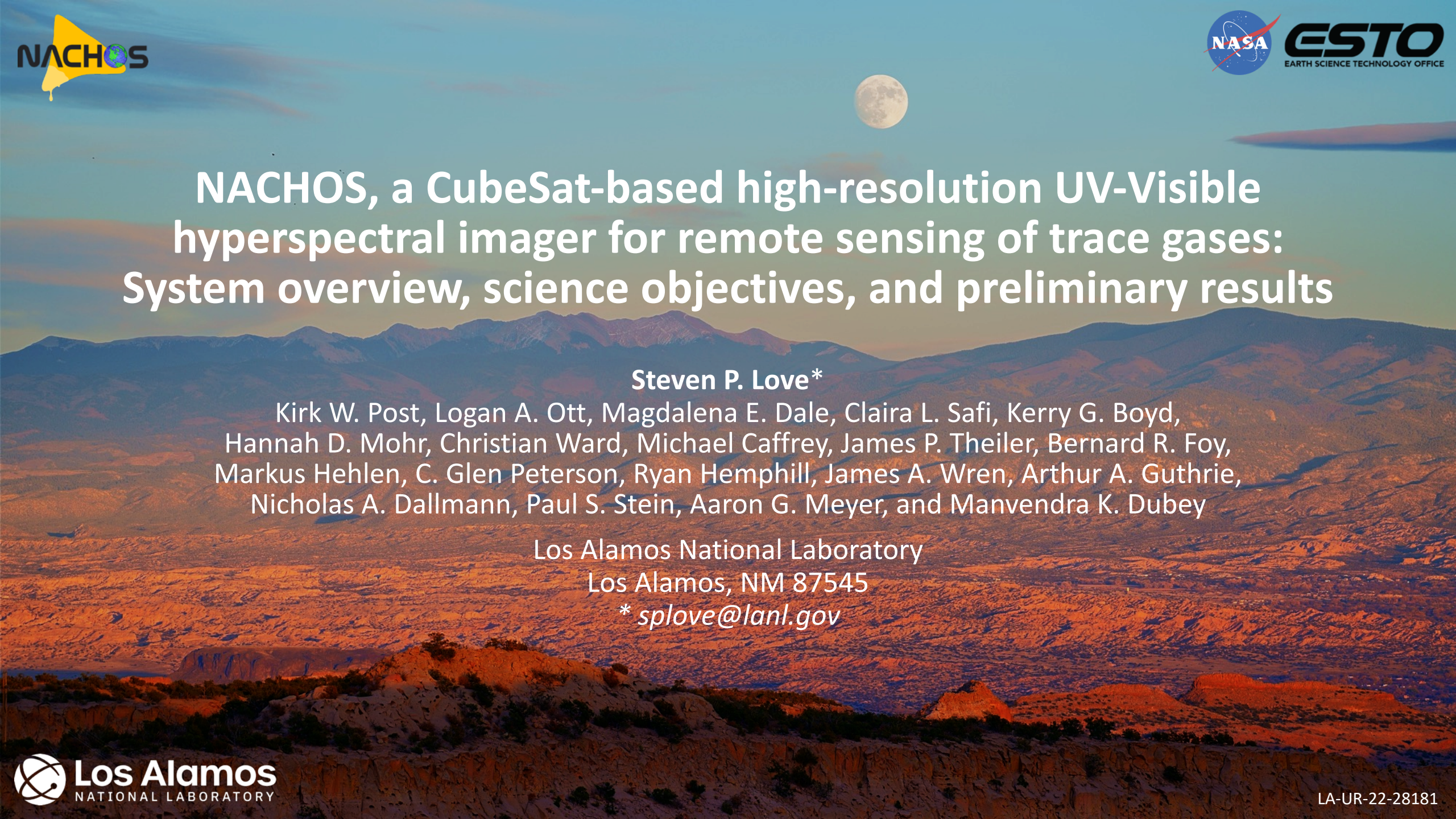

NACHOS, a CubeSat-based high-resolution UV-Visible hyperspectral imager for remote sensing of trace gases: System overview, science objectives, and preliminary results

Steven P. Love*

Kirk W. Post, Logan A. Ott, Magdalena E. Dale, Claira L. Safi, Kerry G. Boyd, Hannah D. Mohr, Christian Ward, Michael Caffrey, James P. Theiler, Bernard R. Foy, Markus Hehlen, C. Glen Peterson, Ryan Hemphill, James A. Wren, Arthur A. Guthrie, Nicholas A. Dallmann, Paul S. Stein, Aaron G. Meyer, and Manvendra K. Dubey

