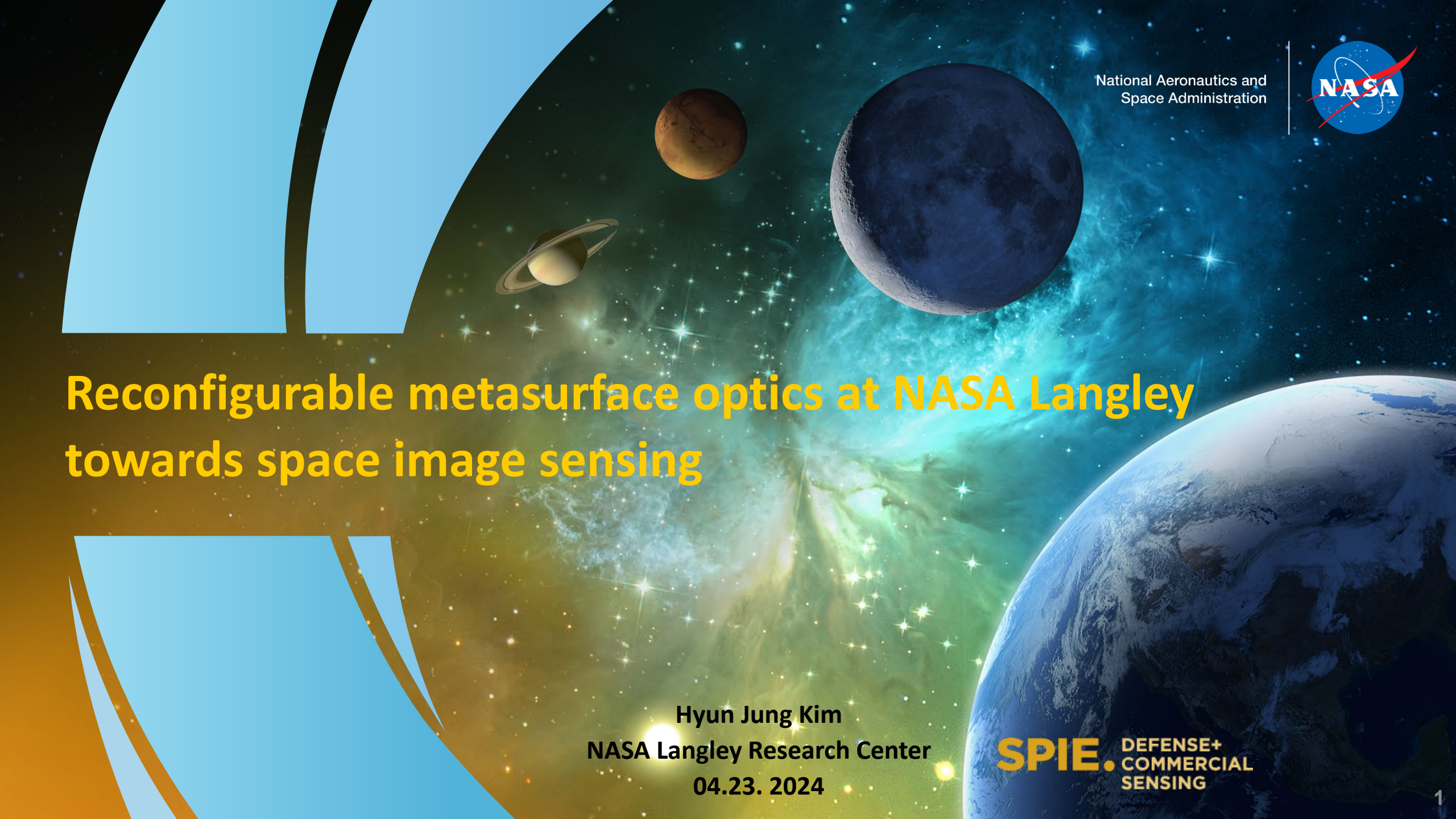


National Aeronautics and Space Administration

Reconfigurable metasurface optics at NASA Langley towards space image sensing

Hyun Jung Kim
NASA Langley Research Center
04.23. 2024

SPIE. DEFENSE+ COMMERCIAL SENSING

Why is NASA researching reconfigurable metasurfaces?

- "Cutting edge innovations by NASA leaderships seek to refine **scientific instrument into smaller, lighter, more versatile** tools for exploration" – *Karl Hille, chief technologist at NASA's GSFC*

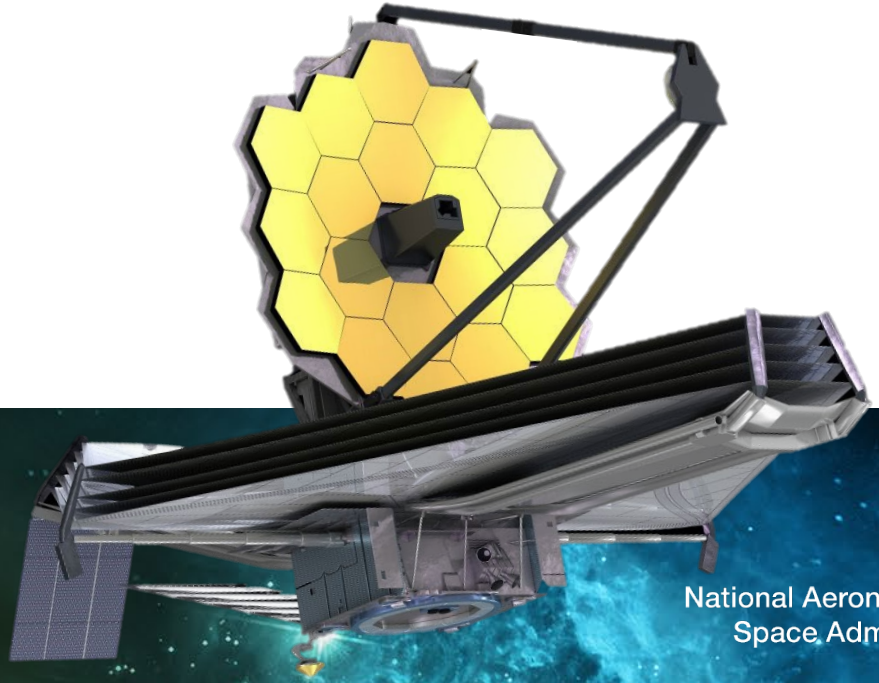
- "**Metasurface optic** technologies are important because of the **precision and versatility** that is offers to LiDAR" – *Cheryl Gramling, assistant chief for technology at GSFC*

- "As recently displayed by the stunning images from the JWST, we often rely on recording the intensity of light (e.g., with a camera) to study the universe. …Metasurfaces enable general manipulations of phase, amplitude, and polarization on the nanoscale, thereby providing **ample opportunity** ….and even **enable functionality not possible using conventional technologies** - *Tobias Wenger, researcher at JPL*

- … "NASA scientists are on the cusp of revolutionizing LEO Earth Observing platforms using novel optical **metamaterials to reduce the size, weight and power (SWaP) of existing architectures**."
  – *Williams Humphreys, chief engineer at LaRC*

- **Metamaterials** are man-made (synthesized) composite materials whose electromagnetic, acoustic, optical, etc. properties are determined by their constitutive structural materials and their configurations.

Reconfigurable Metafilter



National Aeronautics and Space Administration

- ❑ Project motivation
- ❑ Research progress
- ❑ Mission-based case study
- ❑ Future direction through NASA MISSE

Filter wheels for NASA missions

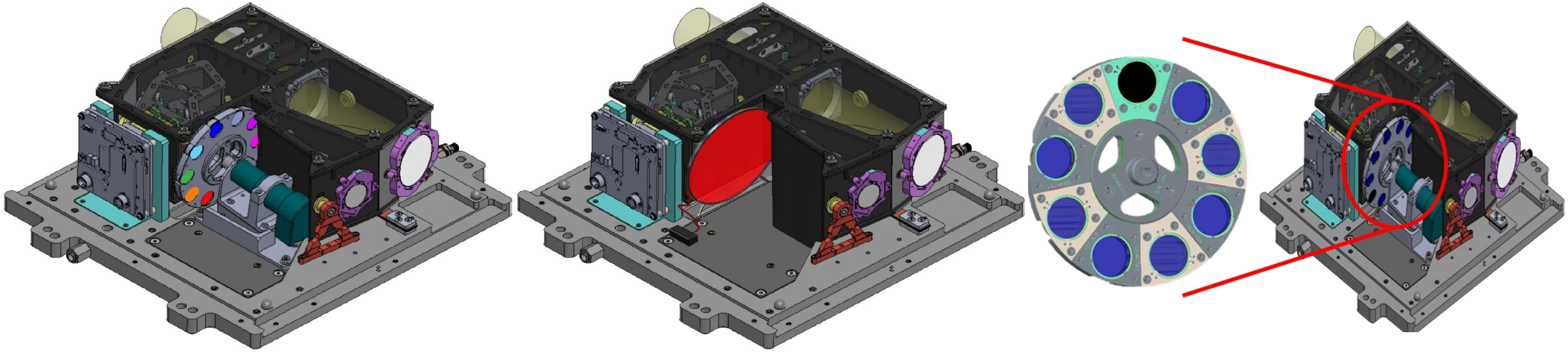
Optical filter wheels are critical components in a plethora of NASA Earth and space science missions, but comes with several drawbacks

SCIFLI SLS project

- **Multispectral Performance for Artemis-I**
- **Slow speed** (1500 rpm) limits the in-situ thermal monitoring? Emissivity variation increases the uncertainty?

SAGE LIDAR mission

- SAGE (Stratospheric Aerosol and Gas Experiment)
- SAGE-IV: 1/10th the cost of SAGE-III in 6U CubeSat platform for Redeshare launches
- **Filter wheel requires bulky optics and limited spectral tunability**

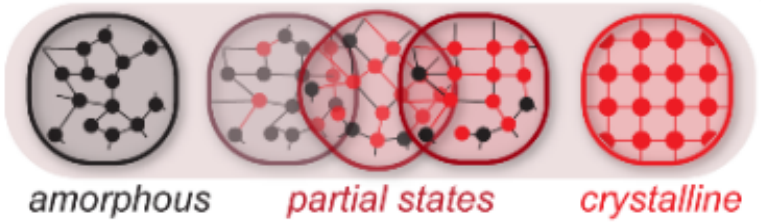


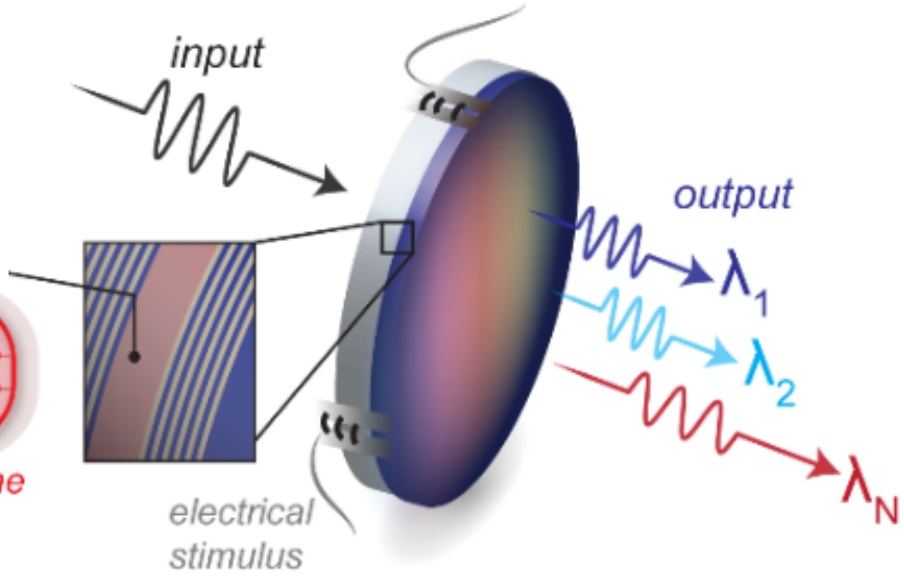
SWaP + No moving part + More WL tunability = More launch opportunity & More science information

