The SCIFLI Airborne Multispectral Image (SAMI) Payload

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SCIFLI AIRBORNE MULTISPECTRAL IMAGER

Presented By
Hyun Jung Kim

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

Agenda

- ABOUT SCIFLI
  - HISTORY
  - PRIMARY GOAL
  - PAYLOAD CAPABILITIES (DyNAMITE vs. SAMI)
- SAMI PAYLOAD (THE SCIFLI AIRBORNE MULTISPECTRAL IMAGER)
  - SPECIFICATION
  - VERIFICATION
  - VALIDATION
  - EXAMPLE (Artemis-I MISSION SUPPORT)
- SUMMARY & FUTURE of SAMI

Everything Changed February 1st, 2003

Inception of HyTHIRM remote thermal observation of crewed launches after the Columbia accident

Breakup of Space Shuttle Orbiter Columbia over Texas. Image credit: Scott Lieberman

https://www.nasa.gov/image-feature/remembering-sts-107-and-her-crew

Requirements to Return to Flight

- Understand the physical cause
- Mitigate risk from a compromised thermal protection system to protect crew and payloads
- Required tool development by Research Centers

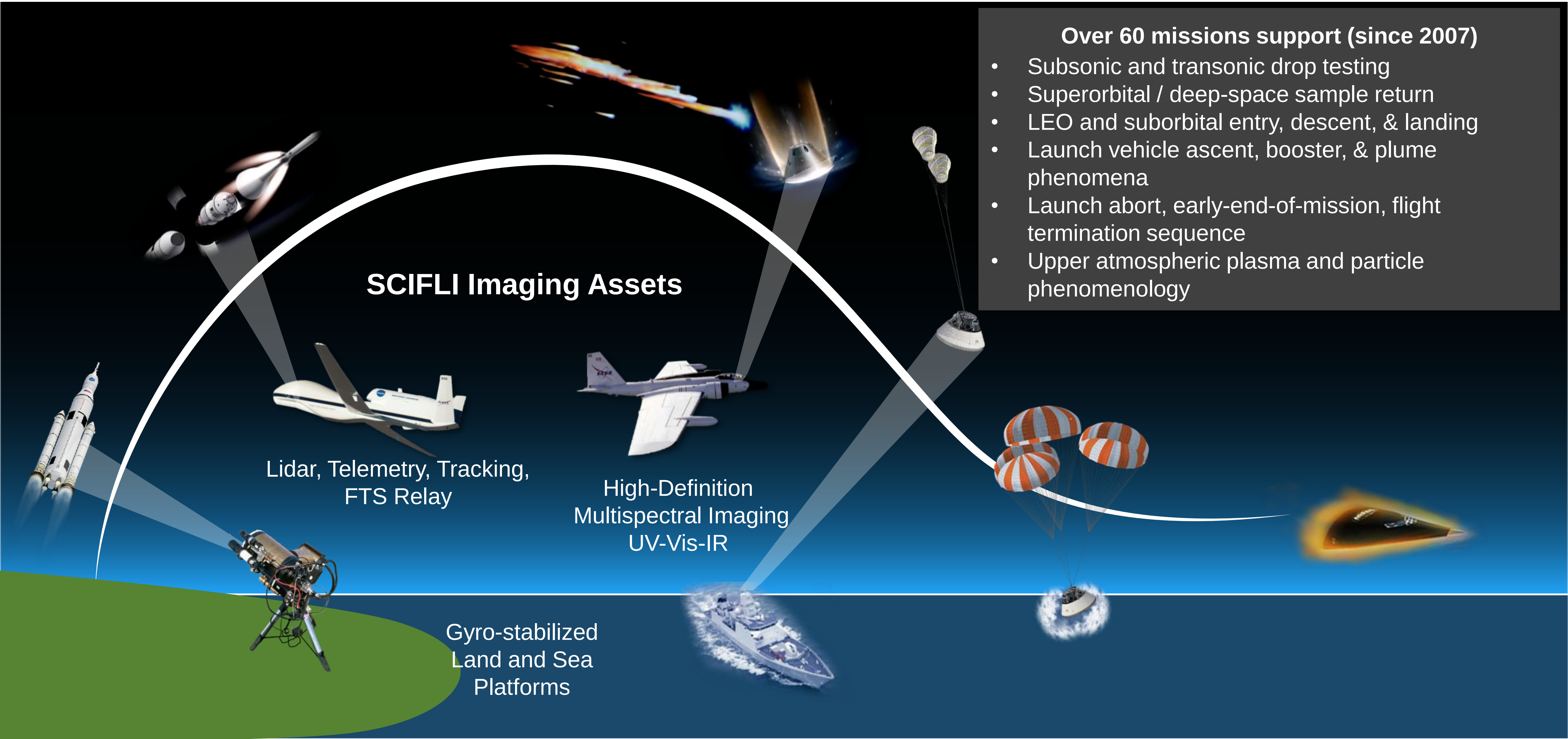
NASA SCIFLI: A Dedicated & Specialized Team

The Scientifically Calibrated In-Flight Imagery (SCIFLI) team is a committed and close-knit group of engineers, scientists, and subject matter experts.

The team has a two-decade-long proven track record of delivering flight-truth datasets, with over 60 missions ranging in complexity across all flight regimes. Our engineering datasets help investigators truly understand the behavior of vehicles under extreme conditions.

Mission-Specific Imaging Solutions

HIGHLY CUSTOMIZABLE MISSION ARCHITECTURES

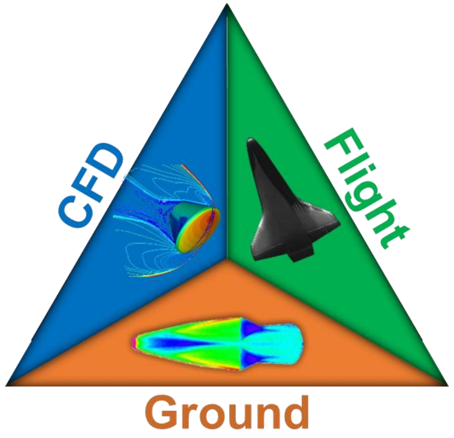


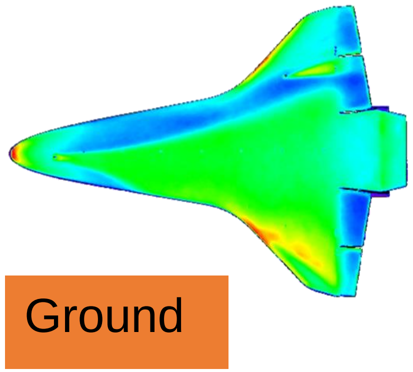
Over 60 missions support (since 2007)

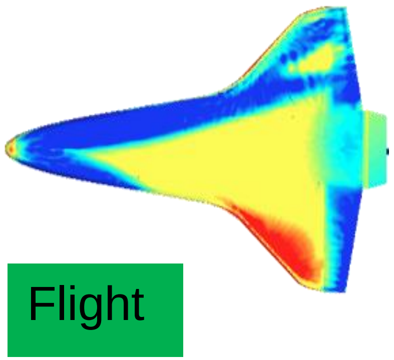
- Subsonic and transonic drop testing
- Superorbital / deep-space sample return
- LEO and suborbital entry, descent, & landing
- Launch vehicle ascent, booster, & plume phenomena
- Launch abort, early-end-of-mission, flight termination sequence
- Upper atmospheric plasma and particle phenomenology

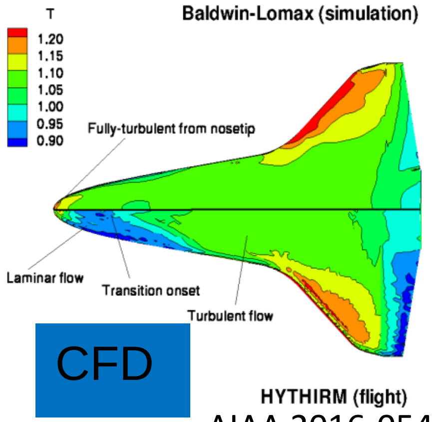
Collecting Flight Data

THE NECESSITY OF REAL-TIME FLIGHT DATA









AIAA 2016-0547

Observing flight conditions is essential

- In extreme conditions, **misunderstanding flight conditions can have tragic consequences**, such as the Columbia accident, the catalyst for SCIFLI's creation.
- Information about vehicle conditions during mission events can be **key to understanding performance of engineering & technology designs**

Flight conditions are difficult to document

- While ground testing and simulations are essential tools, they cannot fully capture in-flight vehicle performance.
- **Onboard instrumentation**, while incredibly helpful, is **subject to occasional failure, may only provide discrete values**, or may not be recovered.

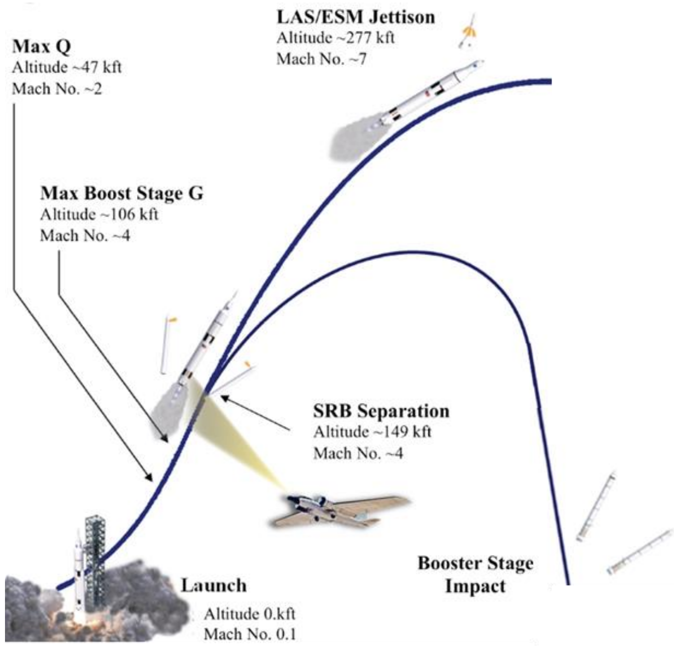
Airborne Imagery for SLS Ascent

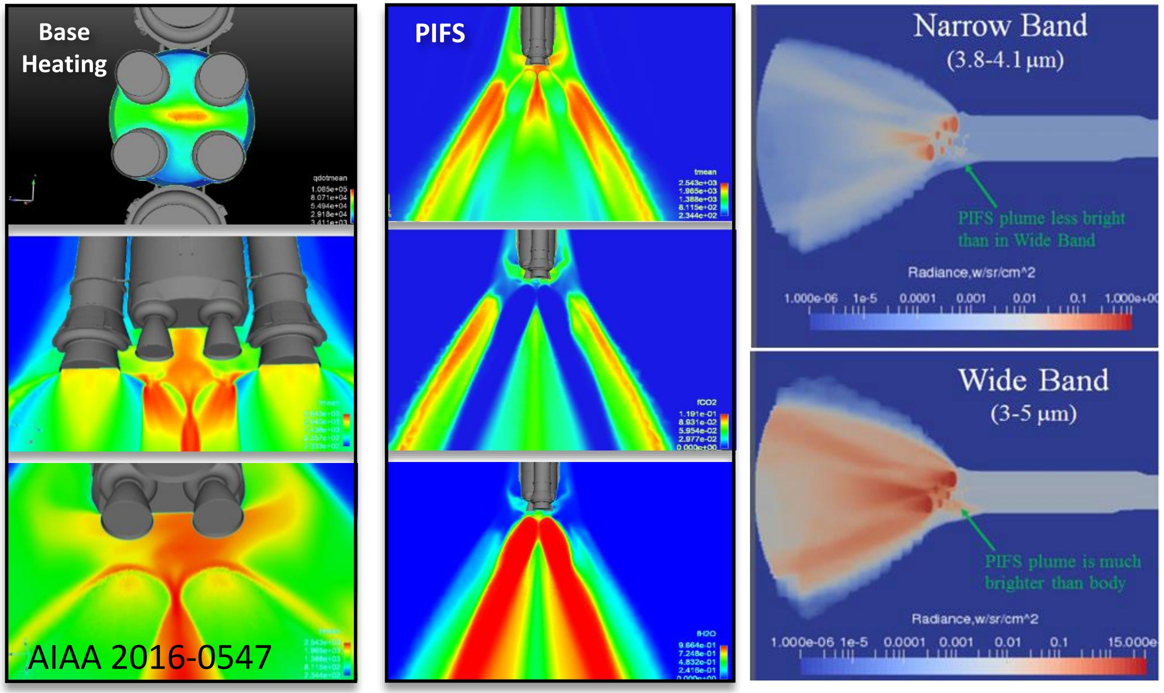
Goal: Collect calibrated **temperature images of the base region of SLS core stage and exhaust plume dynamics** during boost phase.