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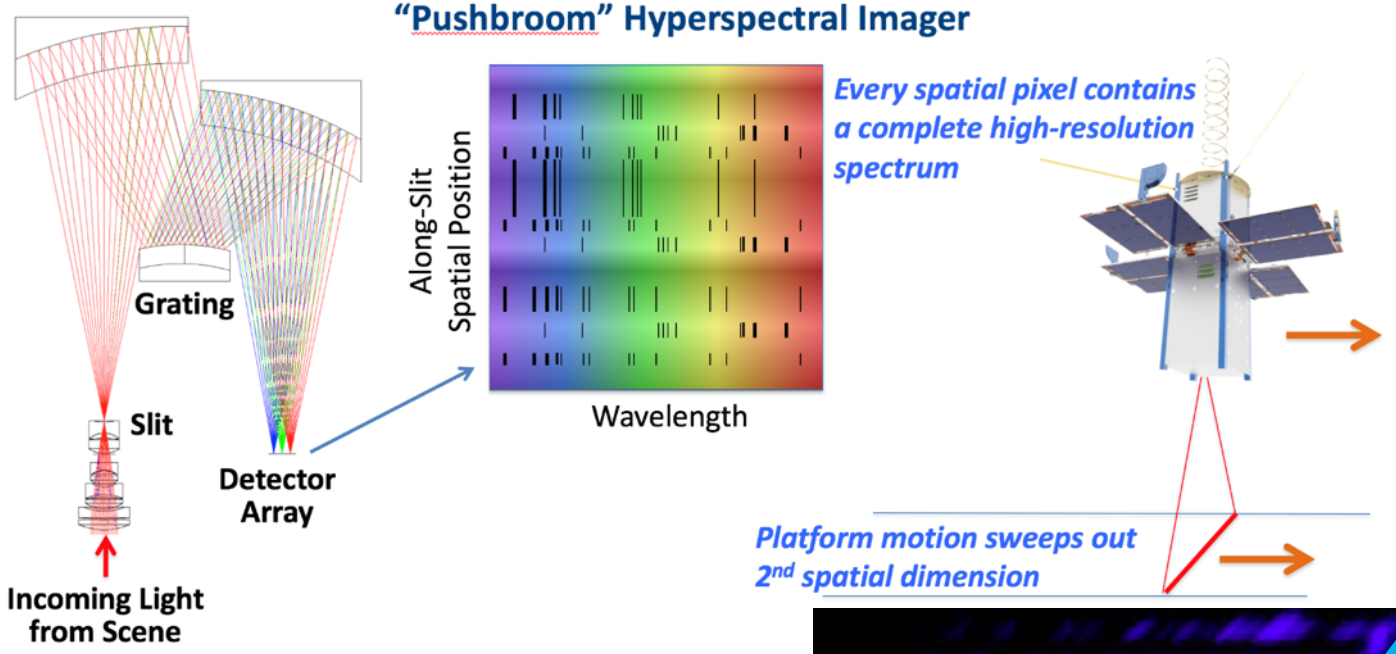
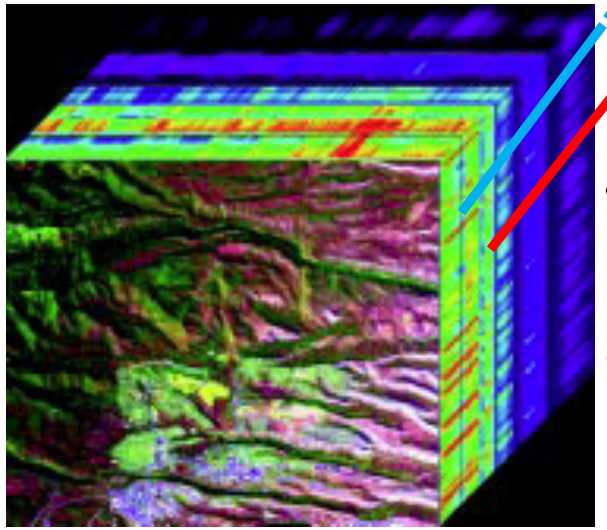
LA-UR-22-28181

NACHOS:
NanoSat Atmospheric Chemistry Hyperspectral Observation System

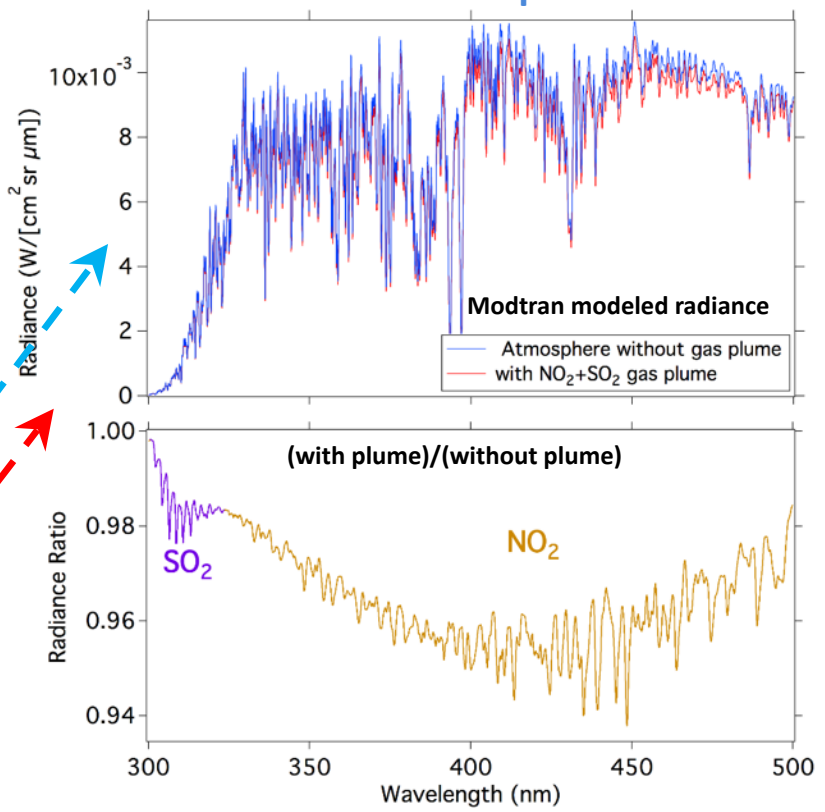
Hyperspectral Imaging: Each pixel contains a high-resolution spectrum





Hyperspectral Data Cube (~400 MB):

Individual Pixel Spectra



- Ground materials: mineralogy, vegetation, etc.
  - Relatively easy; requires only modest spectral resolution and sensitivity.