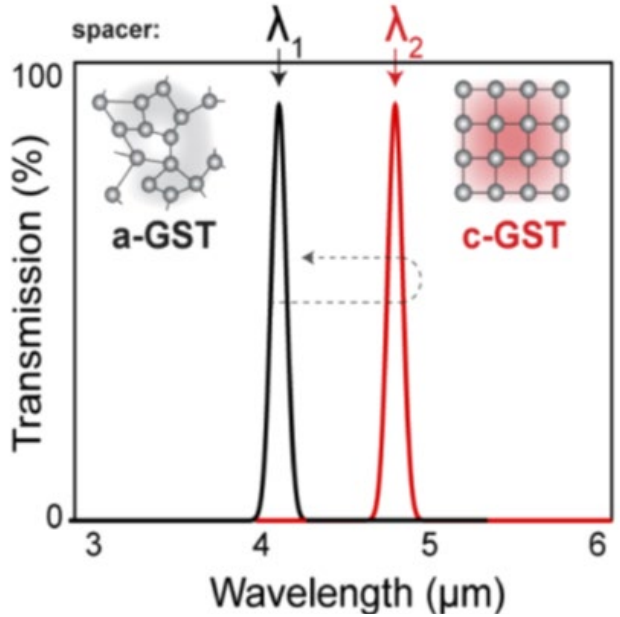
PCM-based Metafilter

Phase Change Material (PCM)-based filter

Phase Change Material (PCM)





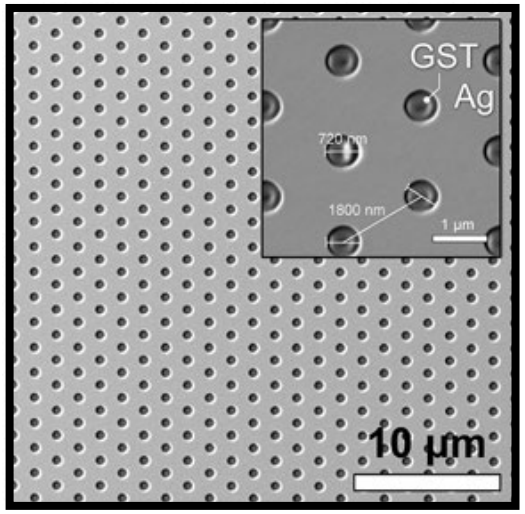


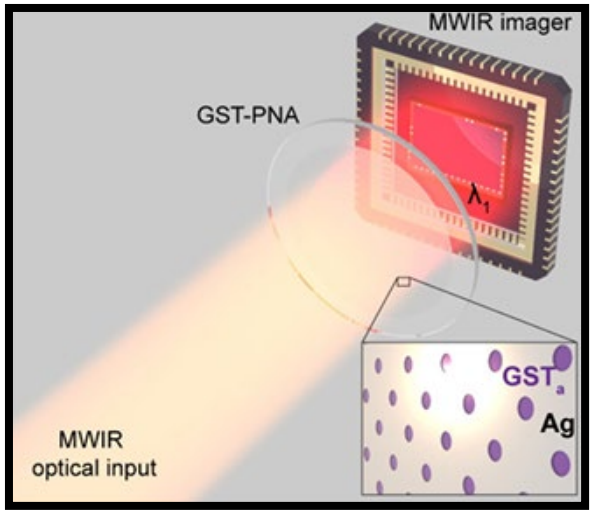


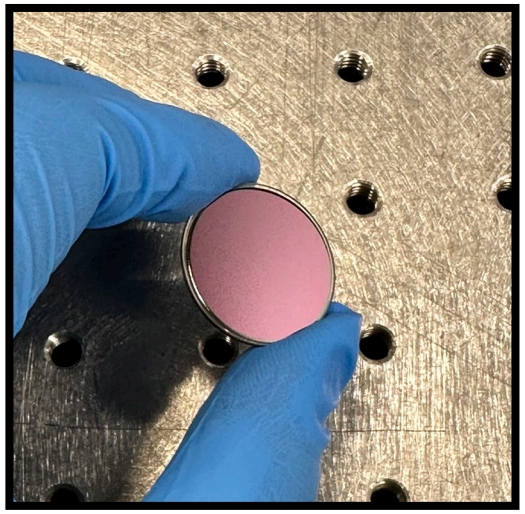
- ✓ Ultrafast (ns) switcing
- ✓ Tunable narrowband filtering
- ✓ Wide waveband coverage