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

Best Effort – Observe Booster and Core Stage separation dynamics.

SLS Ascent Imagery of SRB (Solid Rocket Booster) Separation with WB-57





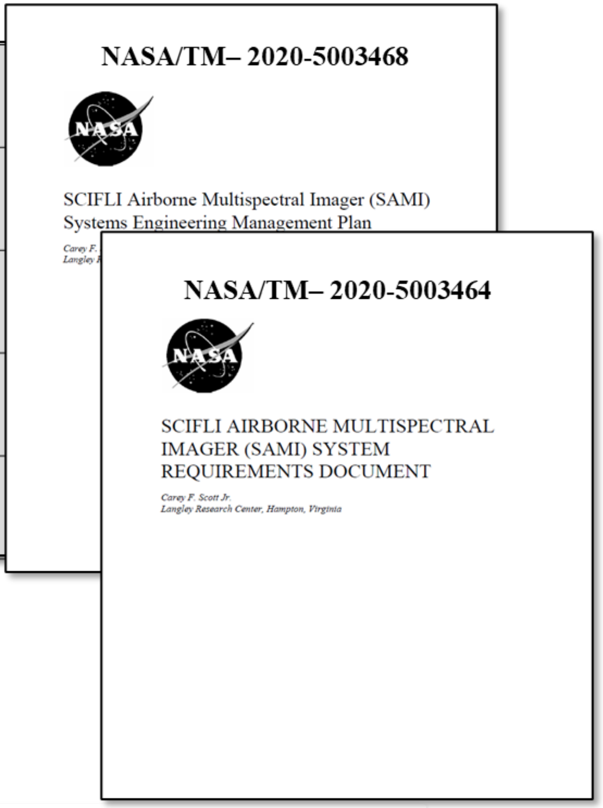
Predictions of Plume Structure & Heating in Base Region

<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

DyNAMITE Existing Payload – Limit on SLS Observation

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


NASA/TM– 2020-5003468

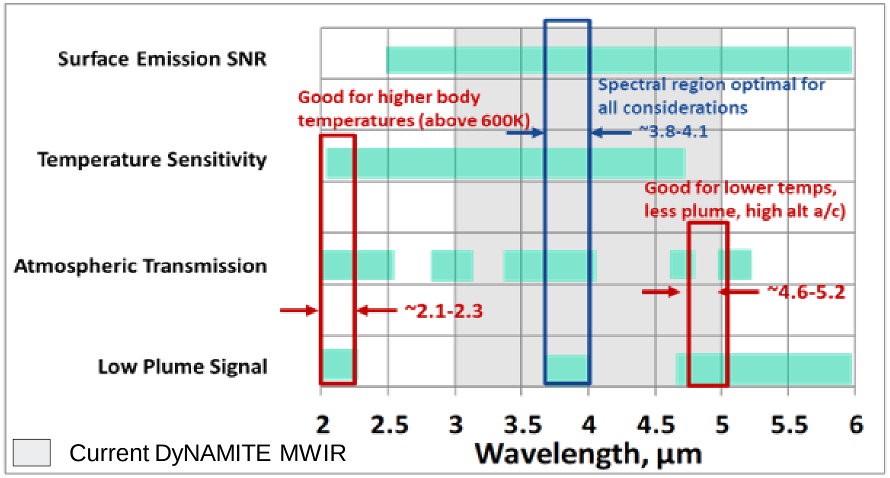
SCIFLI Airborne Multispectral Imager (SAMI)
Systems Engineering Management Plan

NASA/TM– 2020-5003464

SCIFLI AIRBORNE MULTISPECTRAL IMAGER (SAMI) SYSTEM REQUIREMENTS DOCUMENT

Carey F. Scott Jr.
Langley Research Center, Hampton, Virginia

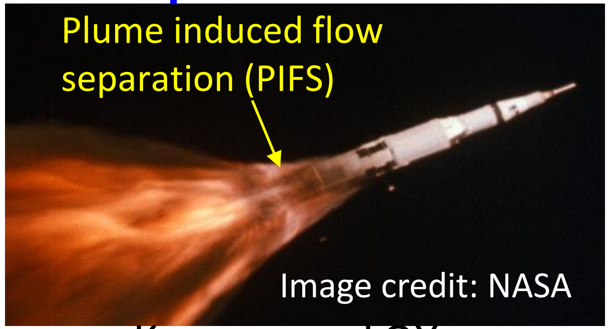
Optimal Wavebands to Meet All Imaging Objectives



- DyNAMITE: Day Night Airborne Motion Imagery for Terrestrial Environments
- DyNAMITE MWIR channel limited to 3-5 µm; static narrow-band filter options only

Observation Requirement of New Airborne Optical System

Apollo Saturn V

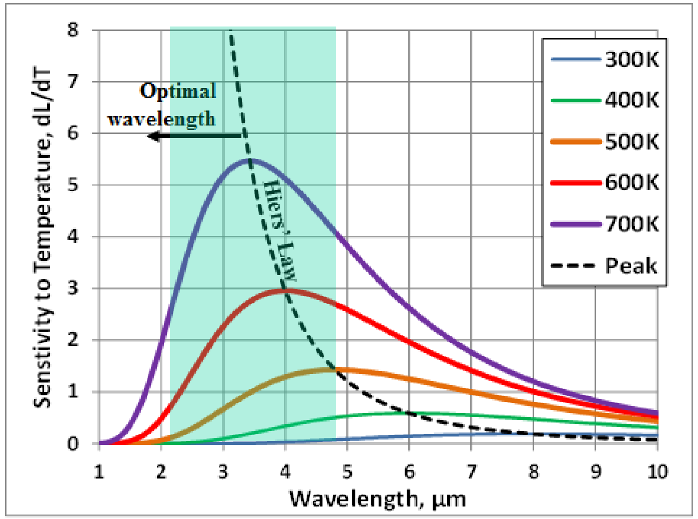


Kerosene + LOX
- Plume in VIS spectrum
- No temperature data

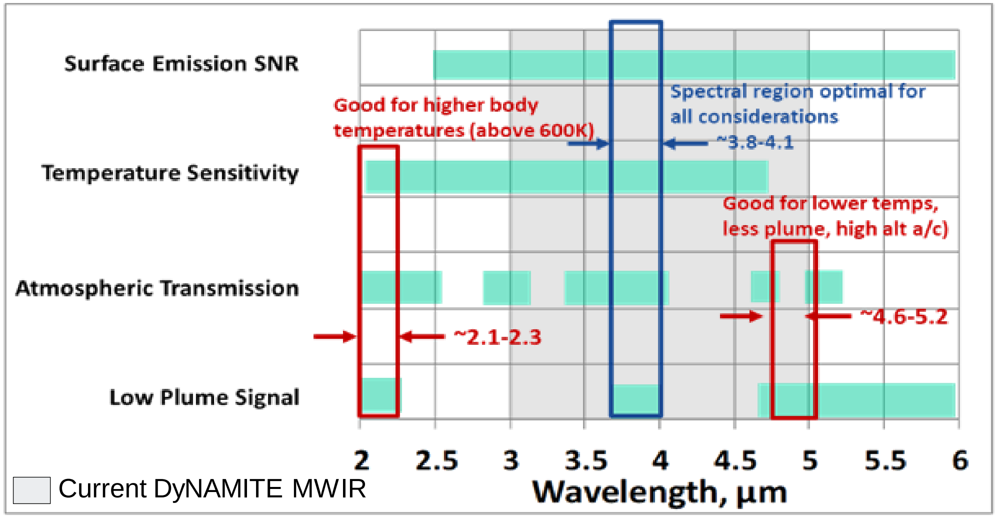
Artemis-I Program

Hydrogen + LOX = H_2O
- Plume in MWIR spectrum
- Temperature retrieval possible

Estimated Temperature Ranges During SLS Observation



Optimal Wavebands to Meet All Imaging Objectives



- Broadband (2-5 µm) MWIR for PIFS imaging; high temp core stage surface data available at 2 µm
- Multispectral Imager will allow for observation of plume features and hardbody thermal signatures with high spatial resolution, and low uncertainty in temperature retrieval

SAMI is Designed to Meet All Requirements

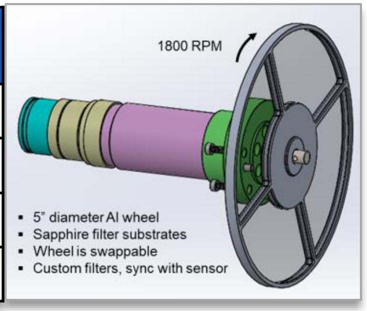
Total 6 multi-spectral channels

4 NFOV channels

- UV-VIS 301 – 750nm
- NIR 770 – 920nm
- SWIR 950 – 1700nm
- MWIR 2000 – 5000nm

- Shared f/8 telescope & beam splitters for wavelength separation
- MWIR 4-positions high-speed-filter-wheel (HSFW) for time resolved image

#	Waveband [µm]	Transmission Window	Target Species
F1	2.1 – 2.3	Plume	Hot Surface - BHS
F2	2.9 – 3.15	Atmosphere	Plume Gas - Hot H_2O
F3	3.8 – 4.1	Plume	Cool Surface - Aft Region
F4	4.5 – 4.7	Atmosphere	Plume Gas - CO/CO_2



2 WFOV channels

- VIS-NIR 470 – 900nm
- MWIR 3000 – 5000nm

- Independent cameras & zoomable lenses
- For the SEO with situational awareness and to facilitate acquisition and tracking
- VIS for daytime & MWIR for nighttime operation and acquisition / tracking of cold targets

SAMI Payload Overview

SAMI
SCIFLI AIRBORNE MULTISPECTRAL IMAGER

Result: A customizable & cost-effective aircraft-agnostic multispectral imaging testbed designed to collect plume and surface temperatures during Artemis I ascent for safety and to validate / reduce required TPS mass for future flights**.**