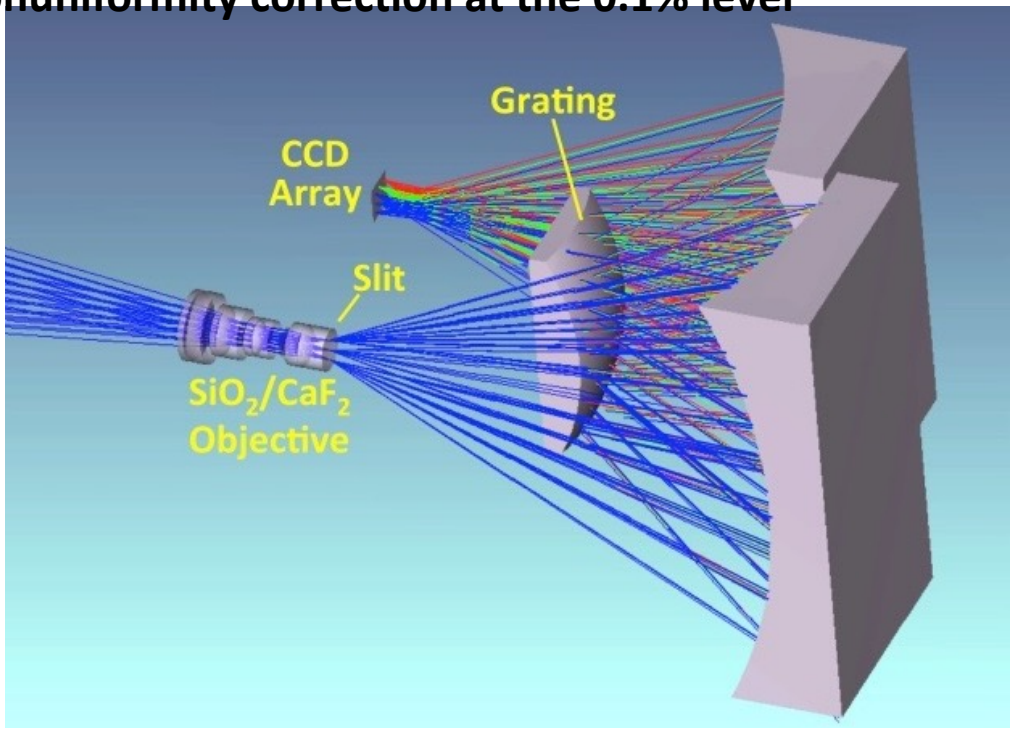
→ **Atmospheric trace gases**

- Requires much higher spectral resolution and sensitivity. Traditionally has required a big, expensive, large-satellite instrument.

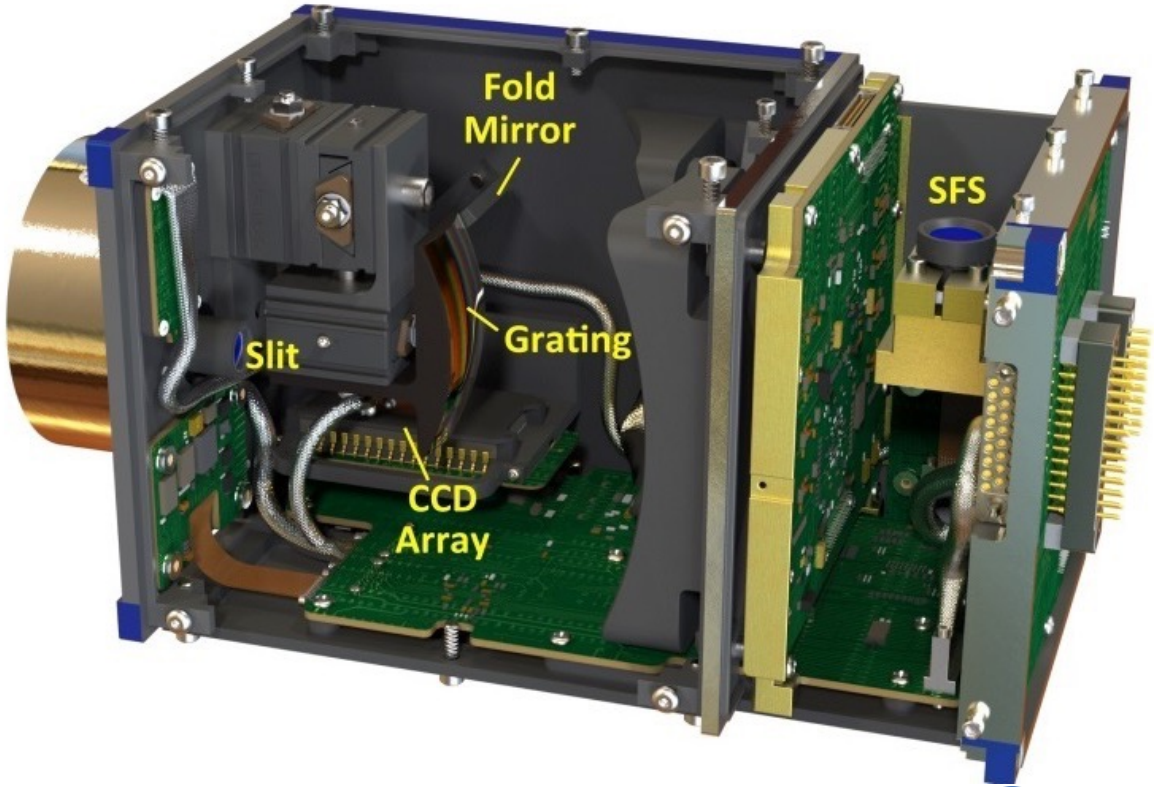
Challenge: Miniaturization to CubeSat scale while maintaining performance