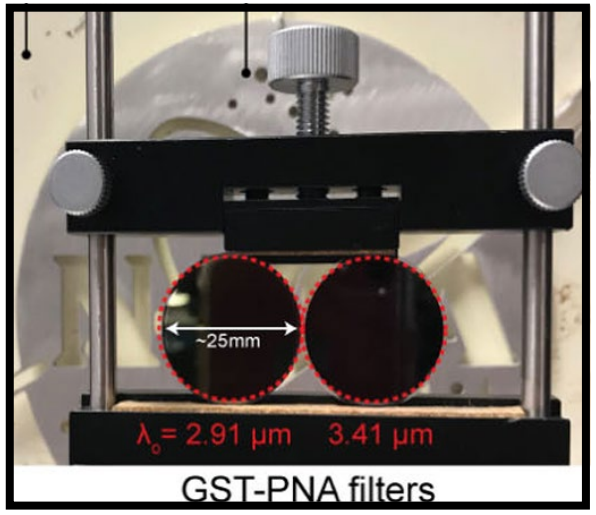


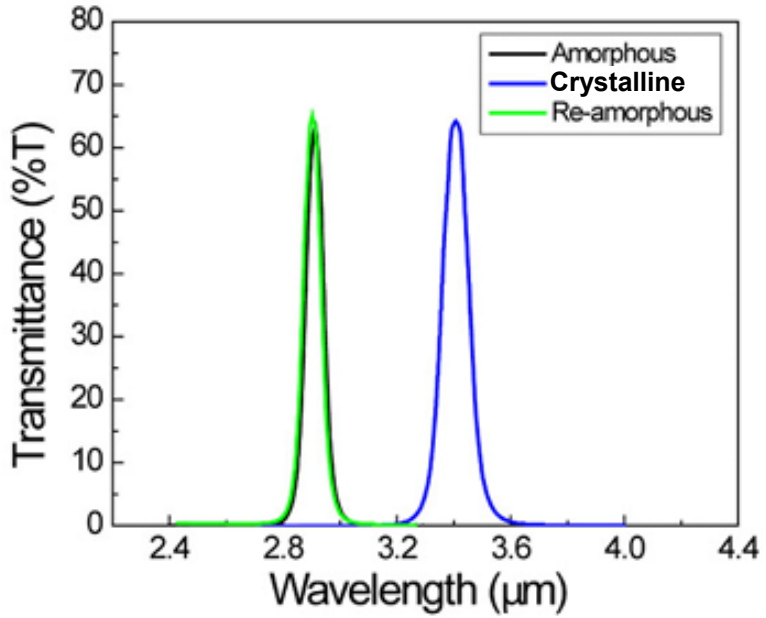
Reconfigurable Metafilter

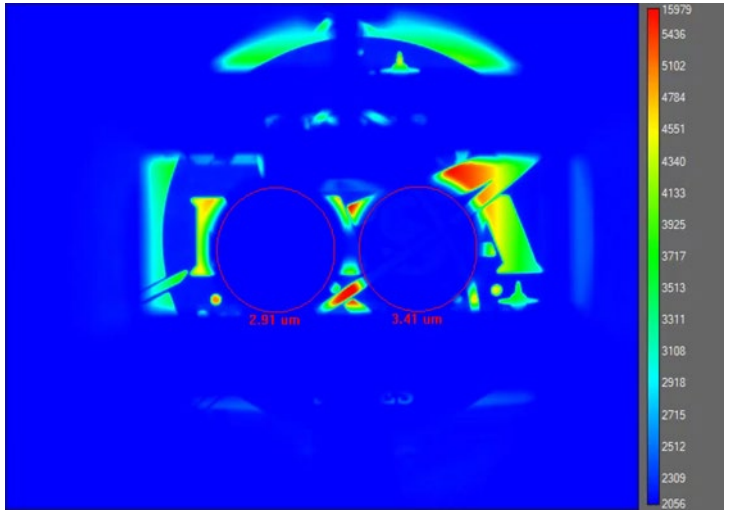


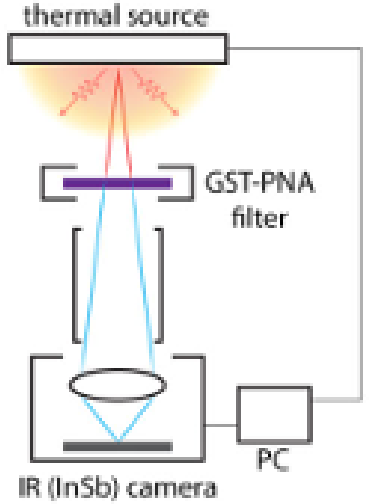






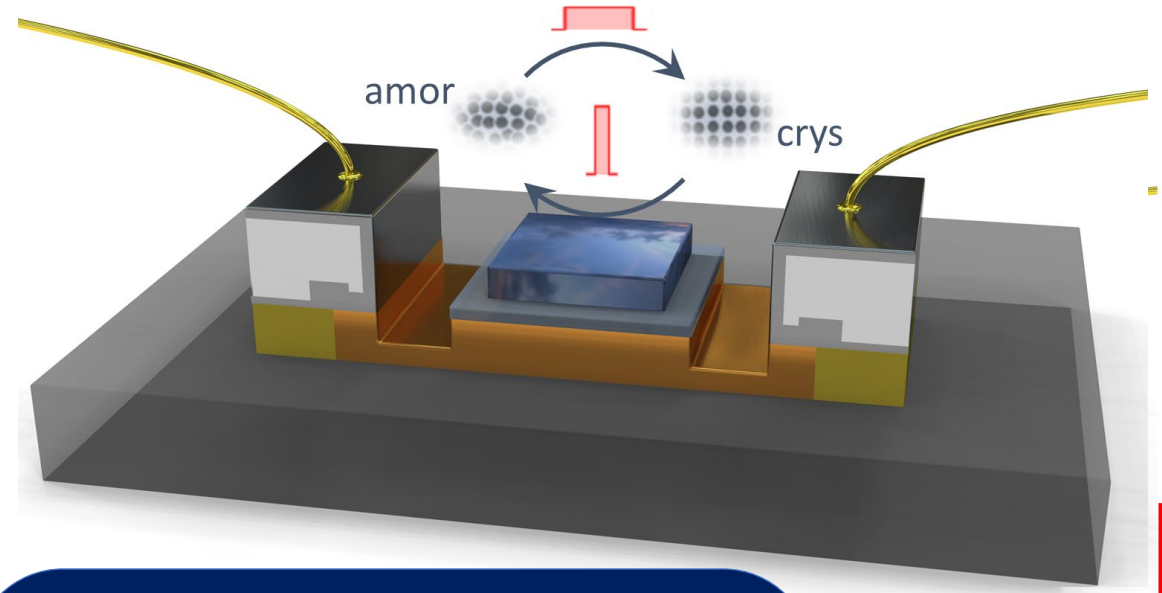




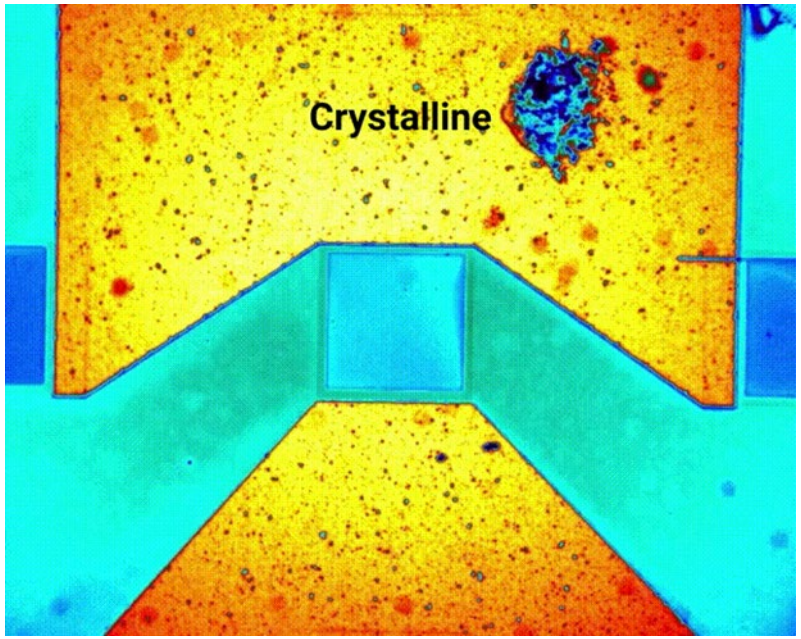


Julian et al. *Optica* 7.7 (2020): 746-754.

Electrode-based tuning mechanism for Metafilter

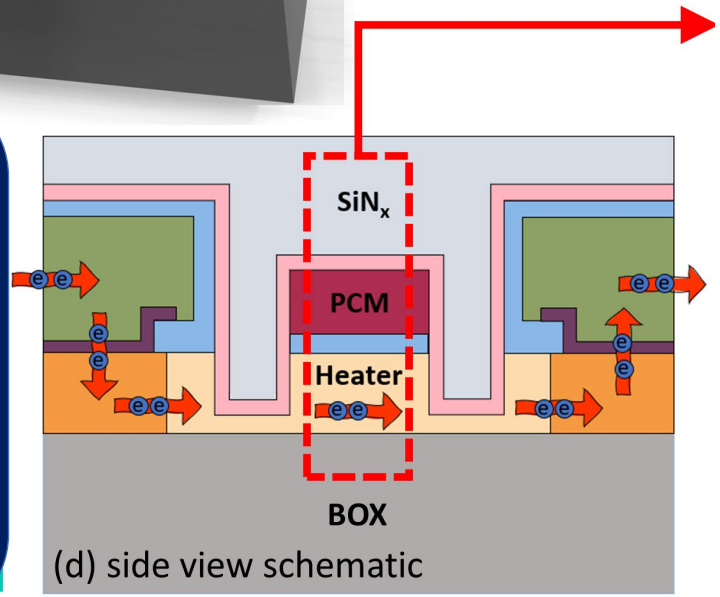


PCM switching volume: ~ 4,000 μm^3
100 million times larger than that in PCMemories!

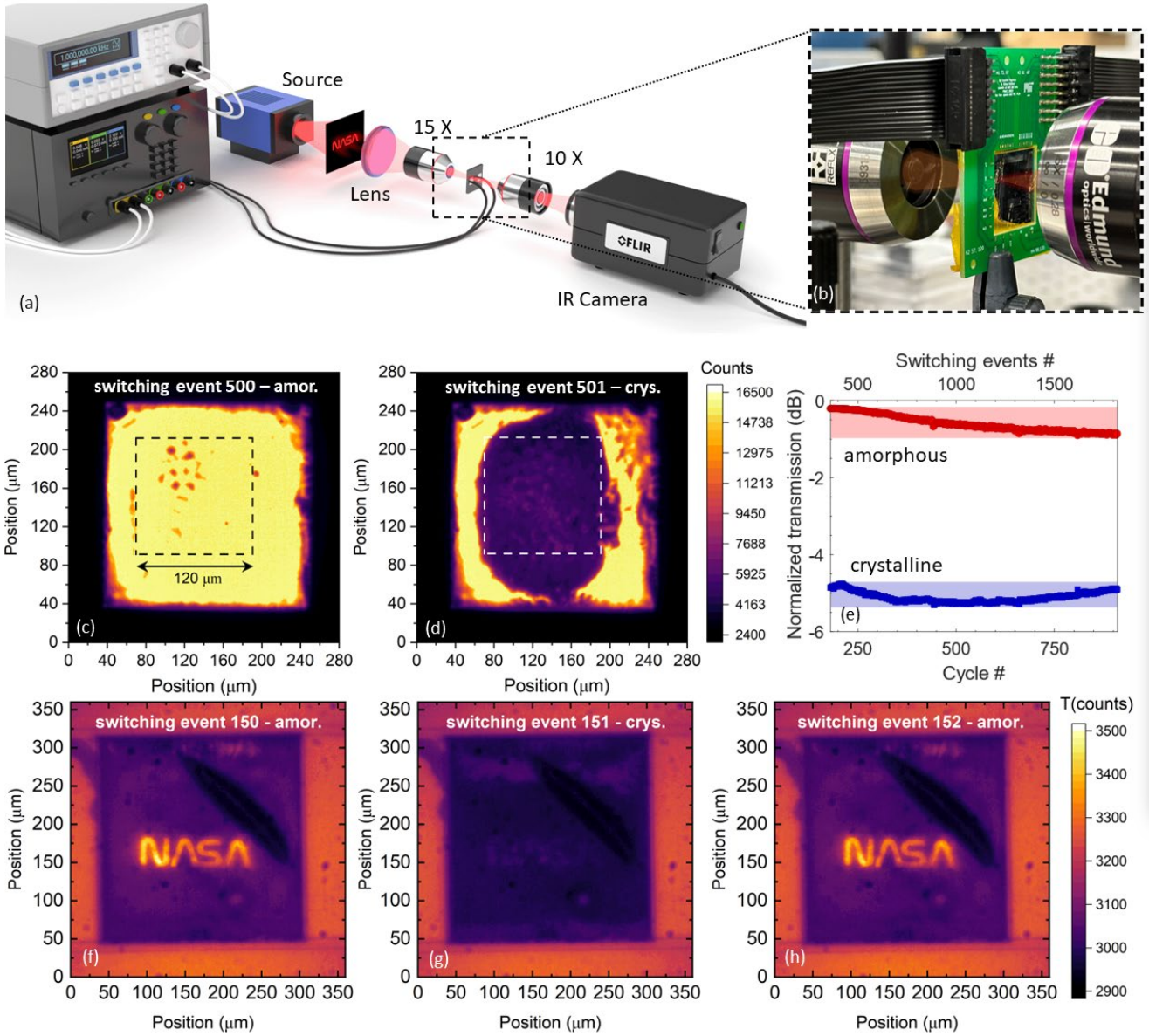


Large-area PCM switching with endurance of over **6 x 10^4** cycles

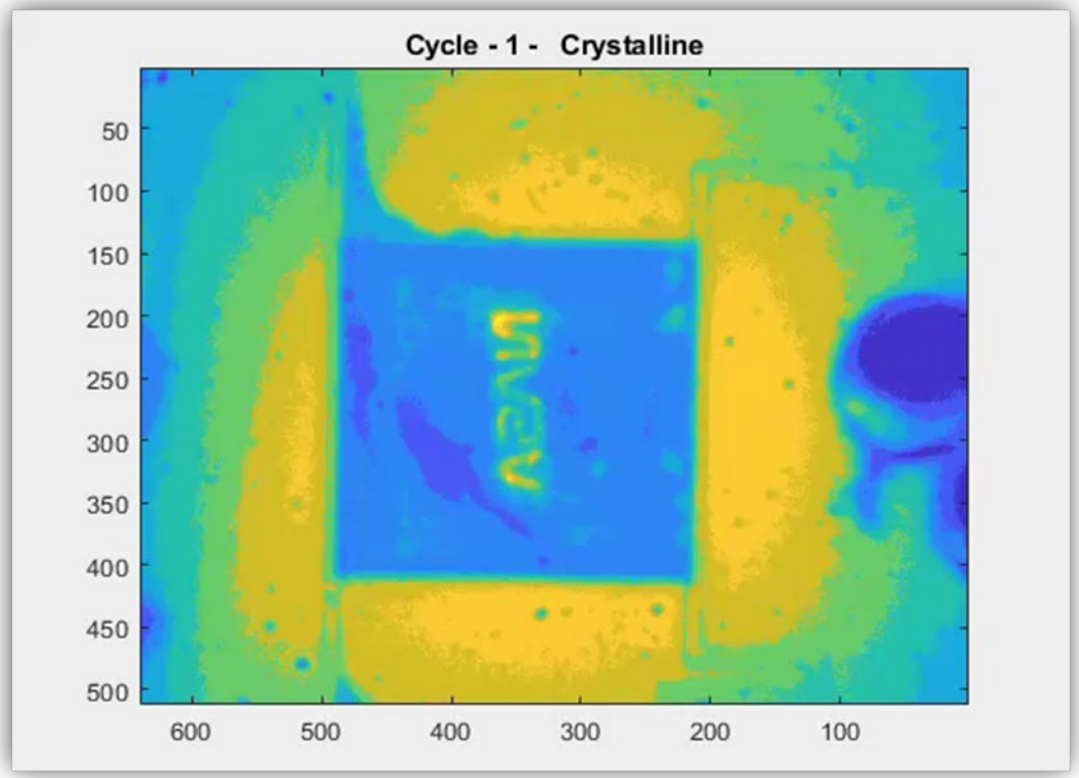
- ✓ Accurate thermal modeling (Aryana *et al.*, Small, 202304144, 2023)
- ✓ Failure mechanism evaluation (Popescu *et al.*, arXiv:2312.10468, 2023)
- ✓ Auto Control of Switching (Garud & Aryana *et al.,* In preparation (2024))