Overall System TRL
Level 8

FEB 2019

System Design
100% COMPLETE

Hardware Fabrication
100% COMPLETE

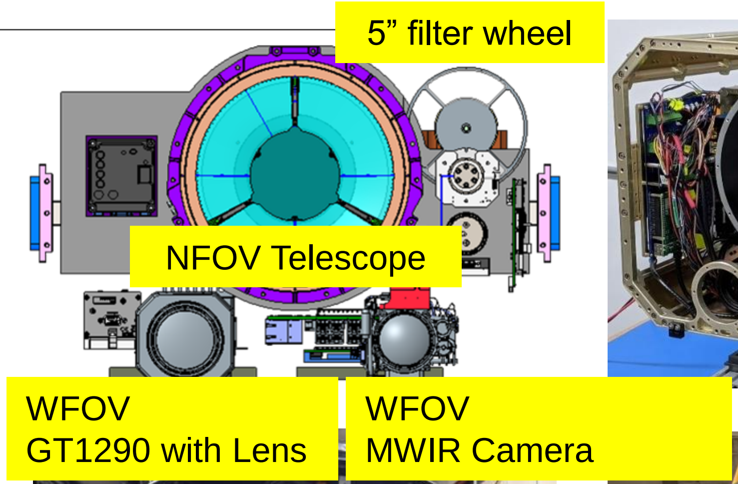
Payload Assembly
100% COMPLETE

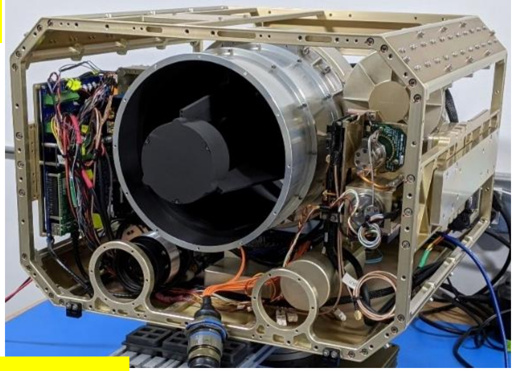
Payload Integration
100% COMPLETE

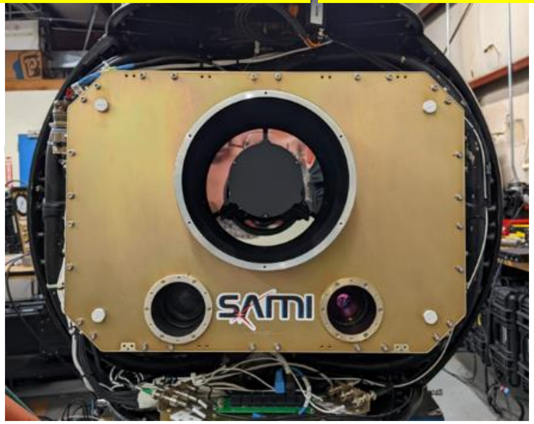
System Checkout
100% COMPLETE

Flight Testing
COMPLETE

NOV 2022

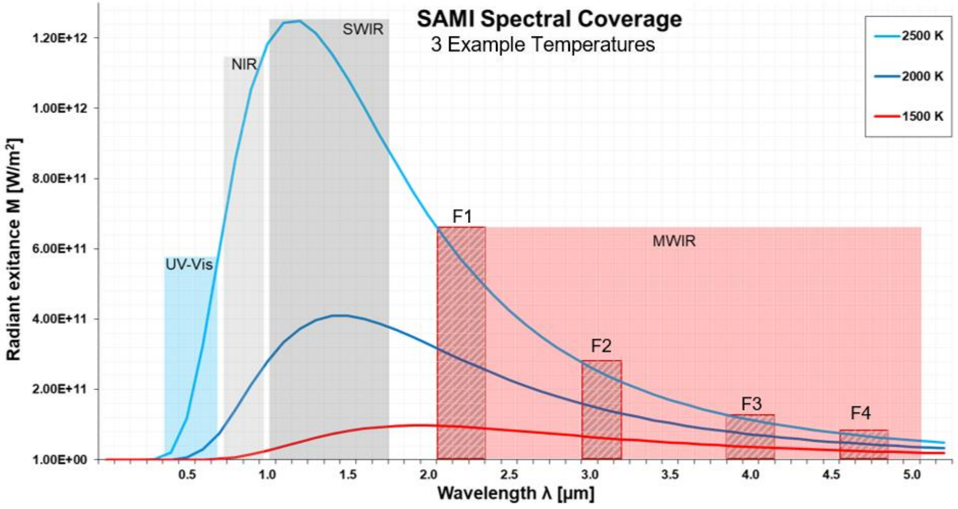




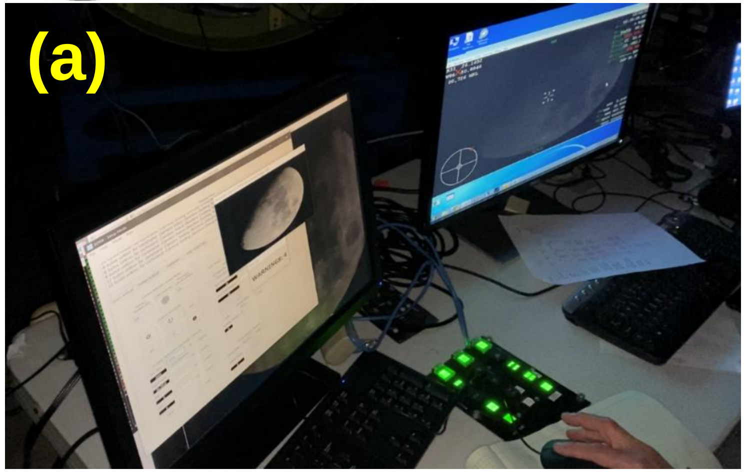


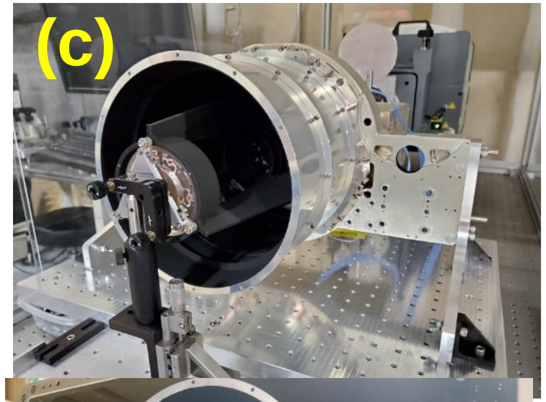
Key Capabilities

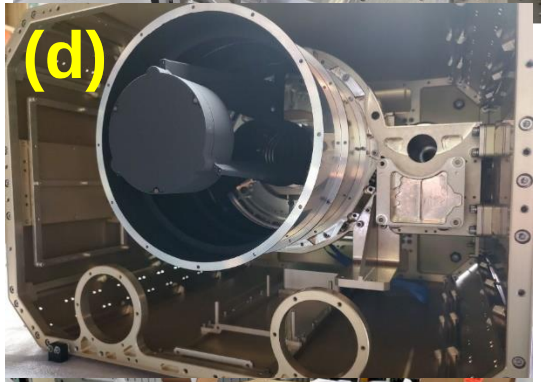
- Passive + active thermal control
- Integration within existing infrastructure (WB-57)
- Multiple sensors + high speed filter wheel
- Reflective optical telescope for image quality
- Semi-modular design to allow customization

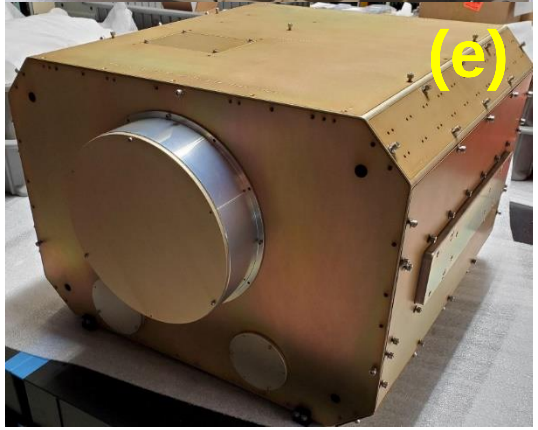


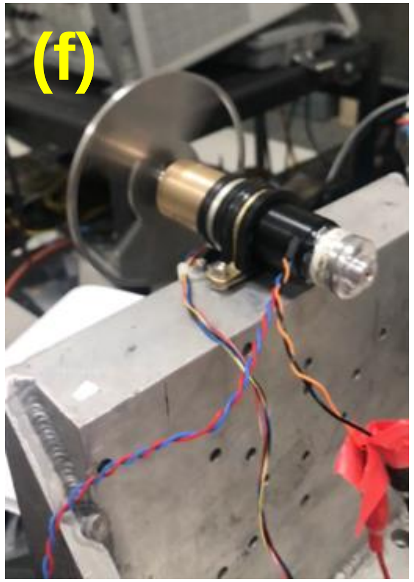
SAMI Hardware

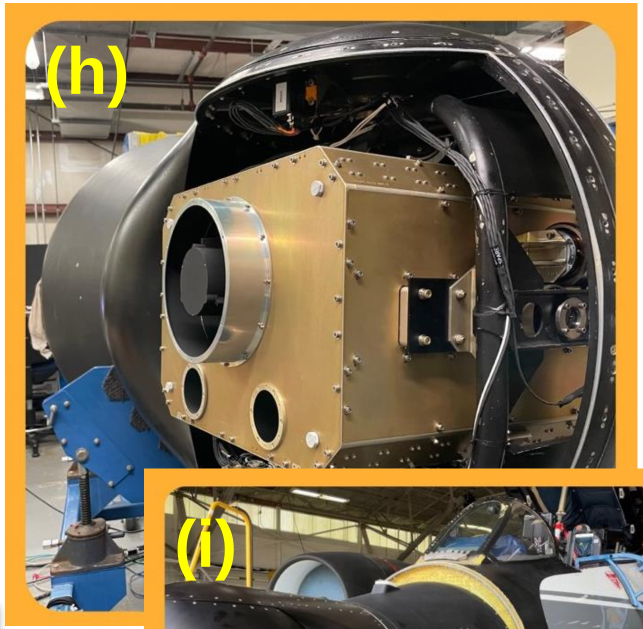






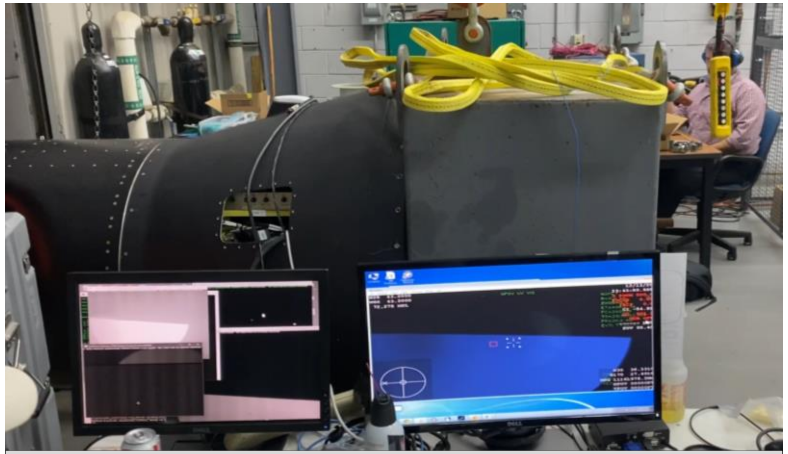






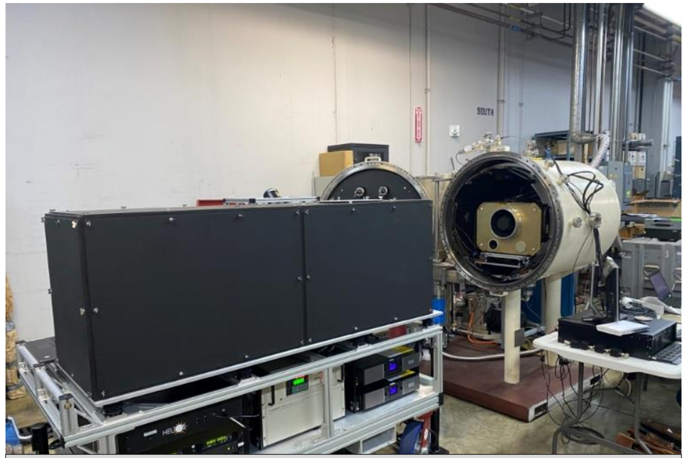
a) SAMI First Light
b) Integrated Ground Testing
c) NFOV telescope during alignment
d) NFOV telescope + optical bench
e) SAMI Payload volume
f) High-speed filter wheel
g) Custom NFOV MWIR sensor
h) Payload fit check
i) SAMI on the NASA WB-57