NACHOS Hyperspectral Payload

- Offner-type hyperspectral imager with f/2.9 optics (high throughput)
- High-efficiency ruled, blazed grating (custom fabricated by Bach Research)
- Teledyne/e2v UV-optimized CCD array, 70% QE: (updated version of array used in New Horizons LORRI instrument)
- Internal LED-based on-board calibration system provides CCD nonuniformity correction at the 0.1% level



Spectrometer & Electronics comprise a 1.5U+ package

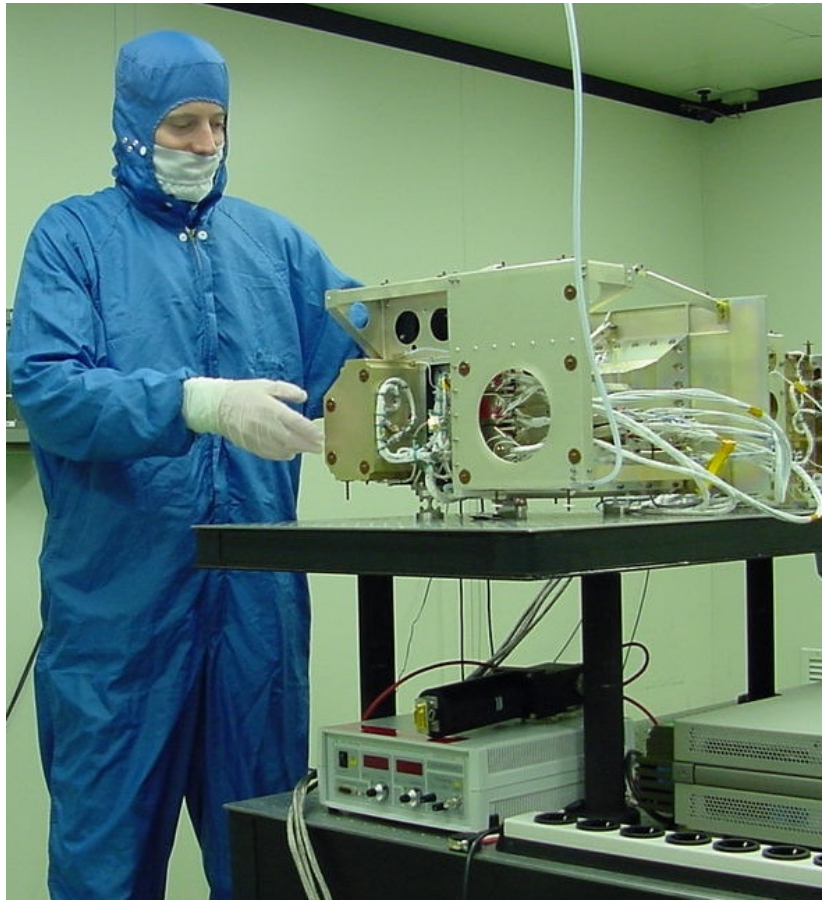


Goal is to produce a trace-gas hyperspectral imaging capability on a CubeSat platform, with eventual multi-satellite constellations

NACHOS

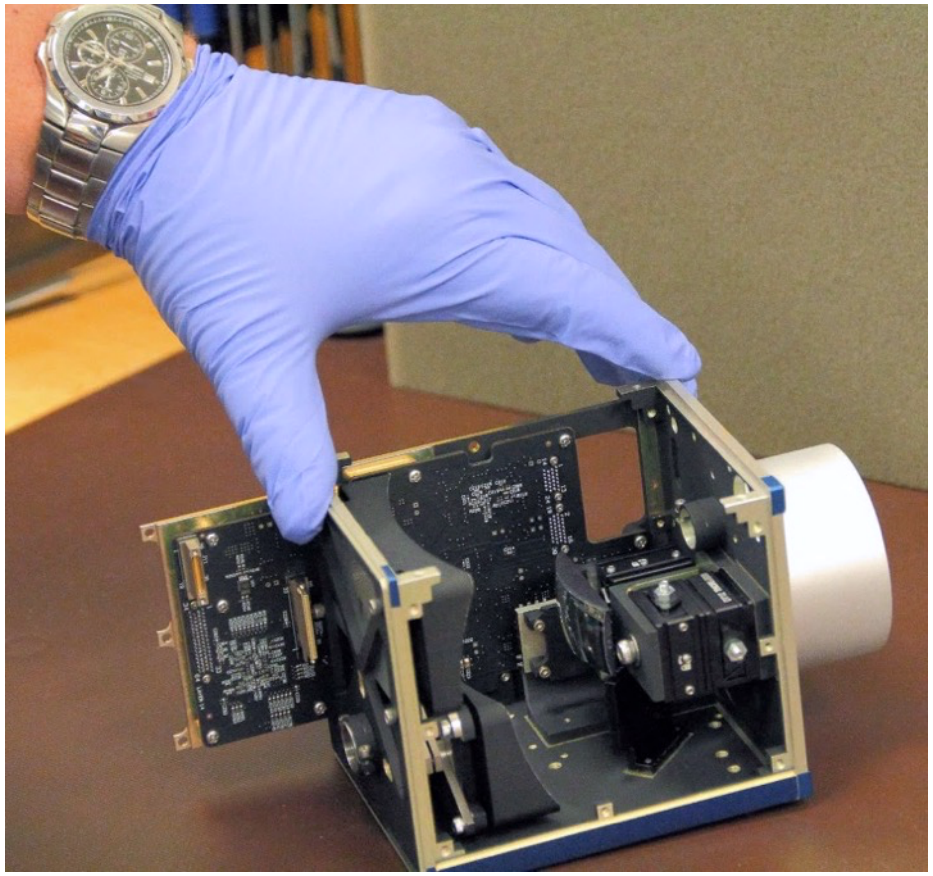
NASA Ozone Monitoring Instrument (OMI)