Demonstration of Metafilter

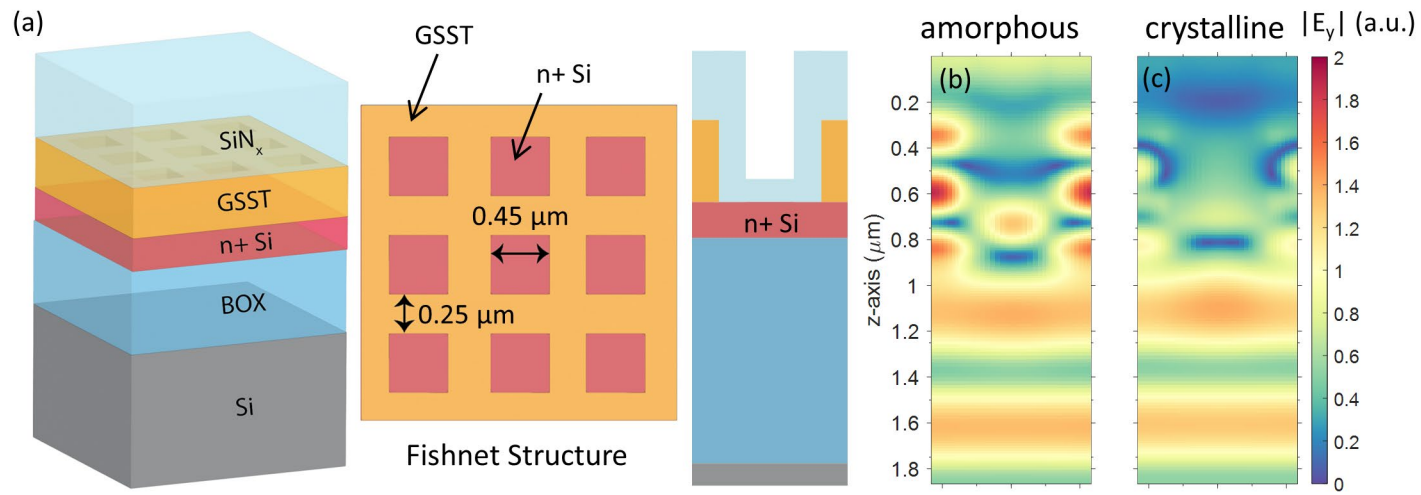


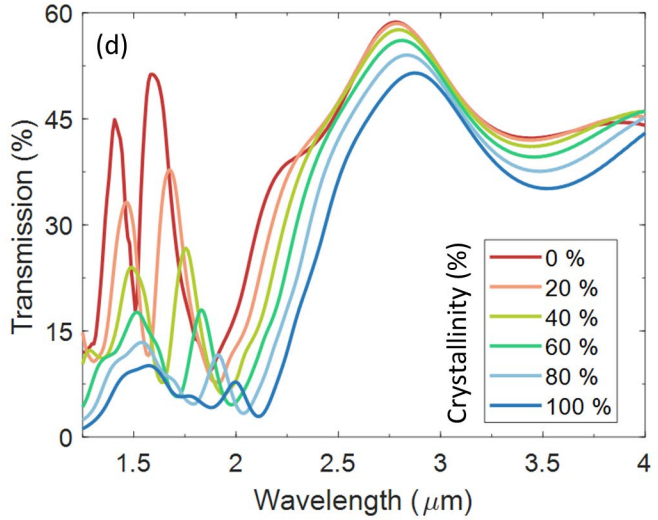
Popescu *et al.* under review, arXiv:2312.10468 (2023).

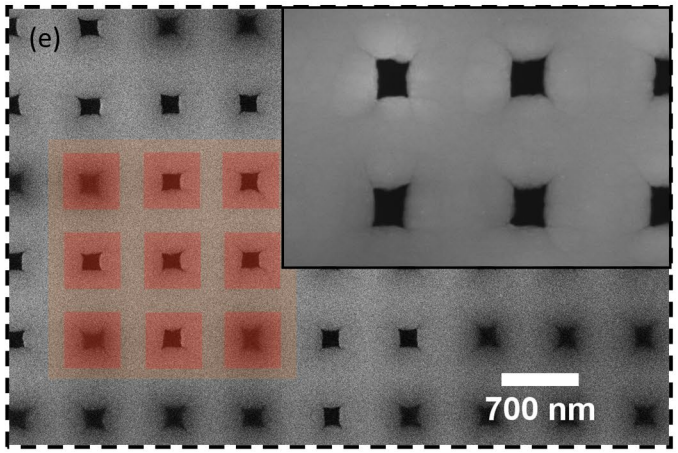


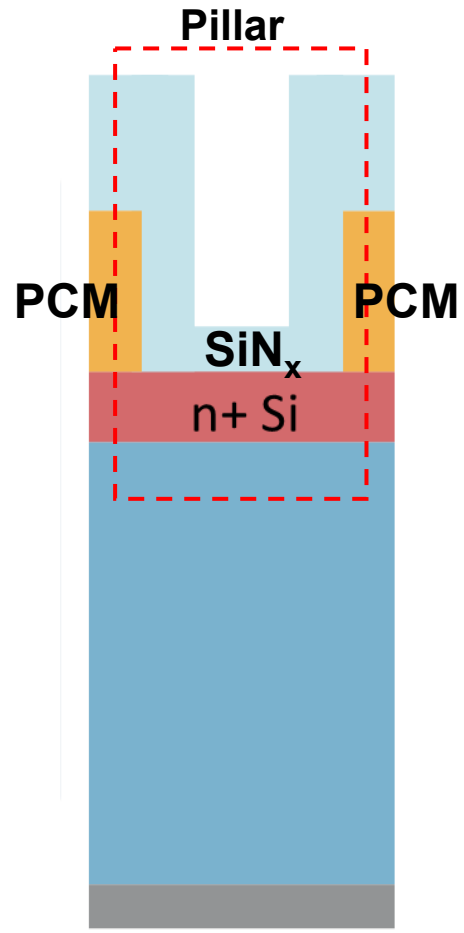
- 10 μs amorphization
- 1 s crystallization pulse

Design and fabrication of Metafilter





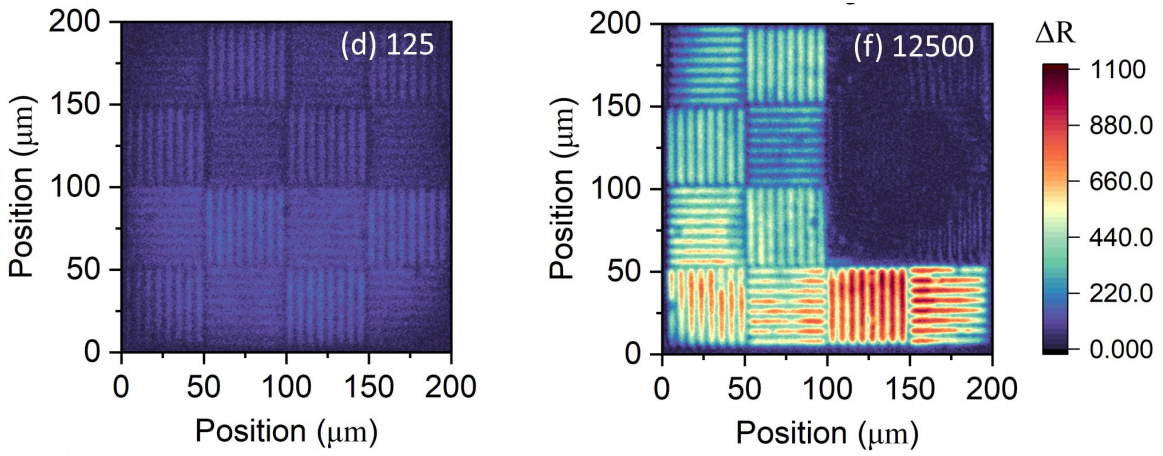




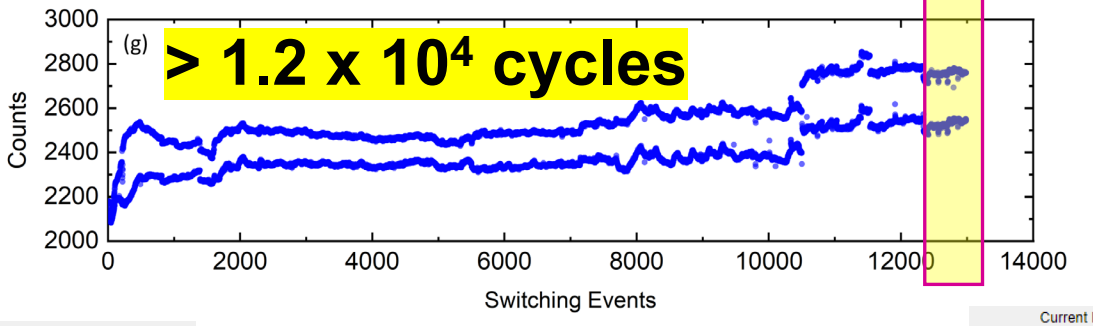
Pillar-shape structures would avoid propagation of damage

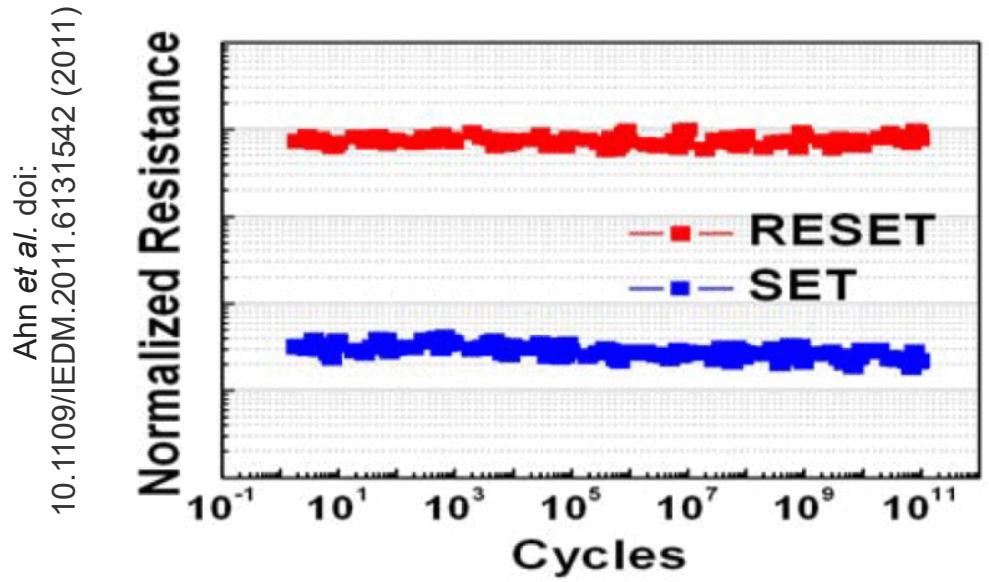
Popescu *et al.* under review, arXiv:2312.10468 (2023).

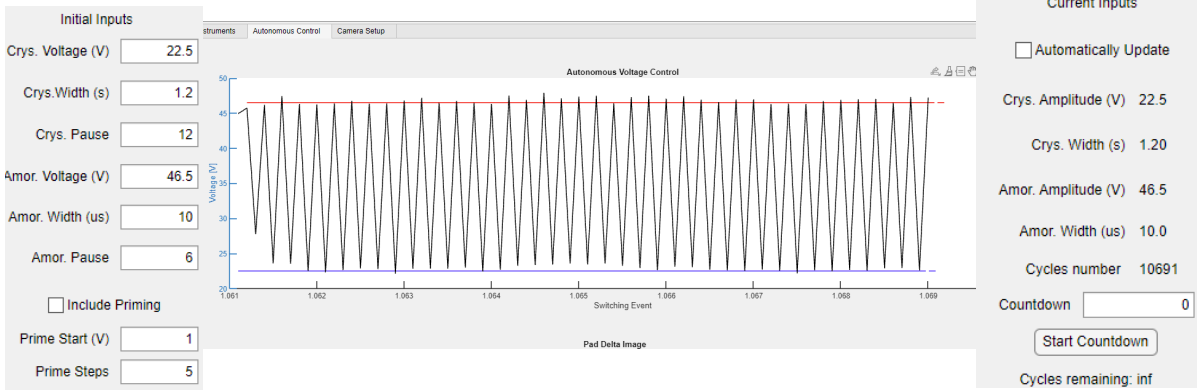
Robust electrothermal switching of Metafilter for longer reliability



Still the device is survived!