SAMI Payload Functional Verification Testing

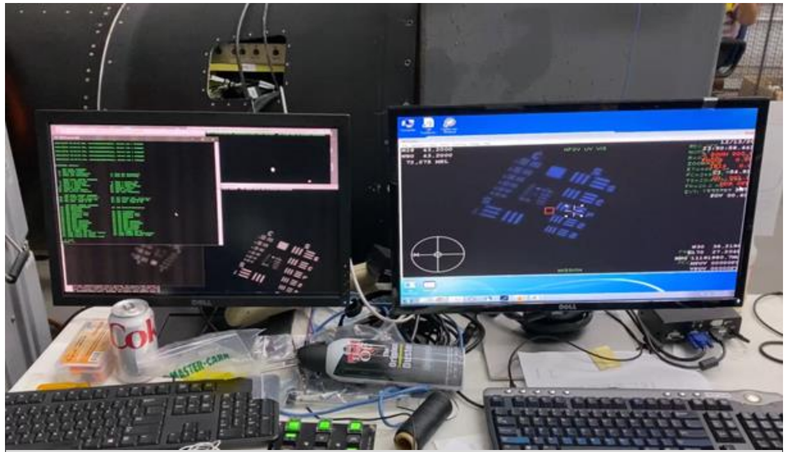


SCC 'half-moon' imaging during vibration test

SAMI 'First Light' integrated imaging/tracking of Luna



SAMI environmental test for AIRS gimbal environment



SCC USAF bar target imaging during vibration test

Filter wheel operation on screen while connected to AIRS

Lab Testing Results:

- ✓ Operational temperature: -40 to +50 C
- ✓ Operational pressure: 5 to 15 psi
- ✓ WB-57 Vibrational environment
- ✓ **Filter wheel sync and functionality**
- ✓ Functional tracking with AIRS Gimbal
- ✓ **Night-time operations**

✓ **= test passed / functionality verified**

All functional requirements were verified via test or demonstration.

SAMI Payload Status

Primary platform selection	SAMI fabrication	Nov. 2018
1st CDR (conceptual design review)		Feb. 2019
2nd CDR (Relocated NIR camera and shift to single focus mechanism for all NFOV channels)		Oct. 2019
Initiate the SAMI fabrication		Oct. 2019
Assembled operation	Lab test	Dec. 2020
Software useability		May 2021
Environmental temp / pressure	Ground test	May 2021
AIRS mechanical integration		Oct. 2021
AIRS electrical integration		Dec. 2021
Vibrational environment		Dec. 2021
Aircraft (WB-57) integration	Flight test	Mar. 2021
Final hardware upgrade / integration (i.e., WFOV MWIR camera integration completion)	Ready for Artemis-I mission	Feb. 2022
Final software unit testing completion		Mar. 2022
Performance validation **flight testing** (field campaign using calibrated / known targets for Spatial resolution & radiometric performance testing)		Aug. 2022
Validation flight testing (Artemis-I mission)		Nov. 2022
SAMI calibration cart completion (providing radiometric and spatial calibration)		Mar. 2021
SAMI regular maintenance (enable reliable SAMI operations and availability)		

Performance Validation Testing

Flight Test Goals:

Performance validation through integrated flight testing

✓ Spatial performance characterization of all SAMI channels

✓ Radiometric performance testing & calibration of science channels

Phase 1: Integrated Functional Checkouts

Phase 2: Ground-based radiometric target imaging

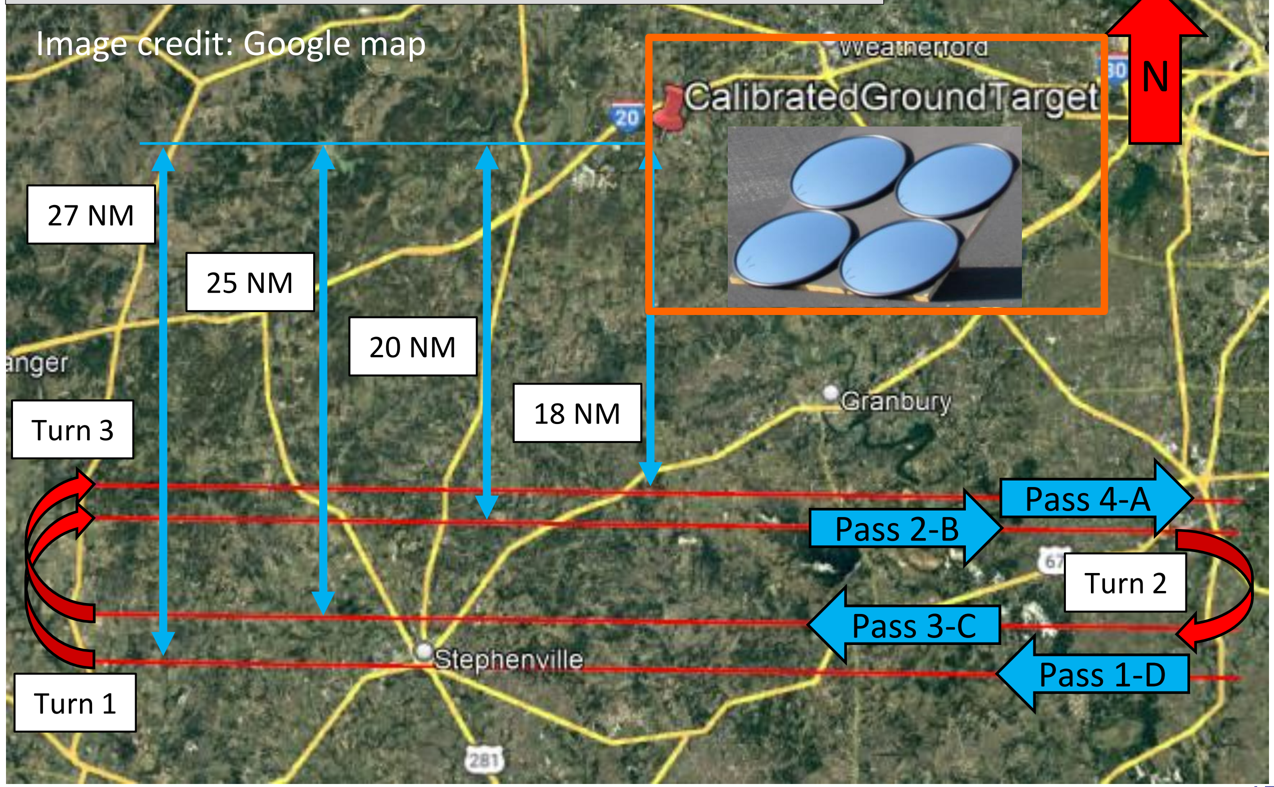
Spatial & Radiometric Performance Testing in August 2022:

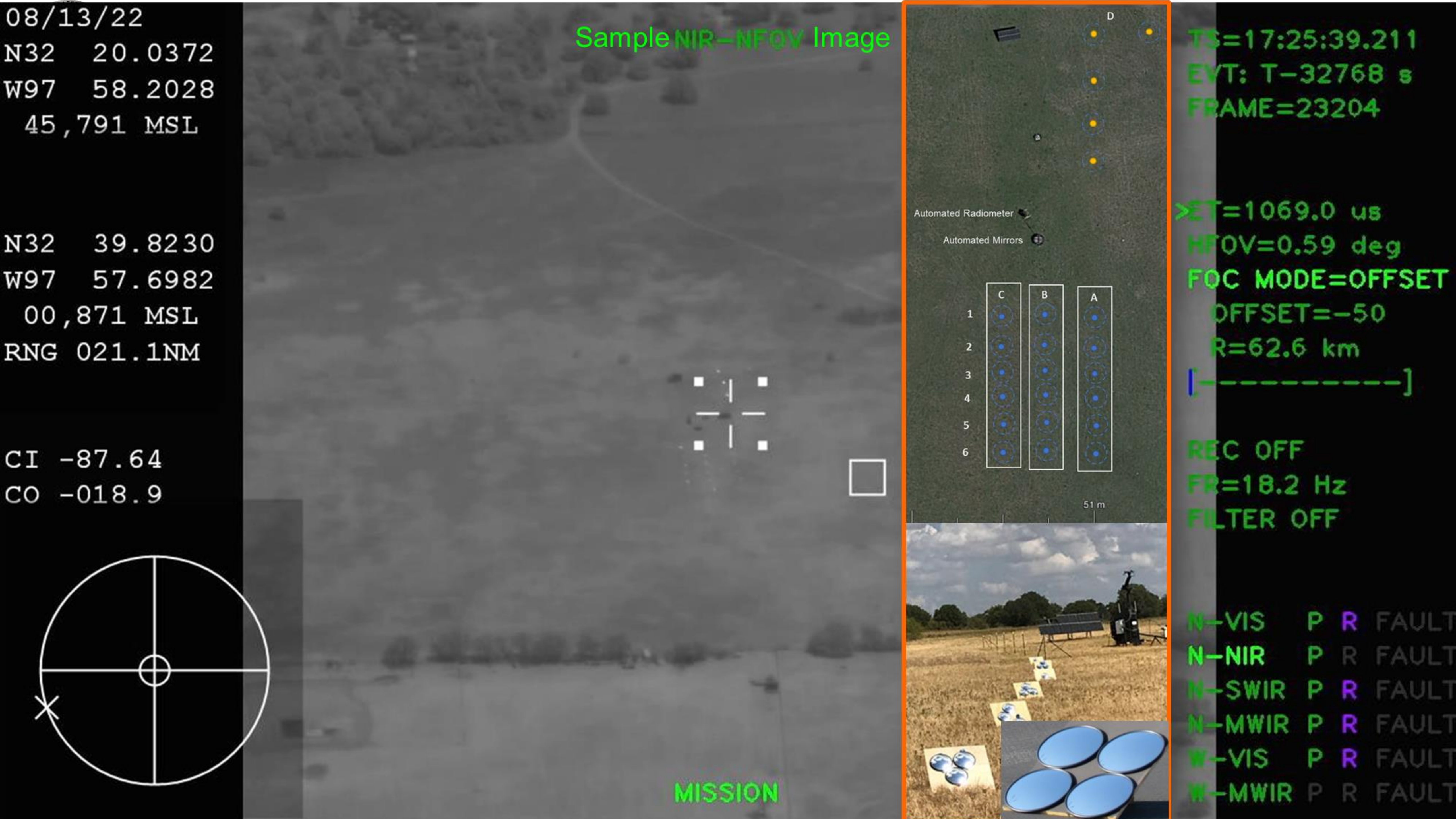
- Spatial and radiometric testing – Complete
- First operation of integrated systems against filed target – Complete
- Airborne, ground, and remote teams' success on communication & fight operation – Complete
- Synchronized measurements and station tracking with aircraft, success– Complete
- Lessons learned / refinements – test run for Artemis-I – Complete