- 270-500 nm, 0.5-1.0 nm resolution
- 65 kg (instrument only)
- 50x40x35 cm^3



NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

- 290-500 nm, 1.3 nm resolution, 0.6 nm sampling
- 4 kg (complete satellite)*
- 10x10x15 cm^3 (1.5U instrument); 10x10x30 cm^3 (3U CubeSat)



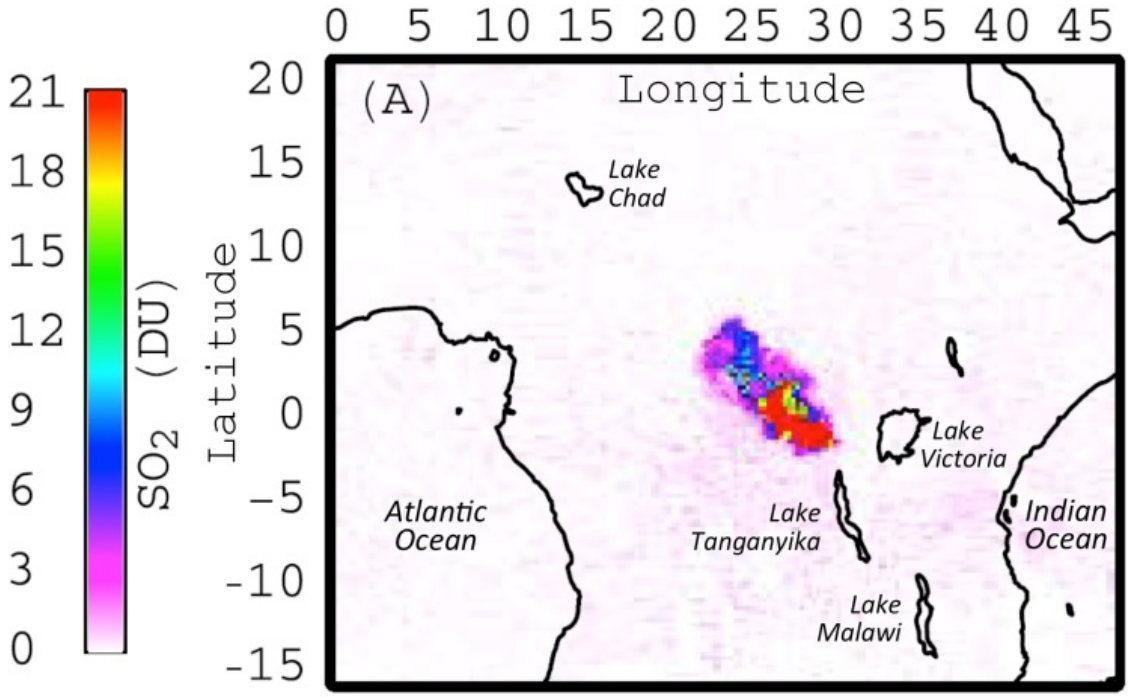
* Now ballasted up to 6.25 kg to increase orbital lifetime

Los Alamos NATIONAL LABORATORY

NASA ESTO EARTH SCIENCE TECHNOLOGY OFFICE

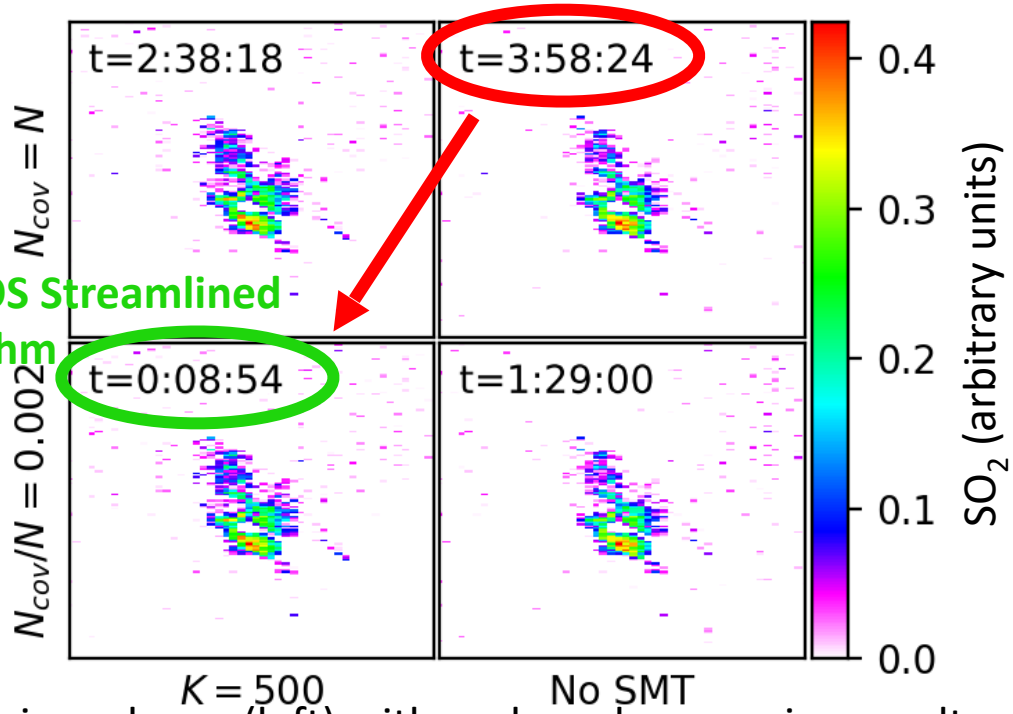
Major NACHOS Project Goal:
On-Orbit validation of our streamlined onboard hyperspectral processing algorithms

Tests of LANL NACHOS Algorithms using OMI data on African volcanic SO_2 plume:



Standard ACE Algorithm: No approximations

NACHOS Streamlined Algorithm



Comparison of published retrieval[1] of the SO_2 plume from Nyamulagira volcano (left) with on-board processing results and execution times of the NACHOS Adaptive Coherence Estimator (ACE) detection algorithm[2] (right) for the same 320x320x1444 OMI dataset.