Mission specific trade study (LIDAR vs. Multispectral Imaging)

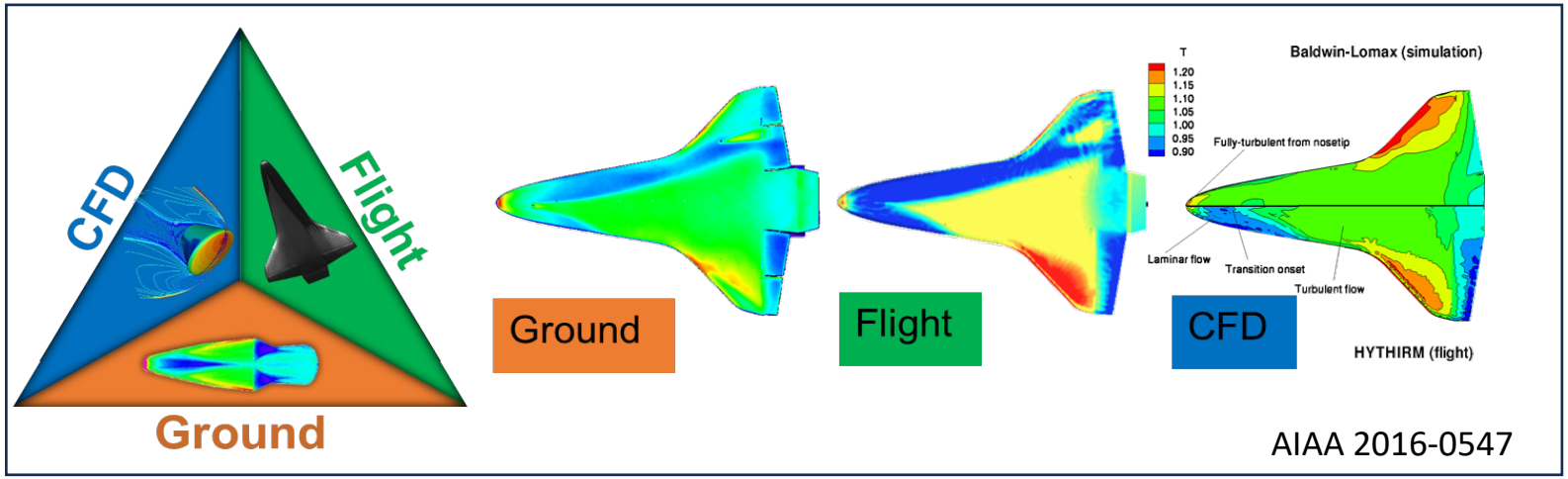
Decision criteria	SAGE IV	DIAL	SCIFLI
Non-volatile	S (Same)	S	S
Tuning speed (GHz)	S	+	+
Tuning range (800nm ~ 10μm)	-	S	S
Multiple wavelength tuning	+	S	+
10^7 tuning cycles	S	S	S
Max. 1nm FWHM	S	-	S
Space qualification (MISSE)	+	+	S
Sum of (+)	2	2	2
Sum of (-)	1	1	0
Sum of (Same)	4	4	5
Selected mission			
Most acceptable technology	**LC or acoustic optical tunable filter**	**Laser (on/off switch)**	**PCM-Metafilter**

Gu *et al.* Nat. Photon. **17**, 48–58 (2023).

- **Taking the Stratospheric Aerosol and Gas Experiment (SAGE IV) as an example, approximately 10^7 cycles are performed per year on orbit based on the estimation.**
  (The science observation events are a maximum length of 6 minutes, and the filter will be switched 5 times per second during the event.
  Normal low earth orbits are approximately 90 minutes long, and one science observation event will take place per orbit.)

Metafilter for SCIFLI project

NASA's Scientifically Calibrated In-Flight Imagery **(SCIFLI) team** obtains engineering datasets from spaceflight vehicles under actual flight conditions, providing the crucial bridge between wind-tunnel testing and computational aerothermal analyses.



AIAA 2016-0547

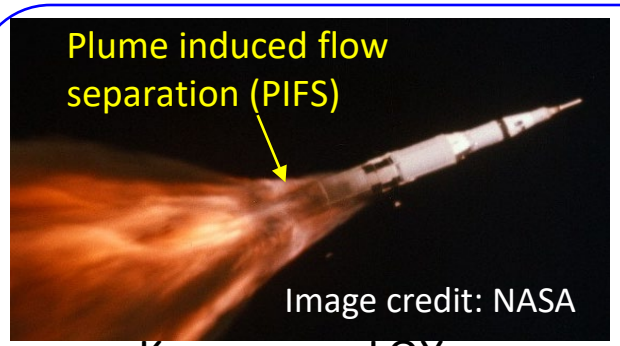


Necessary of Real-time Flight Data for our "Safety"

- **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

Apollo Saturn V



Kerosene + LOX

- Plume in VIS spectrum
- No temperature data

Artemis-I Program

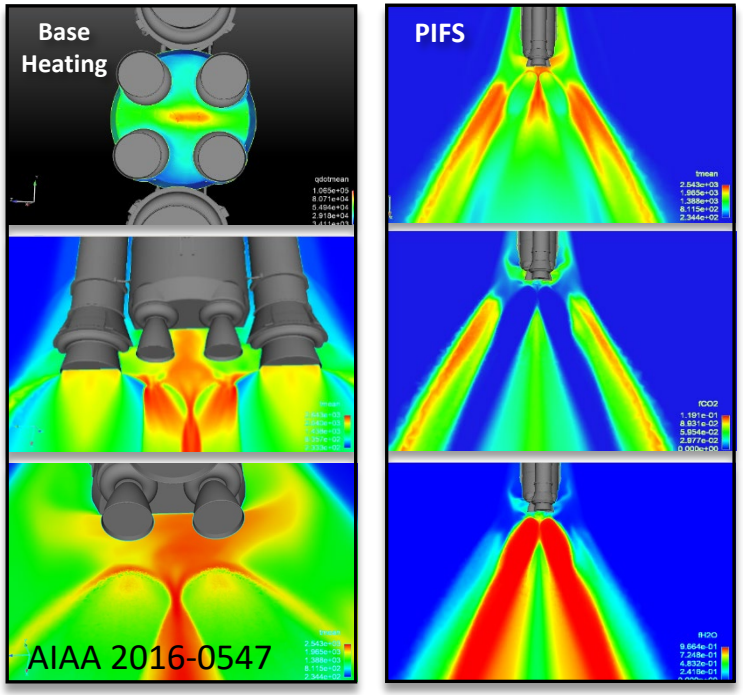


Hydrogen + LOX = H_2O

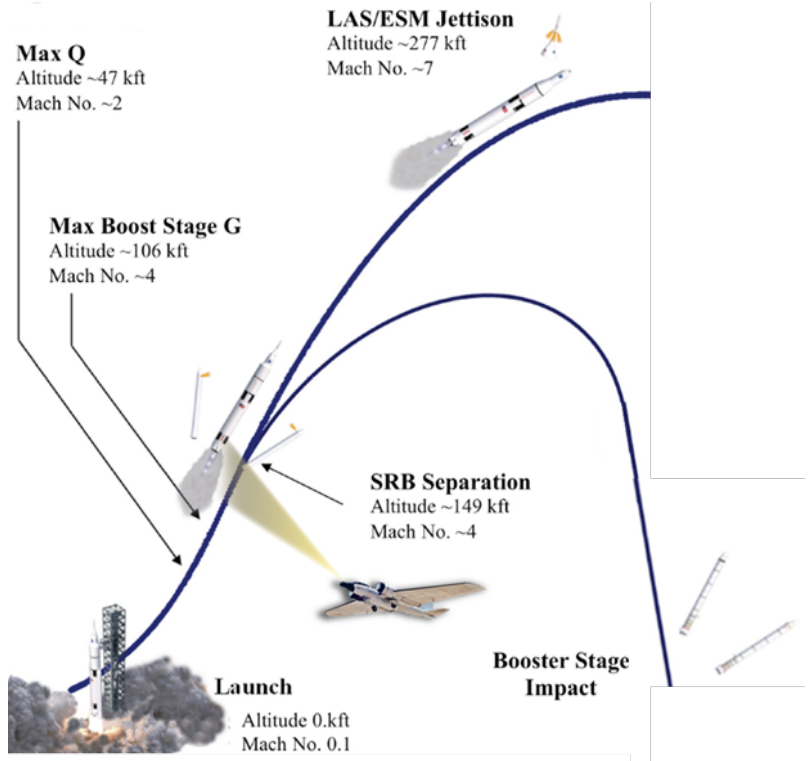
- Plume in MWIR spectrum
- Temperature retrieval possible

Goal:

- Collect calibrated temperature images of the base region of Space Launch System (SLS) core stage and exhaust plume dynamics during boost phase
- to validate / reduce required TPS mass for future flights – increased payload



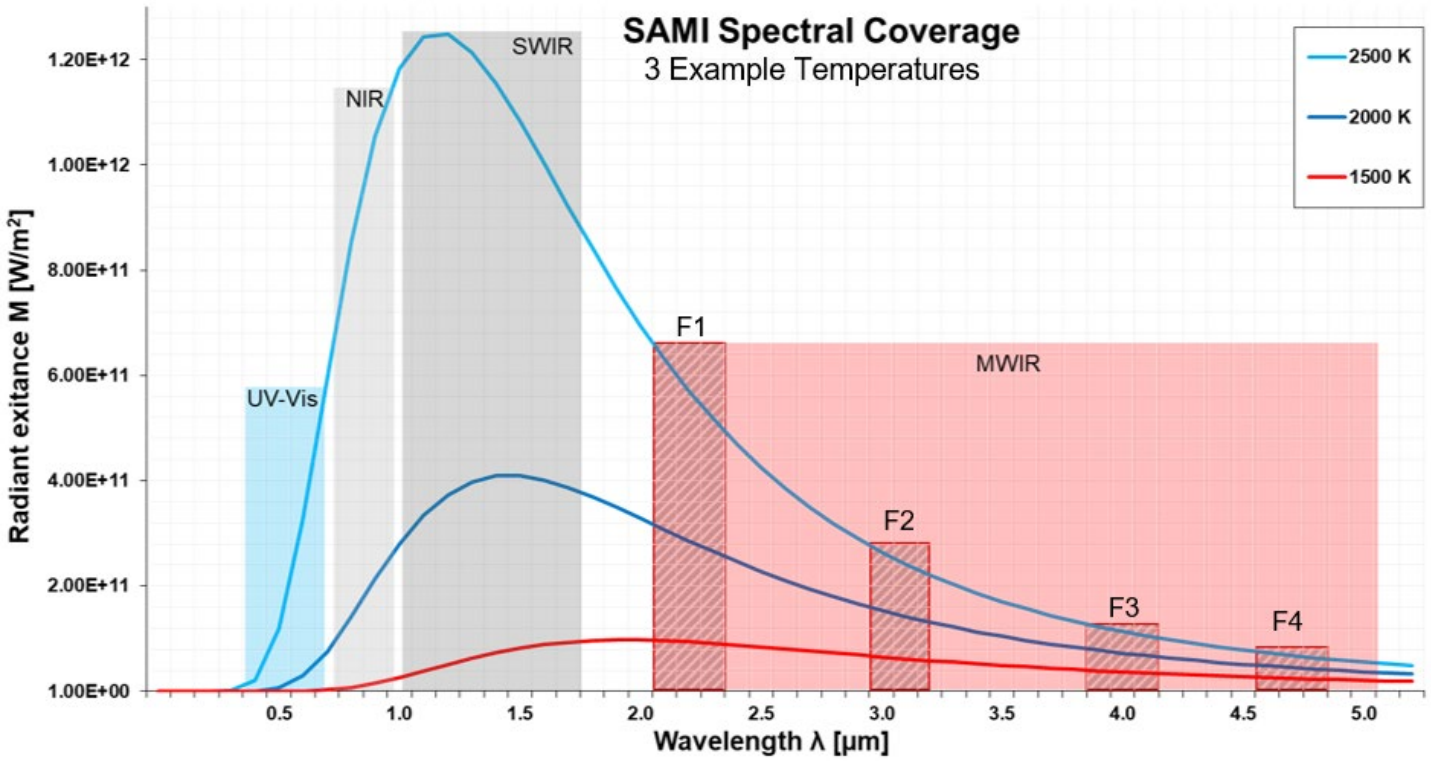
Predictions of Plume Structure & Heating in Base Region



