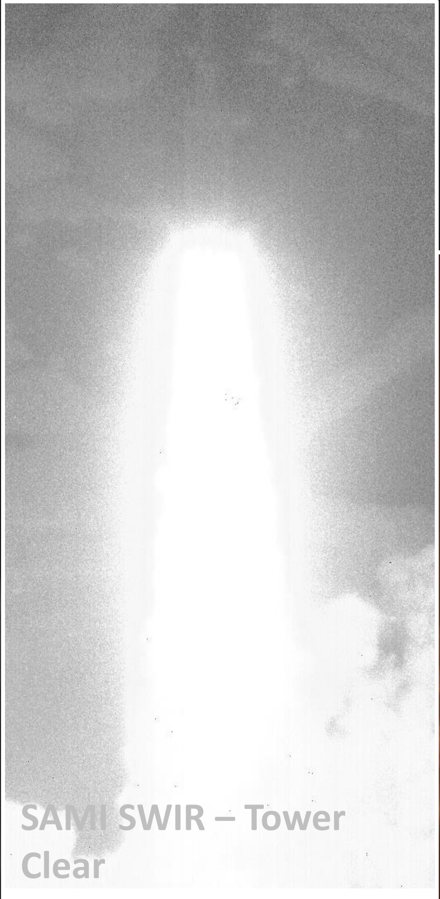
- **SCIFLI** produced a **multispectral** dataset for Artemis 1 Ascent
- **SCIFLI's** solution **SAMI** was designed to assess complex thermal environment in SLS Base region
  - Provide a unique dataset against ground and CFD to evaluate vehicle performance
- **SAMI** successfully measured base heatshield temperatures with a maximum 2σ uncertainty of 7.8%
- Temperature data has been handed off and are currently being evaluated by **SLS program**



Thank you


SAMI NIR – Tower Clear


SAMI MWIR – Tower Clear


SAMI SWIR – Tower Clear


SAMI VIS – Ignition