[1]K. Yang, N. A. Krotkov, A. J. Krueger, S. A. Carn, P. K. Bhartia, and P. F. Levelt, "Retrieval of large volcanic SO2 columns from the Aura Ozone Monitoring Instrument: Comparison and limitations," *J. Geophysical Research: Atmospheres* **112**, p. D24S43 (2007).

[2]J. Theiler, B. R. Foy, C. Safi, and S. P. Love, "Onboard CubeSat data processing for hyperspectral detection of chemical plumes", *Proc. SPIE* **10644**, *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XXIV*, 1064405 (2018); https://doi.org/10.1117/12.2305278

Two NACHOS CubeSats are now in orbit

NACHOS-1
Launched Feb. 19, 2022
NG-17 Cygnus
ISS resupply mission

400 km, 51.6˚inclination orbit

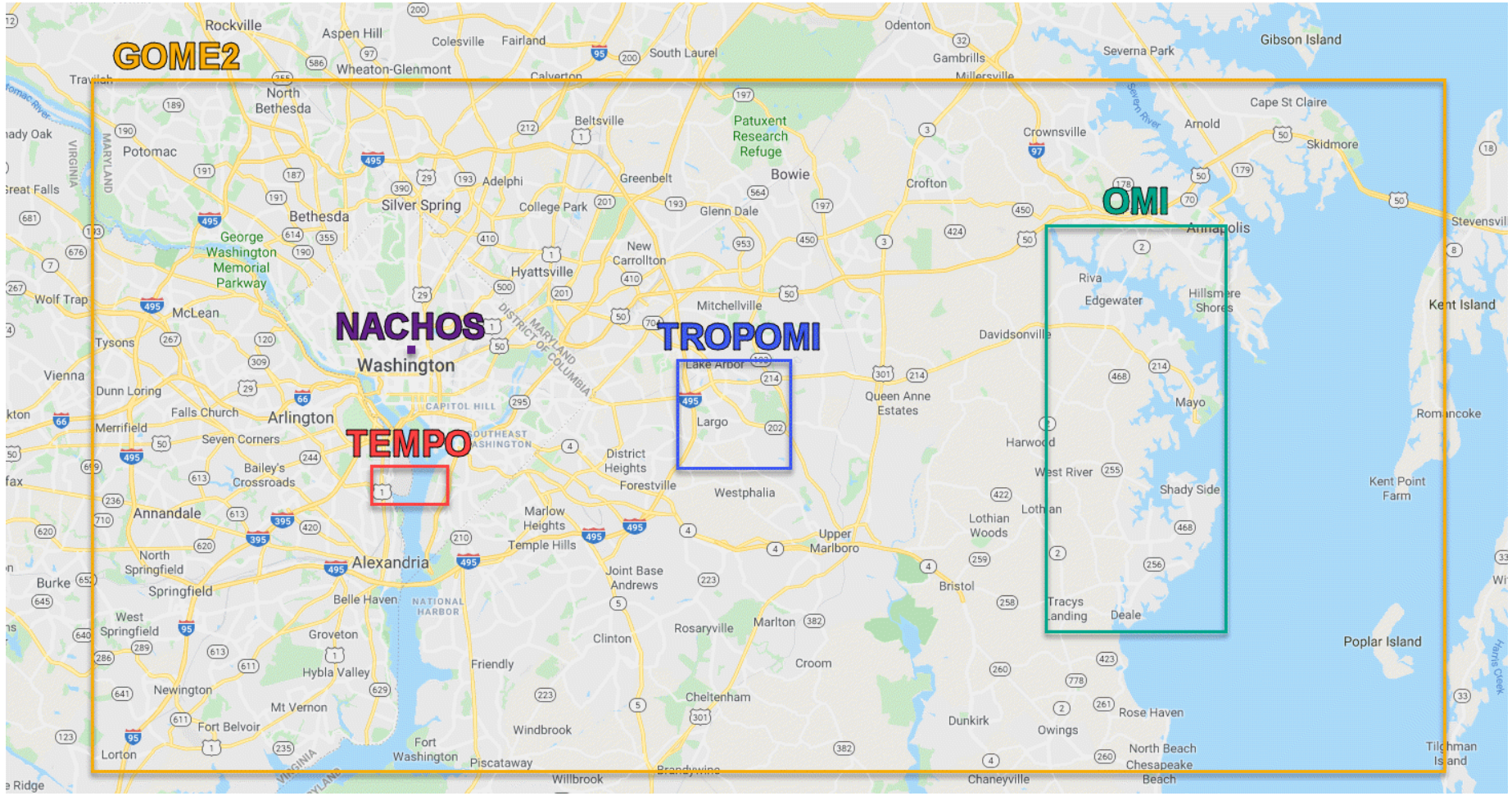
Deployed
June 28, 2022

NACHOS-2
Launched July 2, 2022
Virgin Orbit S28A “Straight Up” mission
500 km, 45˚inclination orbit