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

Born of SCIFLI Airborne Multispectral Imager (SAMI)

Multispectral (visible – MWIR) Imager will allow for observation of plume features and hardbody thermal signatures with **“high spatial resolution”**, and **low uncertainty in temperature retrieval**.



SCIFLI Airborne Multispectral Imager (SAMI)

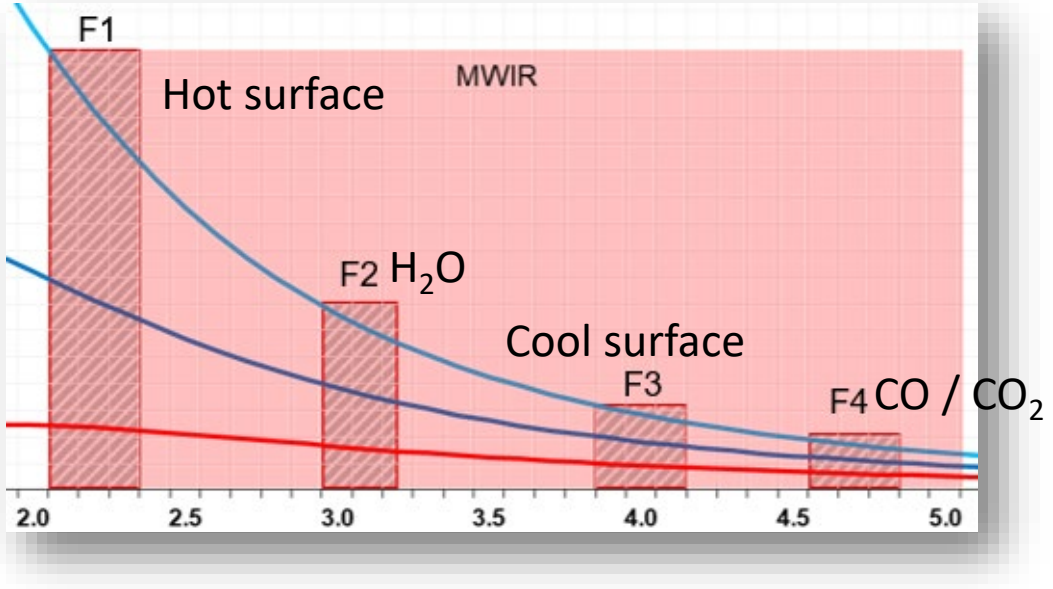
SCIFLI AIRBORNE MULTISPECTRAL IMAGER

A customizable & cost-effective aircraft-agnostic multispectral imaging testbed



Key Capabilities

- **Multiple sensors + high speed filter wheel**
- **Broadband (2-5 µm) MWIR for PIFS imaging**
- **High temp core stage surface data available at 2 µm**



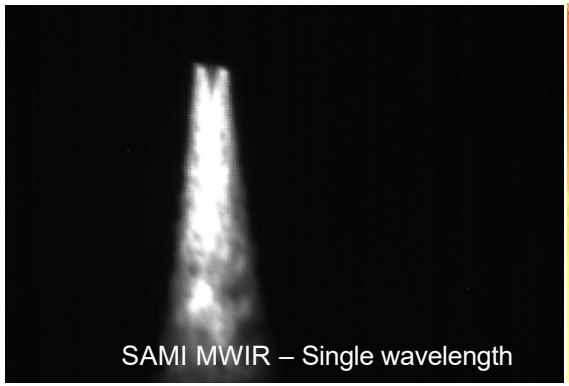
Metafilter for SAMI

Key Lesson Learned

- Several factors influenced the imaging performance and data quality during the observation (i.e., night observation & scattering)
- Non optimal sensor setting in substandard imagery in MWIR wavebands

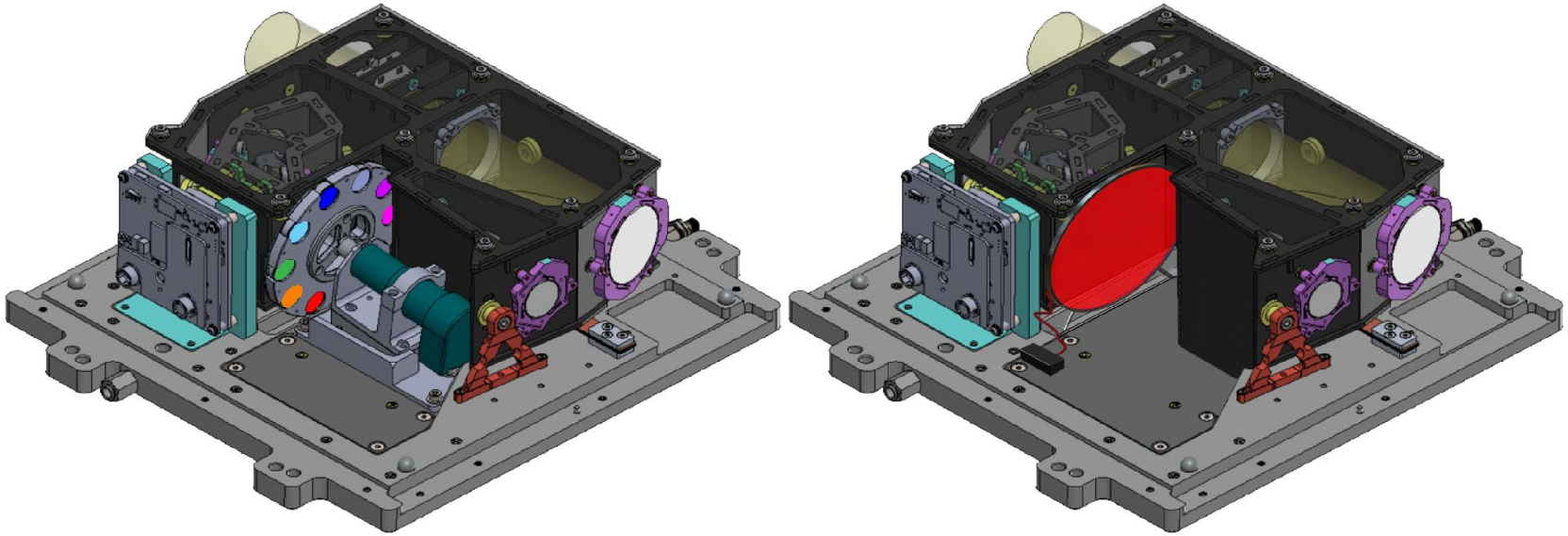
Technical Challenges

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


SAMI MWIR – Single wavelength


SAMI Visible – Ghosting image

Scott *et al.*, "The SCIFLI Airborne Observation of Artemis-I Ascent" talk at TFAWS (2023)



HDRi for multi-spectral imaging pyrometer
NASA Tech Briefs (Highlights in February 2024)

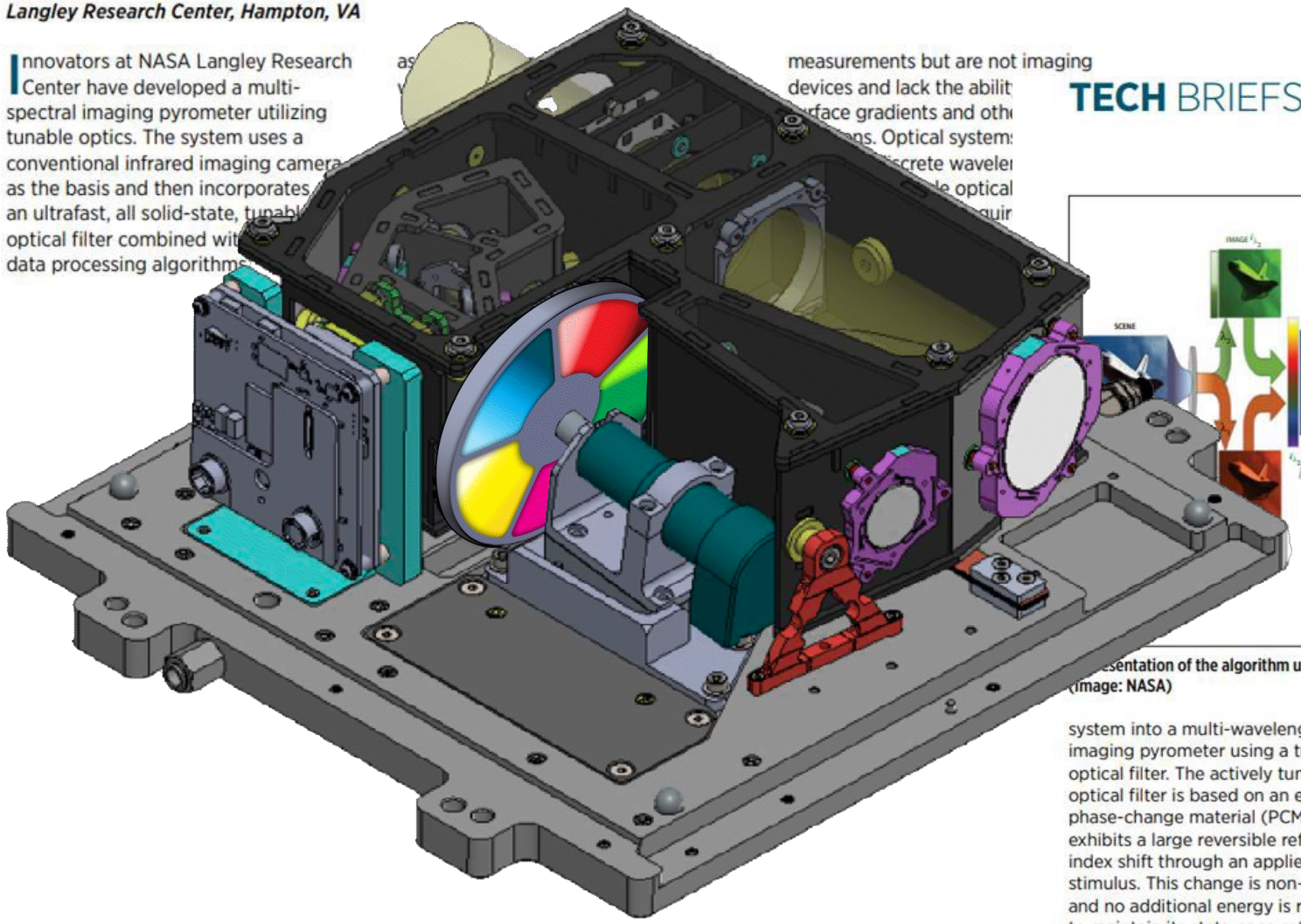
- 10^7 reliability
- 1” diameter
- micro-seconds tuning speed

Multi-Spectral Imaging Pyrometer

A solid-state broadband infrared imaging system with high dynamic range.