Phase 3: Operational Test Flights

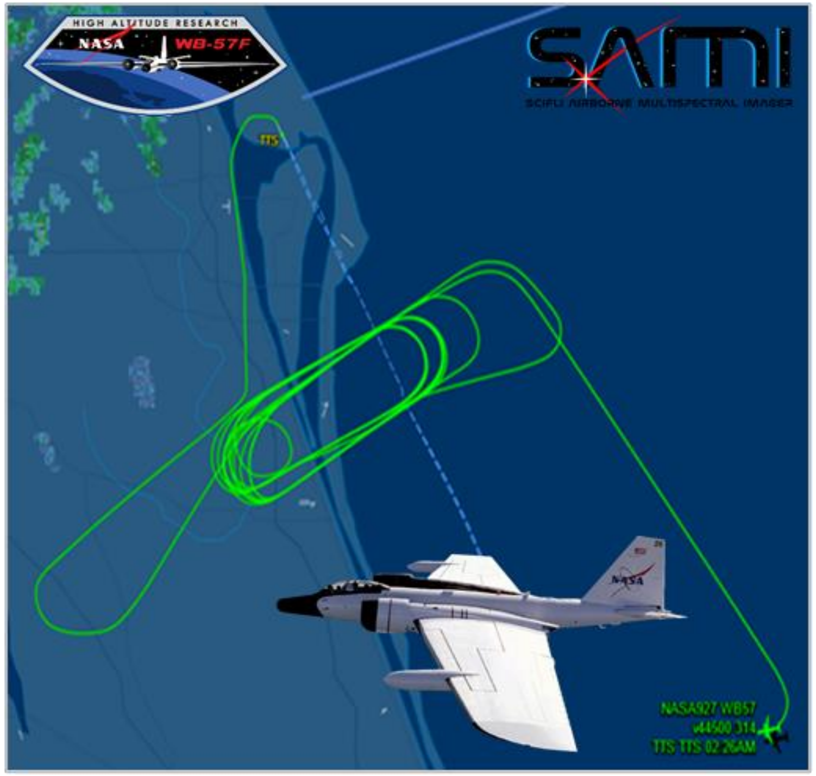

SAMI payload integrated onto WB-57 aircraft

Example of custom ground-based radiometric targets:




Sample NIR–NFOV Image
08/13/22
N32 20.0372
W97 58.2028
45,791 MSL
N32 39.8230
W97 57.6982
00,871 MSL
RNG 021.1NM
CI -87.64
CO -018.9
MISSION
D
Automated Radiometer
Automated Mirrors
C
B
A
1
2
3
4
5
6
51 m
TS=17:25:39.211
EVT: T-32768 s
FRAME=23204
>ET=1069.0 us
NFOV=0.59 deg
FOC MODE=OFFSET
OFFSET=-50
R=62.6 km
[-----------]
REC OFF
FR=18.2 Hz
FILTER OFF
N-VIS P R FAULT
N-NIR P R FAULT
N-SWIR P R FAULT
N-MWIR P R FAULT
W-VIS P R FAULT
W-MWIR P R FAULT

SCIFLI Artemis-I Ascent Imaging using SAMI



- **Mission Date:** 06:47:44Z 16 November 2022
- **Imaging Platforms:** NASA 927 WB-57F Airborne Platform w/ SAMI Payload
- **Data Types to Collected using SAMI**
    - Vis and NIR (improper SWIR and MWIR exposure)
- Consequences of Night launch
    - No sunlight illumination in NIR or Vis (less bias error)
    - No background intensity

Example Data Products using SAMI: Artemis-I

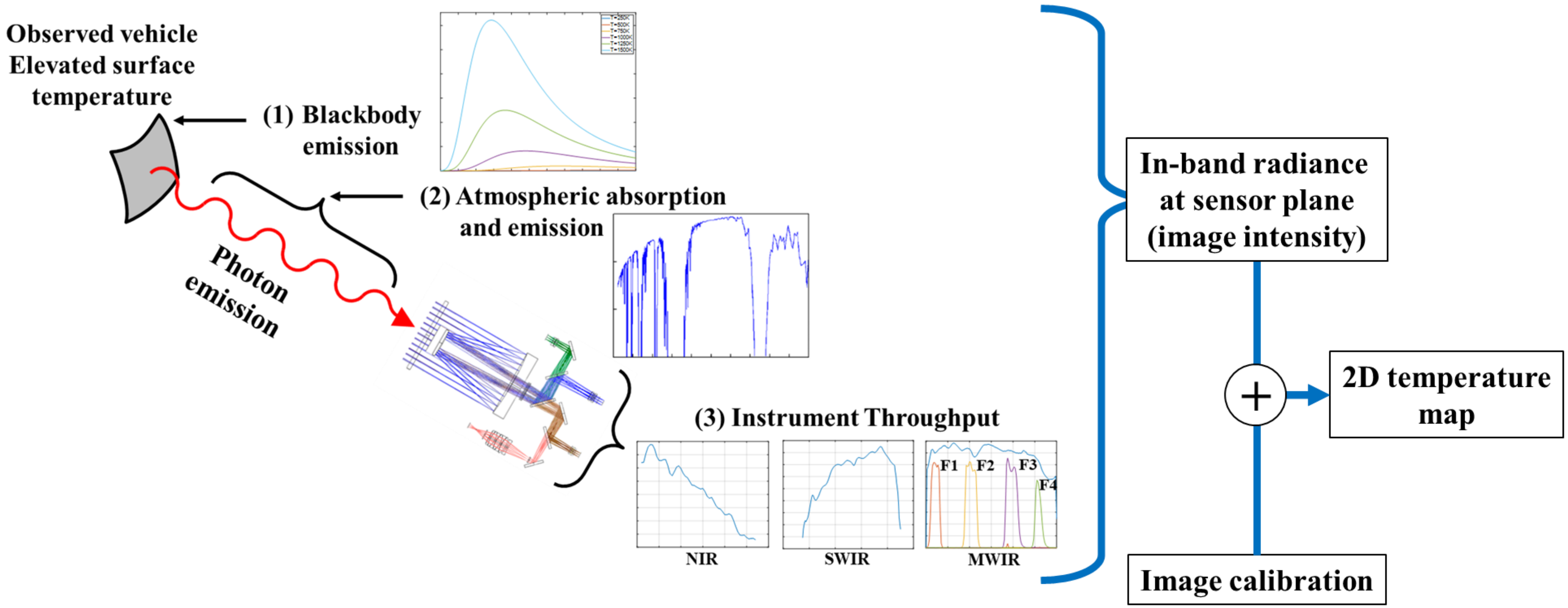
(Left) Artemis 01 Launch: *SWIR Frame 59219 Tower Clear*
(Right) Artemis 01 Launch: *SWIR Frame 54815*

Captured Image (@ launch)

Captured Image (before booster separation)

Temperature Extraction Process

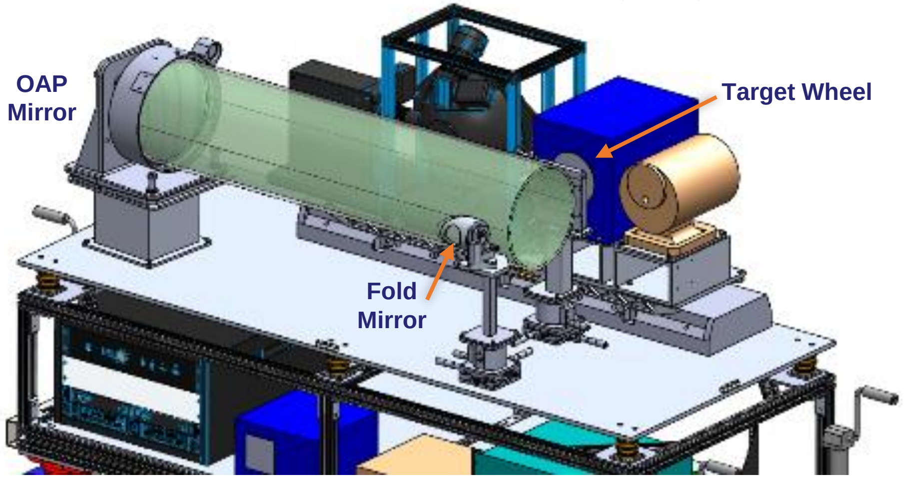
Pre-Flight		Mission Operations		Data Analysis		Results
Sensor Characterization	Model Development	Data Collection	Sensor Calibration	Atmospheric Modeling	Trajectory Modeling	Image Mapping



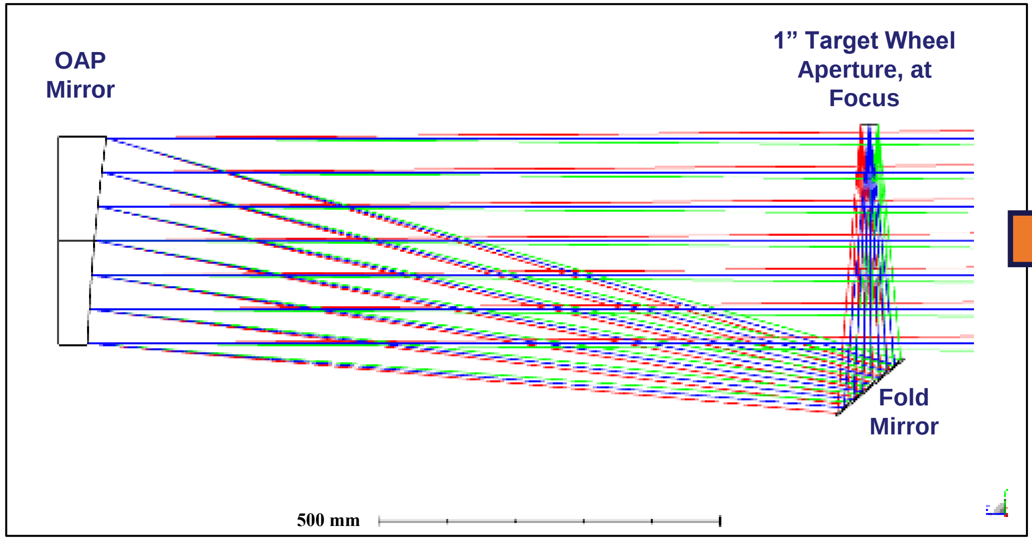
Radiometric Calibration

SAMI Calibration Cart (SCC)
- ✓ Simultaneous calibration of all SAMI sensors with flooded aperture
- ✓ Images are collected over a wide range of conditions pre- and post flight
  - ✓ Characterize and calibrate the sensors
  - ✓ Convert pixel intensity to in-band radiance at entrance aperture
  - ✓ Image statistics for noise characterization and bad pixel detection

SAMI Calibration Cart (SCC)