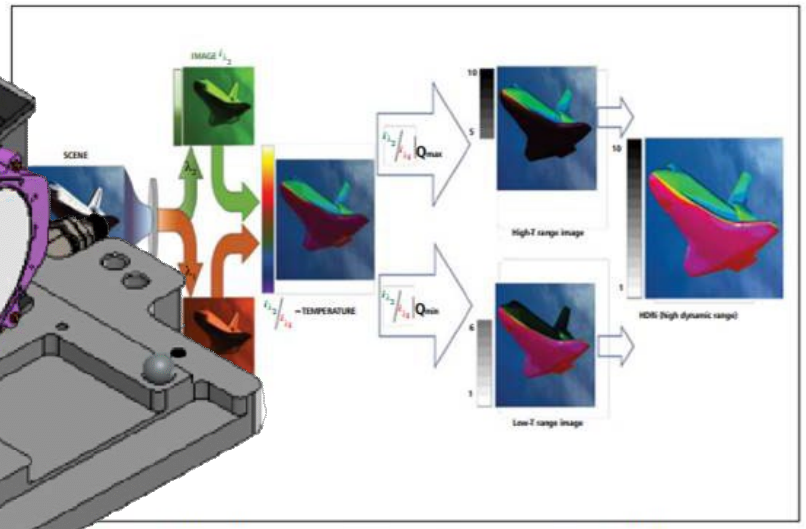
Langley Research Center, Hampton, VA

Innovators at NASA Langley Research Center have developed a multi-spectral imaging pyrometer utilizing tunable optics. The system uses a conventional infrared imaging camera as the basis and then incorporates an ultrafast, all solid-state, tunabl optical filter combined wit data processing algorithms



measurements but are not imaging devices and lack the abilit rface gradients and oth ns. Optical system screte wavele le optical quir

TECH BRIEFS



esentation of the algorithm used to create a high dynamic range infrared (HDRi) image. (Image: NASA)

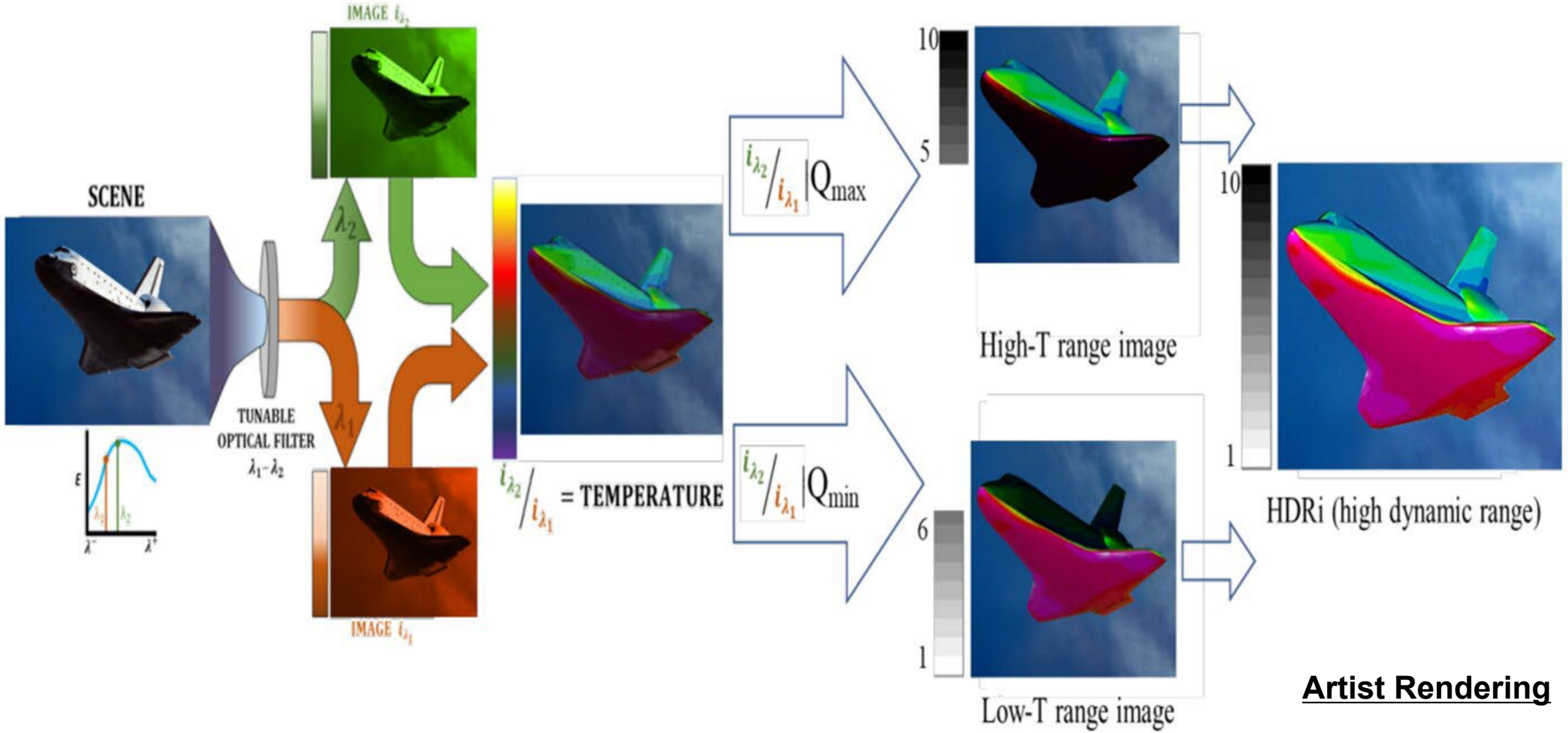
system into a multi-wavelength imaging pyrometer using a tunable optical filter. The actively tunable optical filter is based on an exotic phase-change material (PCM), which exhibits a large reversible refractive index shift through an applied energetic stimulus. This change is non-volatile, and no additional energy is required to maintain its state once set.

The filter is placed between the scene and the imaging sensor and switched between user-selected center-wavelengths to create a series of single-wavelength, monochromatic, two-dimensional images. At the pixel level, the intensity values of these monochromatic images represent the wavelength-dependent, blackbody energy emitted by the object due to its temperature. Ratioing the measured spectral irradiance for each wavelength yields emissivity-independent temperature data at each pixel.

The filters Center Wavelength (CWL) and Full Width Half Maximum (FWHM), which are related to the quality factor (Q) of the filter, are actively tunable on the order of nanoseconds-microseconds (GHz-MHz). This behavior is electronically controlled and can be operated time-sequentially (on a nanosecond time scale) in the control electronics, a capability not possible with conventional optical filtering technologies.

The technology has applications in aerospace: imaging and analysis of rocket plumes, combusting flows, and heat shields; metals manufacturing: process monitoring the melting of metallic ores in mixed states or the formation of surface slag; welding: accurate imaging of weld pool temperatures; and kiln processing: process monitoring in cement kilns.

NASA is actively seeking licensees to commercialize this technology. Please contact Licensing Concierge at Agency-Patent-Licensing@mail.nasa.gov or call at 202-358-7432 to initiate licensing discussions. For more information, visit https://technology.nasa.gov/patent/LAR-TOPS-362. ■



Artist Rendering

A flowchart for generating a high dynamic range image in accordance with an exemplary embodiment of the technology.
S. Borg and H.J. Kim, US patent US20230336846A1 (2023)

P-ACTIVE for **SCIFLI Airborne Multispectral Imager (SAMI)**

Extra information

Temporal

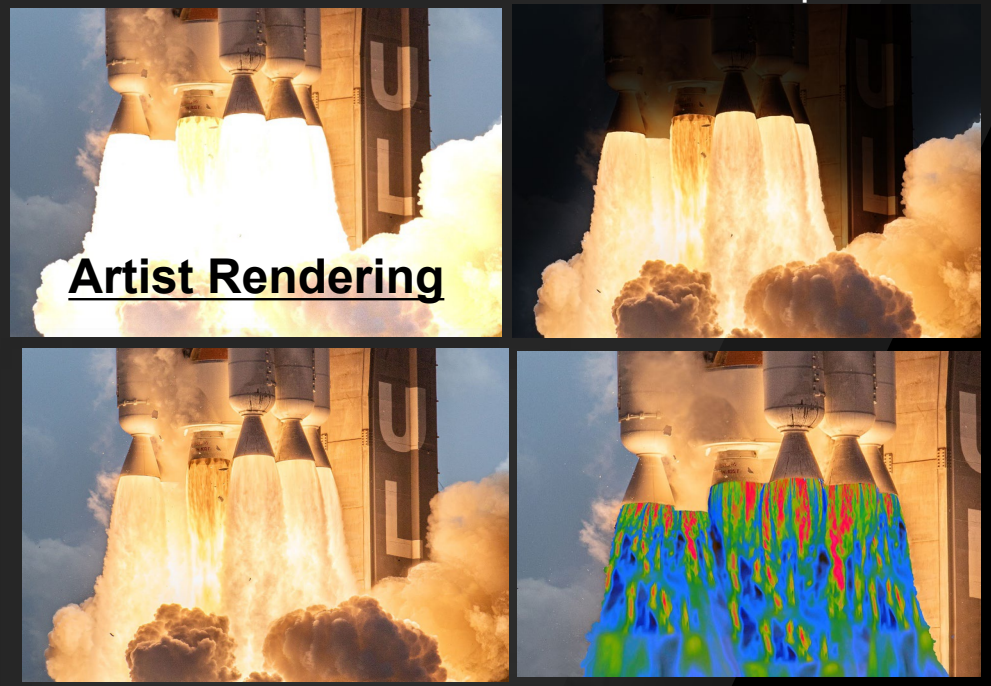
Spectral resolution

Accuracy improvement

Independent emissivity

Image detail improvement

Dynamic range improvement

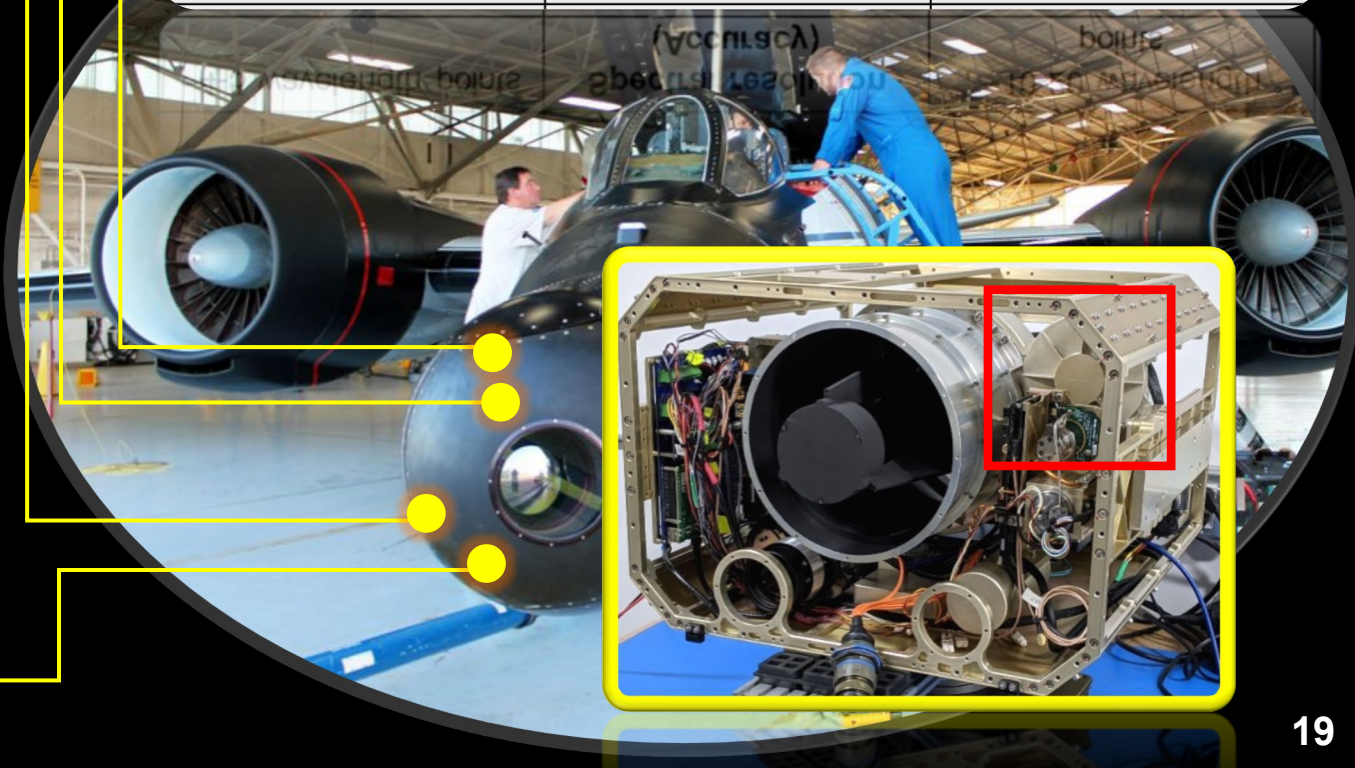


New aircraft opportunity

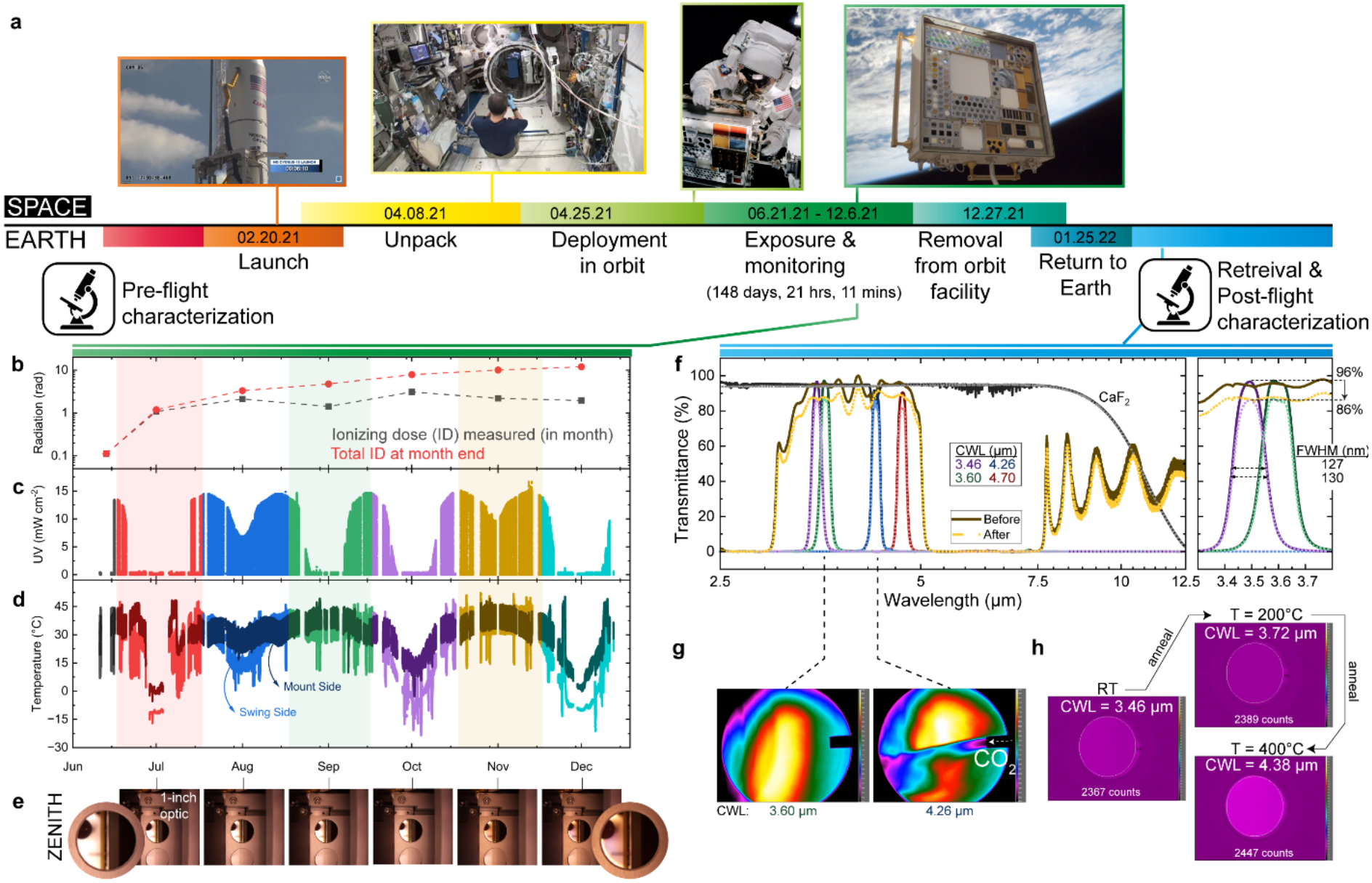
Smaller space

SWaP-C benefits

Filter wheel		PCM-based Metafilter
800g	**Weight**	10g
725cm^3	**Volume**	0.253cm^3
15W to power motor	**Power**	~mW average power to tune filter
10s of milliseconds (< kHz imaging)	**Temporal resolution (Speed)**	10s of nanoseconds (GHz imaging)
~4-5 wavelength points	**Spectral resolution (Accuracy)**	~10-20 wavelength points

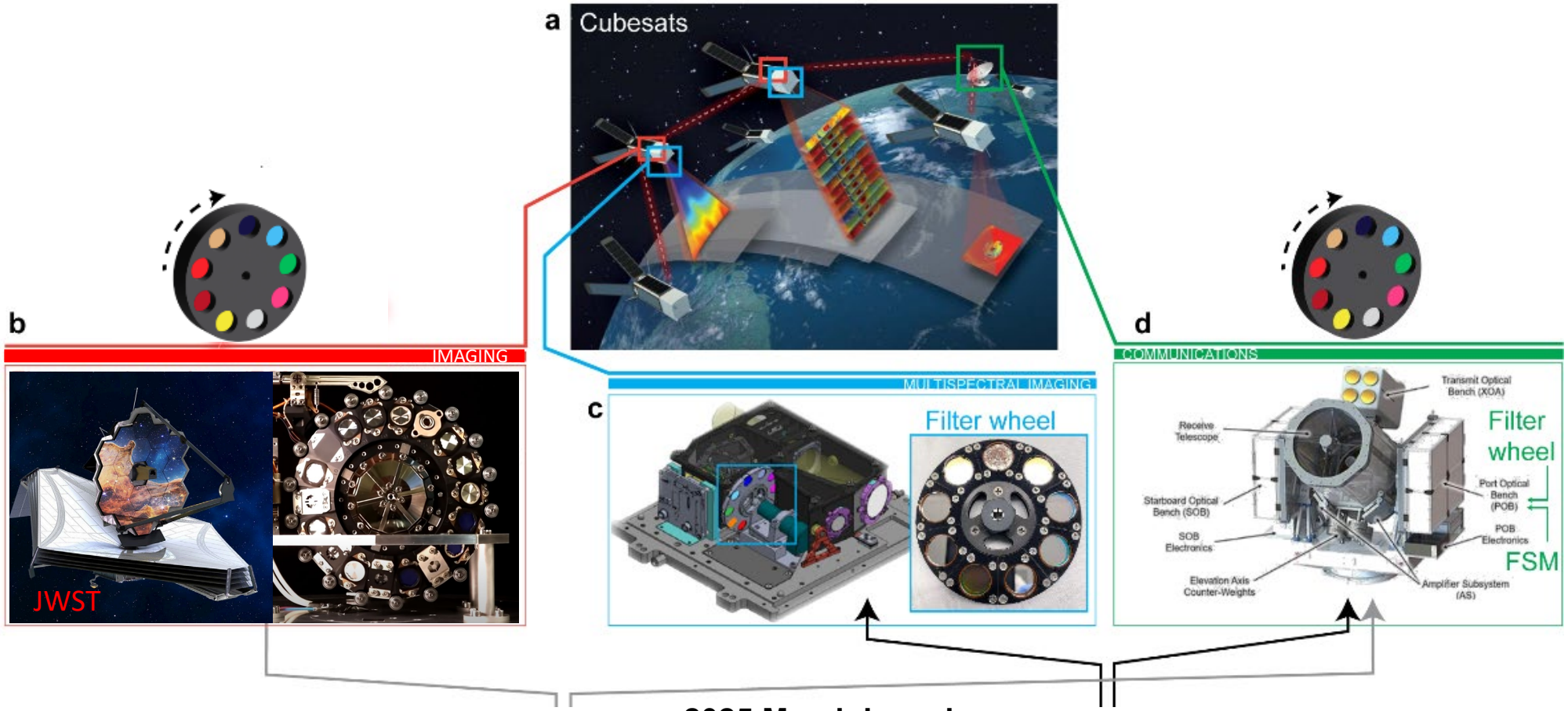


MISSE-14 mission (2021 – 2022)



Kim *et al.* npj Microgravity **10**(1), 20 (2024)

Metafiler for Spaceborn Remote Sensing



Kim *et al.* npj Microgravity **10**(1), 20 (2024)

2025 March launch

MISSE Materials International Space Station Experiment

Electrically reconfigurable metafilter

MISSE-21 Experiment Summary Chart

Principal Investigator (PI): Hyun Jung Kim (LaRC)
Primary Collaborators: Prof. Juejun Hu (MIT)

Teams

NASA LaRC R&D Team

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