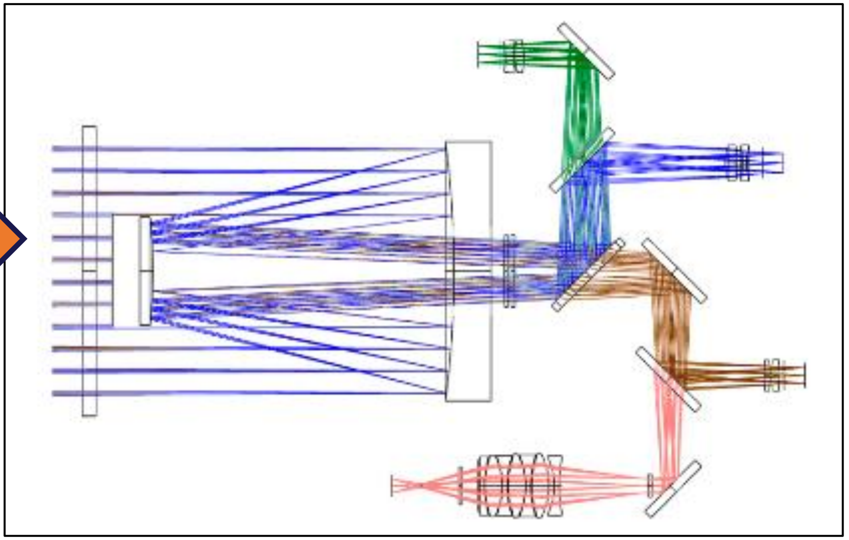


Ray Diagram of SAMI Calibration Cart



To Sensors

SAMI sensor layout



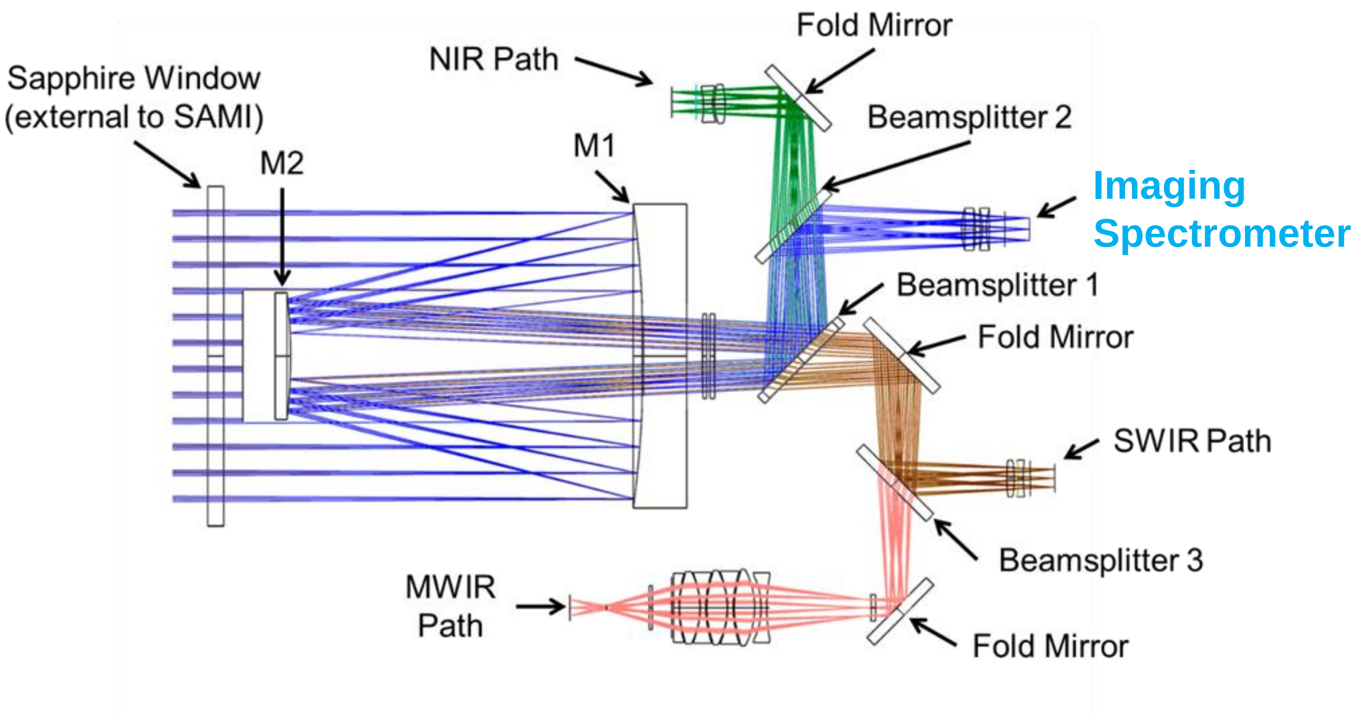
SAMI Payload Modification

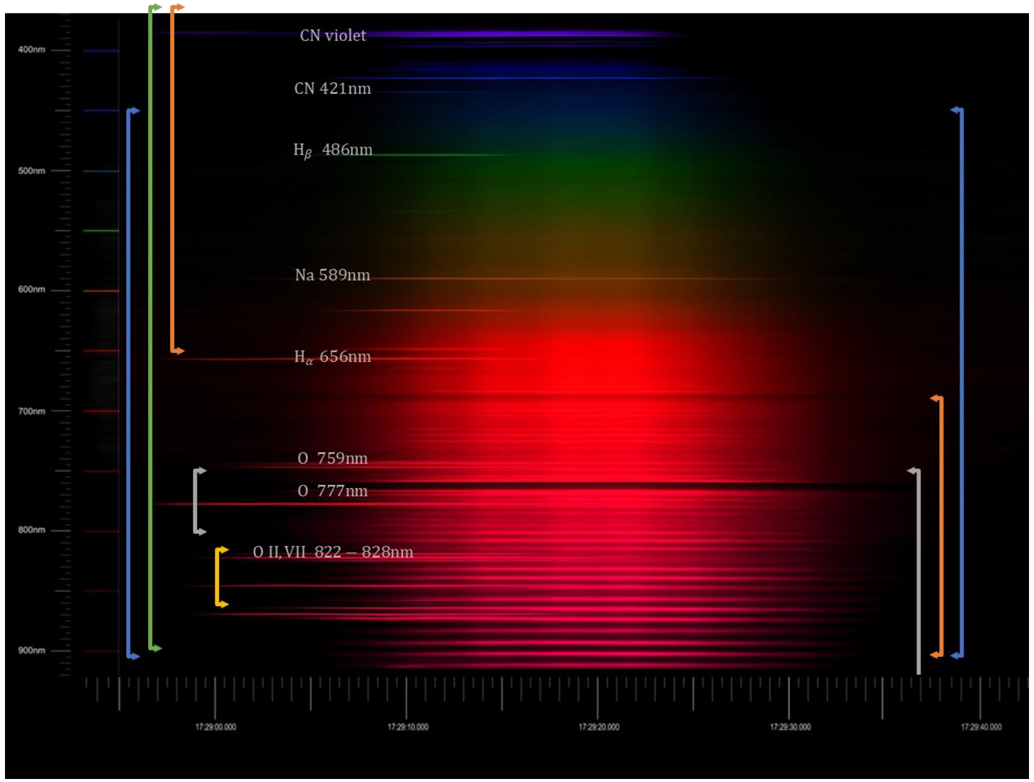
- Motivated by OSIRIS-REx sample return mission
- Imaging spectrometer replaces existing UV-VIS camera in SAMI
- SAMI payload modification design review based on science requirement
  - Near-vehicle wake radiation measurement: N_2, No, and NO_2 band systems (UV-VIS / 315 – 700nm)
  - Surface temperature analysis: broad thermal emission from surface

Image credit: NASA

OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer) NASA asteroid-study and sample-return mission

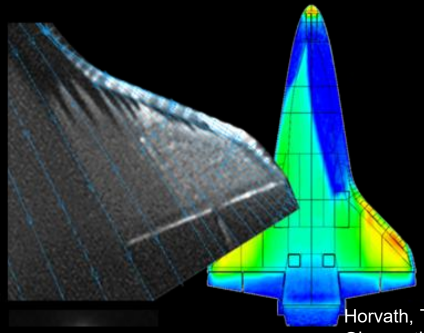
Asteroid Bennu
(>60 grams sample)



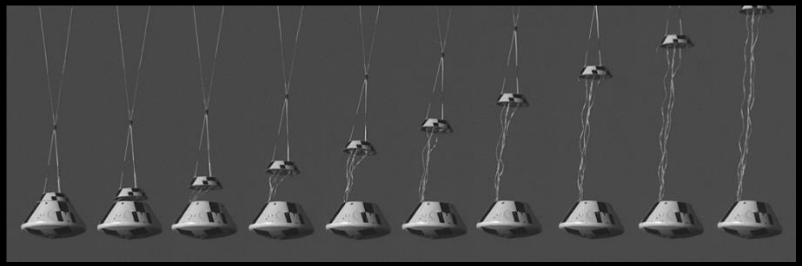


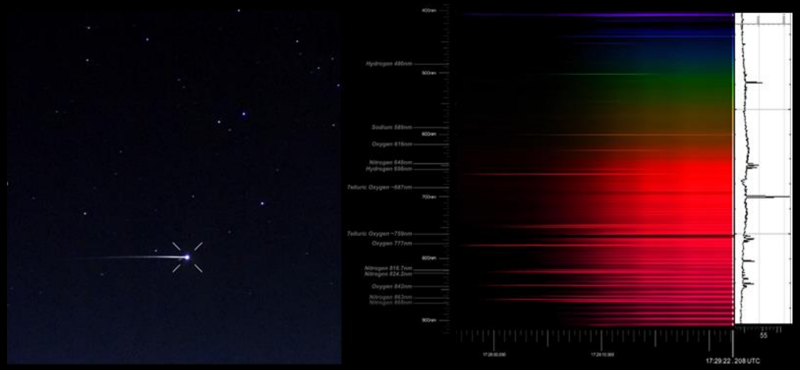
Future of SAMI Capabilities

Expand capability for future mission: reconfigurable either imaging or spectrometer



Horvath, T. et al., "Global Infrared Observations of Roughness Induced Transition on the Space Shuttle Orbiter." (2012).





Infrared

- Global thermal maps of vehicle surface
- Exact temperatures (extra calibration required)
- Waveband-specific

Use Cases

- Verify onboard instrumentation
- Boundary layer transition and hypersonic fluid dynamics
- Plume interactions

Visual

- Qualitative, high resolution
- Real-time streaming capabilities

Use Cases

- Document mission events such as parachute deployment and booster separation

Spectral

- Chemical analysis of vehicle conditions in-flight

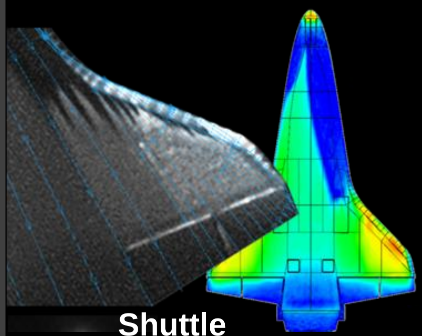
Use Cases

- Hypersonic reentry of asteroid sample return missions
- Heat shield ablation analysis
- Vehicle heath monitoring

Future SAMI Applications

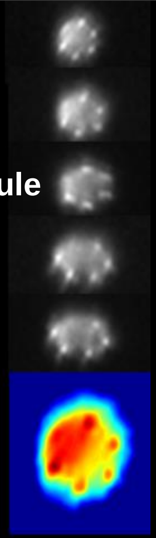
SCIFLI'S Industry Partnerships

Government



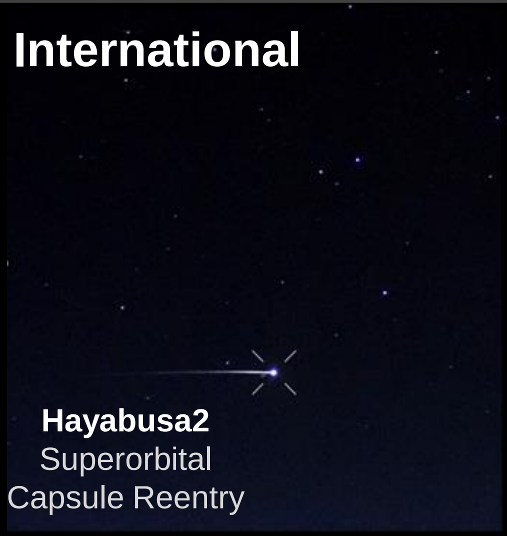
Shuttle
Boundary Layer
Transition

Orion Capsule
Reentry

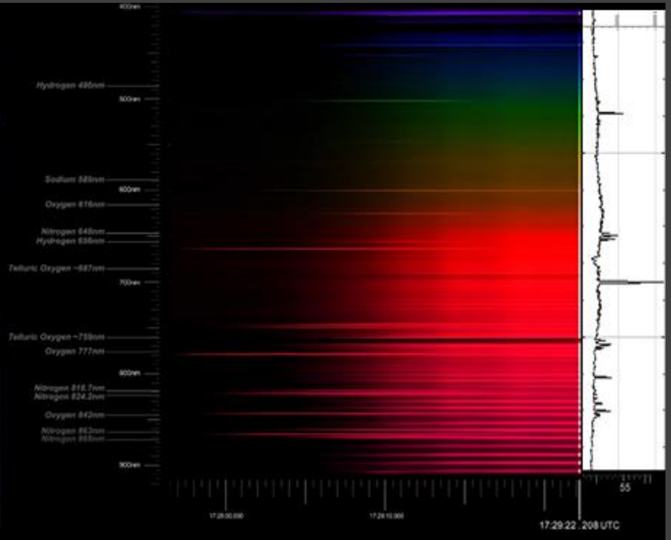


ISS
Long Range
Tracking
Image credit: MARS

International



Hayabusa2
Superorbital
Capsule Reentry

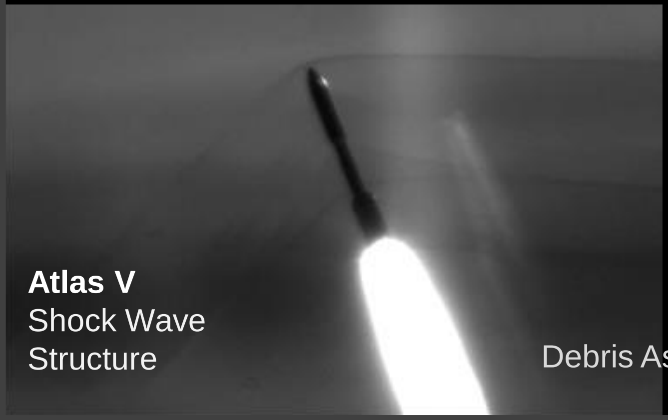


Commercial

Sierra Space
Dream Chaser

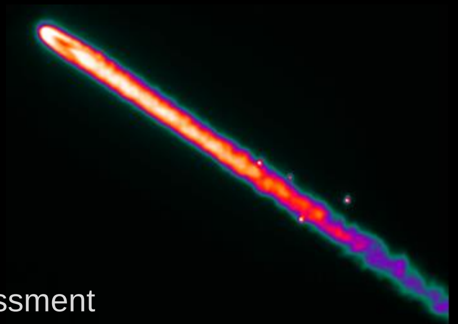
SpaceX
Falcon 9
Image credit: MARS

Defense



Atlas V
Shock Wave
Structure

Plume Phenomenology



Debris Assessment

- SCIFLI’s imaging solutions enable the collection of engineering data from vehicles in flight, allowing for better understanding of performance under extreme flight conditions.
- SCIFLI’s new payload, SAMI, expanding the envelope of the quality and type of flight data possible (to meet customer objectives).
- The UV-VIS imaging spectrometer provides new technical capabilities.

https://scifli.larc.nasa.gov/

Back-up

SAMI is Designed to Meet All Requirements

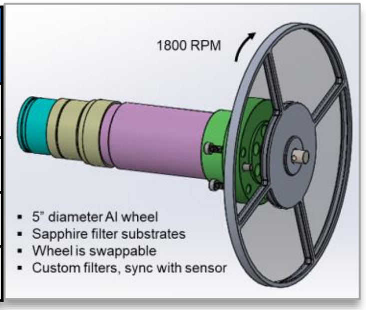
Total 6 multi-spectral channels

4 NFOV channels
- UV-VIS 301 – 750nm
- NIR 770 – 920nm
- SWIR 950 – 1700nm
- MWIR 2000 – 5000nm

2 WFOV channels
- VIS-NIR 470 – 900nm
- MWIR 3000 – 5000nm

- Shared f/8 telescope & beam splitters for wavelength separation
- MWIR 4-positions high-speed-filter-wheel (HSFW) for time resolved image

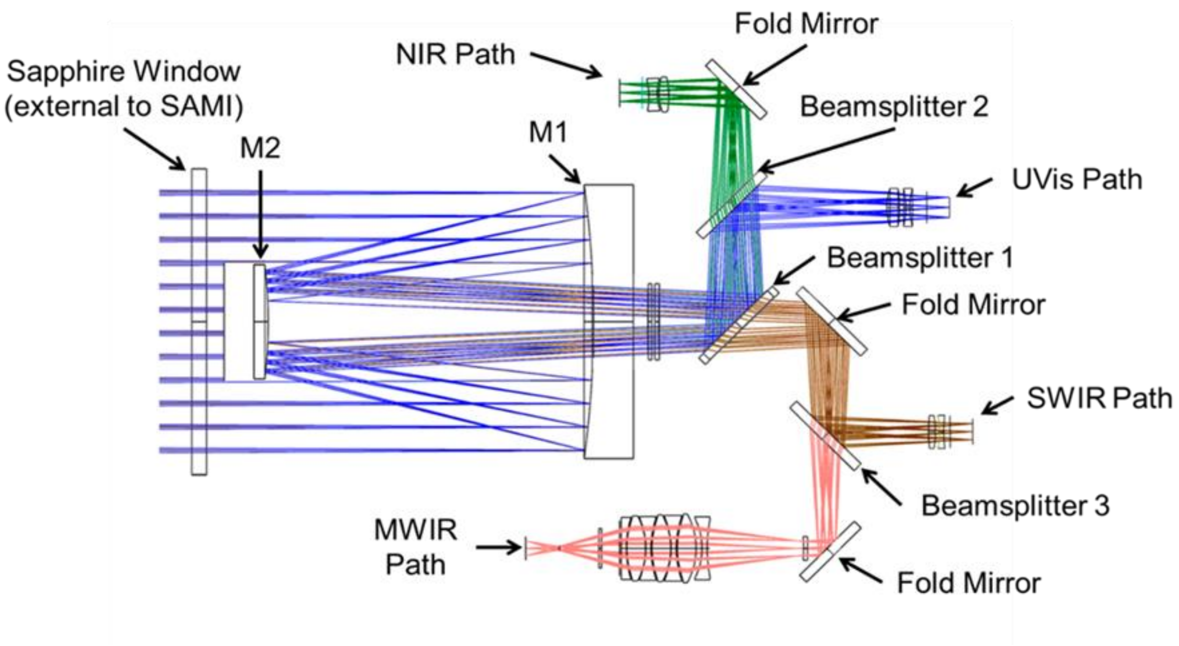
#	Waveband [μm]	Transmission Window	Target Species
F1	2.1 – 2.3	Plume	Hot Surface - BHS
F2	2.9 – 3.15	Atmosphere	Plume Gas - Hot H_2O
F3	3.8 – 4.1	Plume	Cool Surface - Aft Region
F4	4.5 – 4.7	Atmosphere	Plume Gas - CO/CO_2

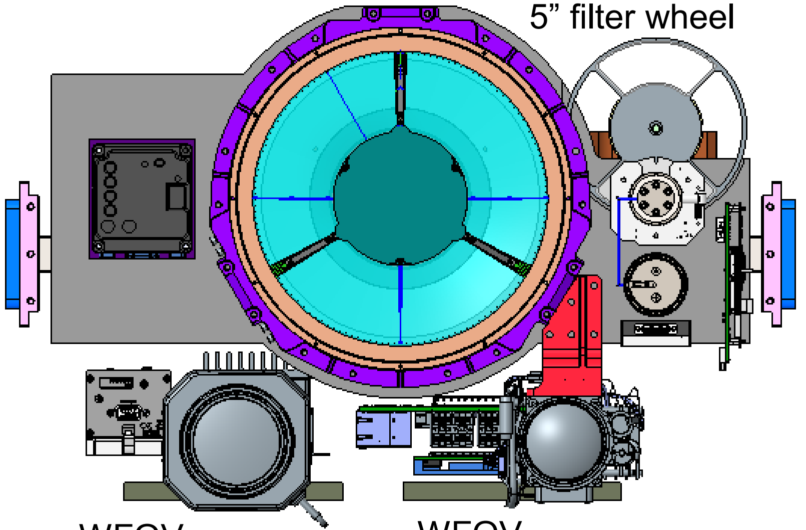


- Independent cameras & zoomable lenses
- For the SEO with situational awareness and to facilitate acquisition and tracking
- VIS for daytime & MWIR for nighttime operation and acquisition / tracking of cold targets

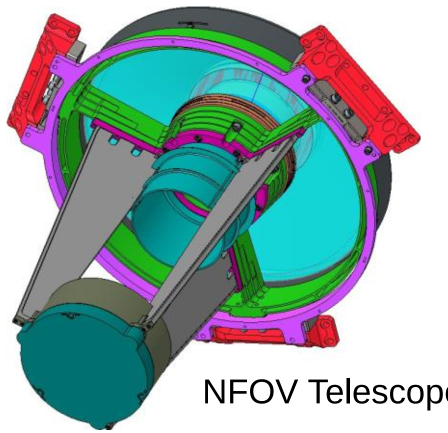
❑ **FDA-STE-AT-1.1 Ascent Aerothermal** ➢ *Airborne Imagery Contributions: Core Stage surface temperatures*	✓ **SAMI**
❑ **FDA-STE-AT-1.2 Plume Radiation Heating** ➢ *Airborne Imagery: Exhaust plume radiation (thermal signature characterization, shape, size)*	✓ **SAMI**
❑ **FDA-STE-AT-1.3 Plume Convection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

SAMI Optics and Sensors





- Main vertical plate provides primary structure
- Closed optical ‘periscope’ reduces thermal air currents and stray light
- SWIR and UV-VIS mount to optic box; modular fold mirror sub- assemblies
- MWIR and NIR mount to the telescope plate
- The box mounts directly to the telescope plate
- Centralized focus mechanism aft of primary mirror; dual actuators provide redundancy
- Ritchey–Chrétien design 8” (203 mm) telescope with f/8 (1625.6 mm focal length), 5.88 kg (12.97 lbs) weight, passive athermalization

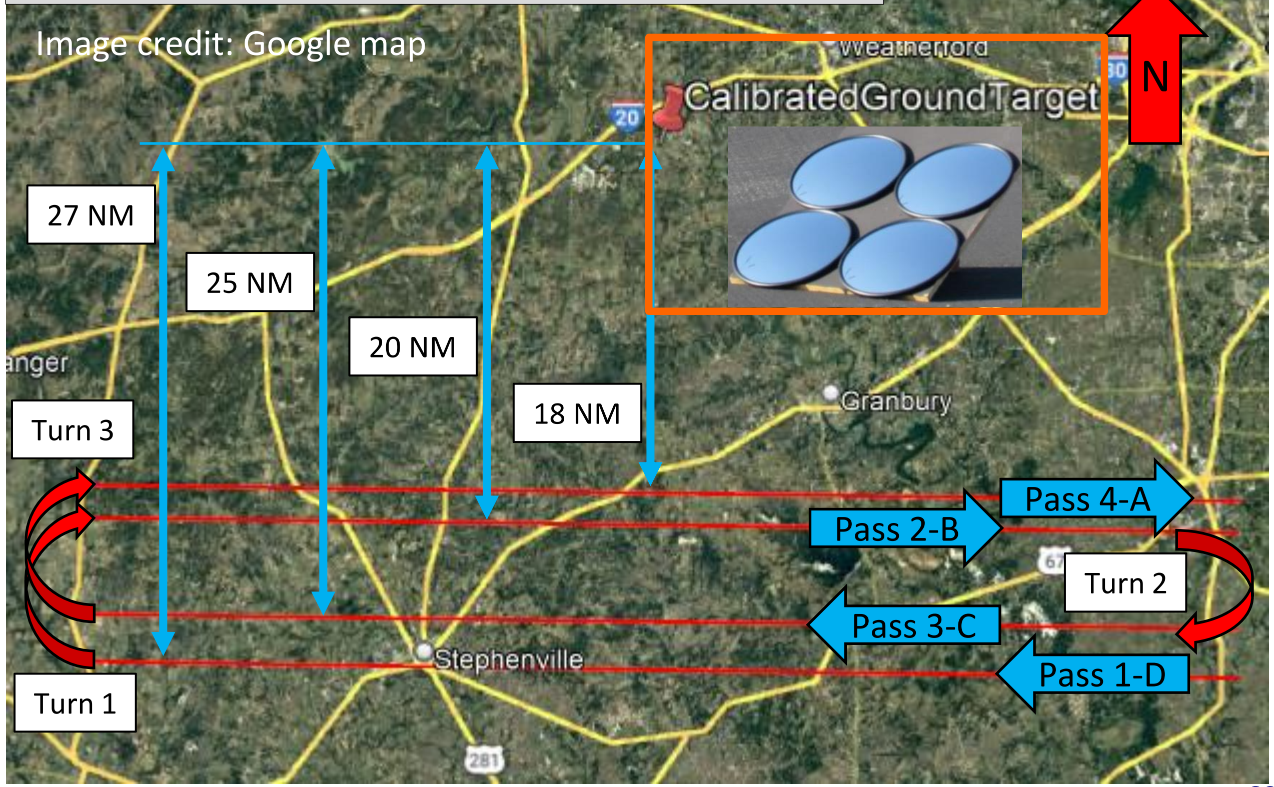


Spatial & Radiometric Performance Testing

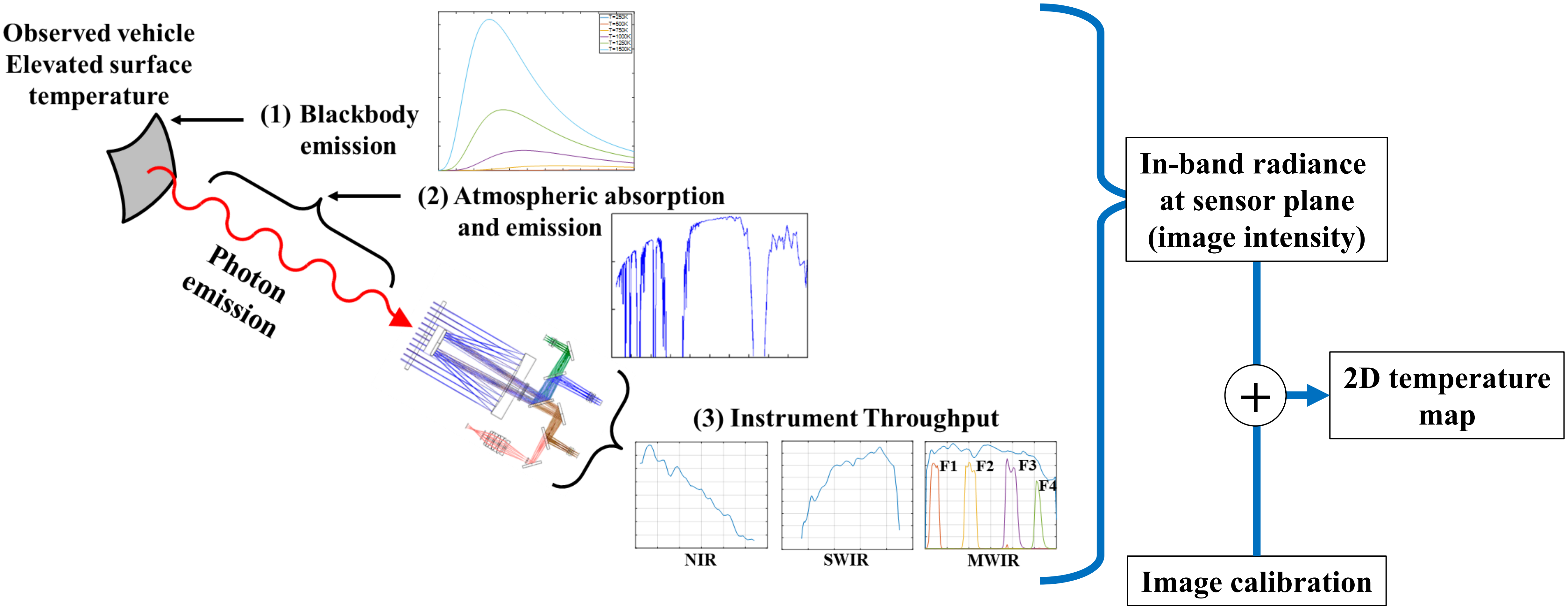
1. Use of FLARE targets for spatial and radiometric testing of SAMI VIS-NIR-SWIR-MWIR full motion video camera system
2. Two main goals of the campaign
   - Characterization of spatial performance of all SAMI wavebands
   - Radiometric performance testing & calibration of VIS-SWIR and MWIR wavebands
3. Multiple target / manual mirrors deployed
   - Targets specified for different SAMI bands / capabilities
     - VIS-SWIR (350 – 2500 nm), Aluminum mirror arrays
     - MWIR (2500 – 5000 nm), Steel mirror arrays
4. SAMI operations test successful
   - Spatial and radiometric testing completed
   - First operation of integrated systems against field targets
   - Airborne, ground, and remote teams: good on communication & flight operation
   - Synchronized measurements and station tracking with aircraft
   - **Lessons learned/refinements – test run for Artemis-I**

SAMI payload integrated onto WB-57 aircraft

Test plan



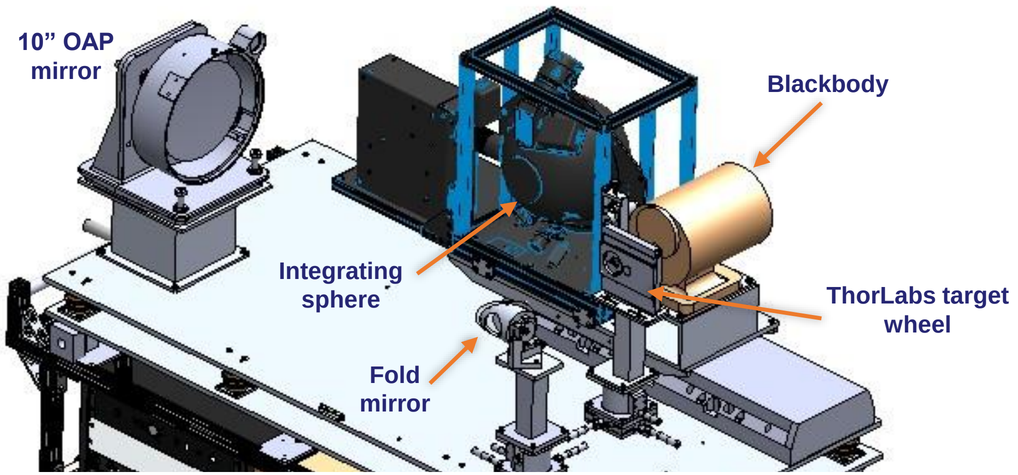
Temperature Determination



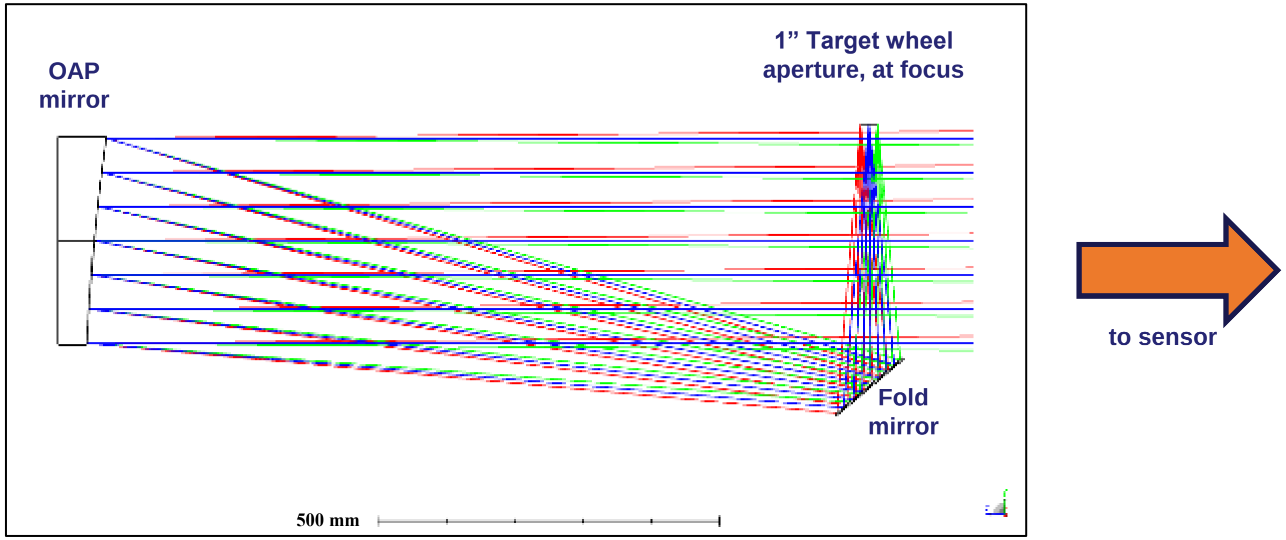
SAMI Calibration Cart (SCC)
- ✓ Simultaneous calibration of all SAMI sensors with flooded aperture
- ✓ Two NIST-traceable calibration sources
  - IR-564/301 blackbody ($0° - 1200°$) with 1" aperture
  - 12" HELIOS labsphere integrating sphere with 2" aperture
- ✓ High efficiency optics
  - SORL off-axis parabolic (OAP) mirror ($D = 10", f = 60"$)
  - Precision applied optics custom mirror (4.75" major axis, $98.5°$ turn)

Images are collected over a wide range of conditions pre- and post flight
- ⇒ Characterize and calibrate the sensors
- ⇒ Convert pixel intensity to in-band radiance at entrance aperture
- ⇒ Image statistics for noise characterization and bad pixel detection

SAMI Calibration Cart (SCC)



Ray Diagram of SAMI Calibration Cart



SAMI sensor layout