NACHOS Niche: Targeted, high spatial resolution gas imaging

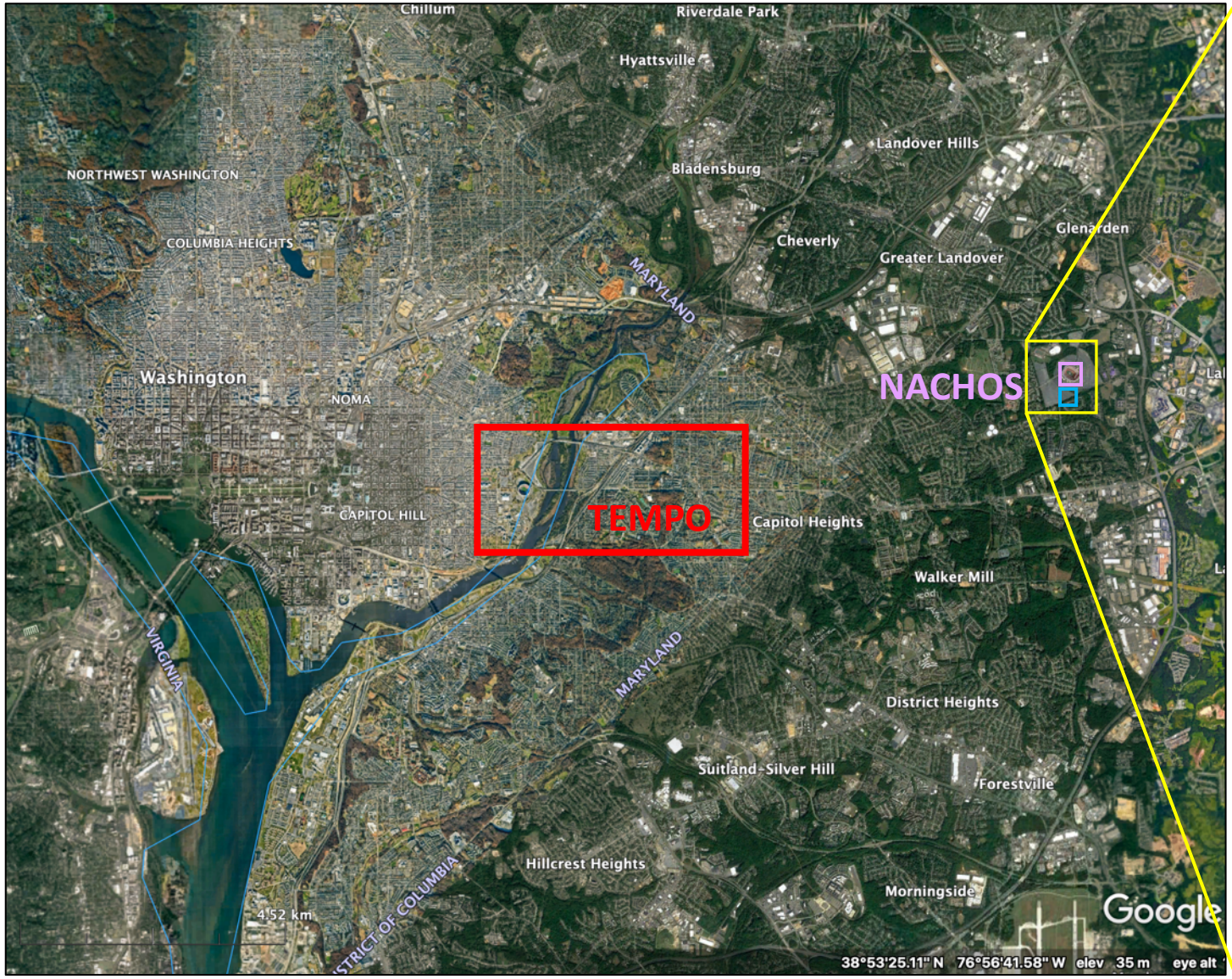
Ground pixel size comparison:

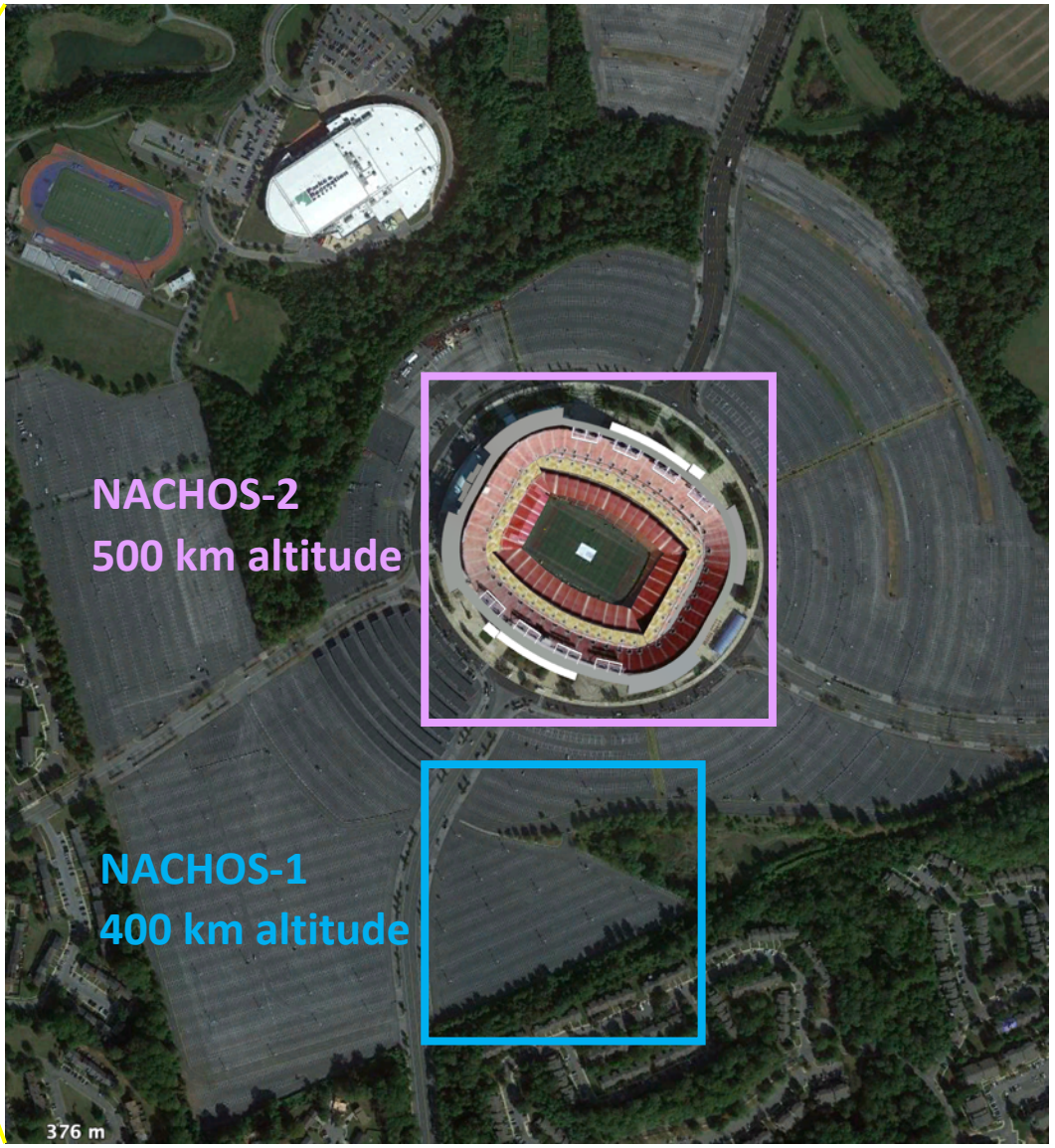
NACHOS *vs.* current & planned gas imaging satellite instruments



- **NACHOS pixel: ~0.375 km at 500 km altitude**
- **NACHOS 350-pixel swath width corresponds to a ~130 km swath at 500 km altitude (15˚full-angle across-track f.o.v.)**
- **Envisioned NACHOS constellation would provide frequent target revisits**

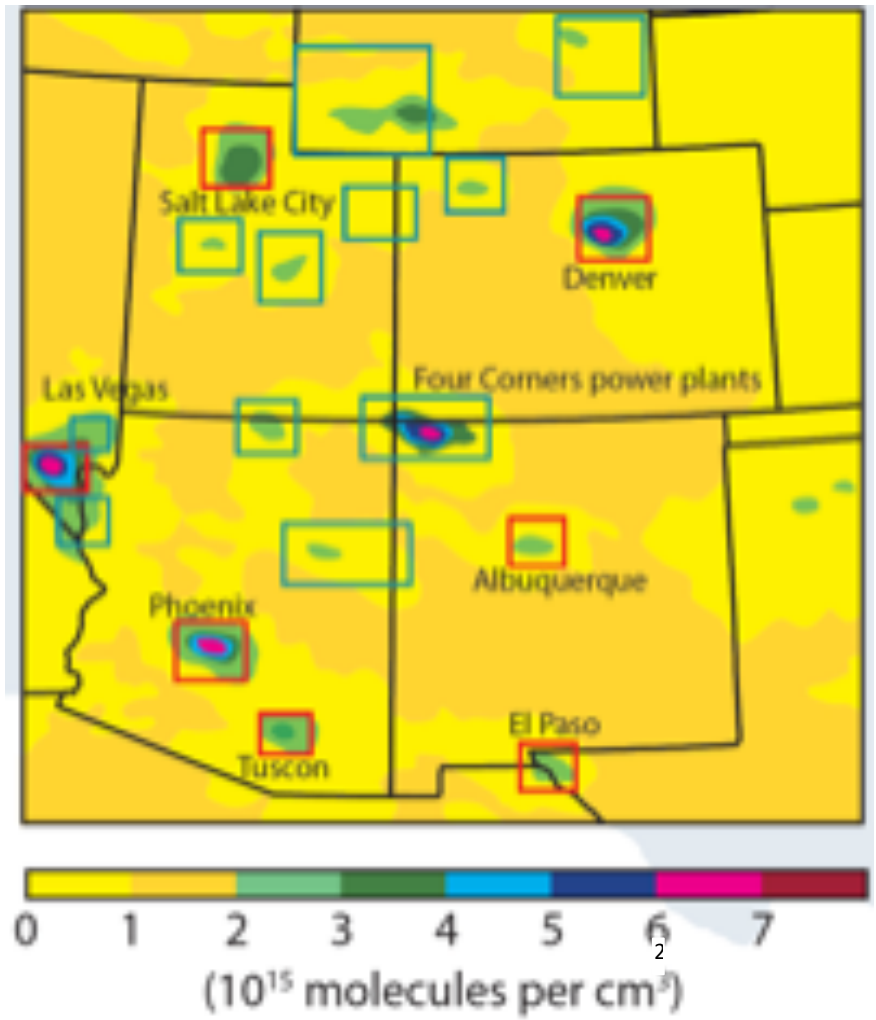
Single-pixel size comparison, NACHOS *vs.* TEMPO





Science applications:
NO_2 – air quality; fossil fuel greenhouse gas tracking and attribution

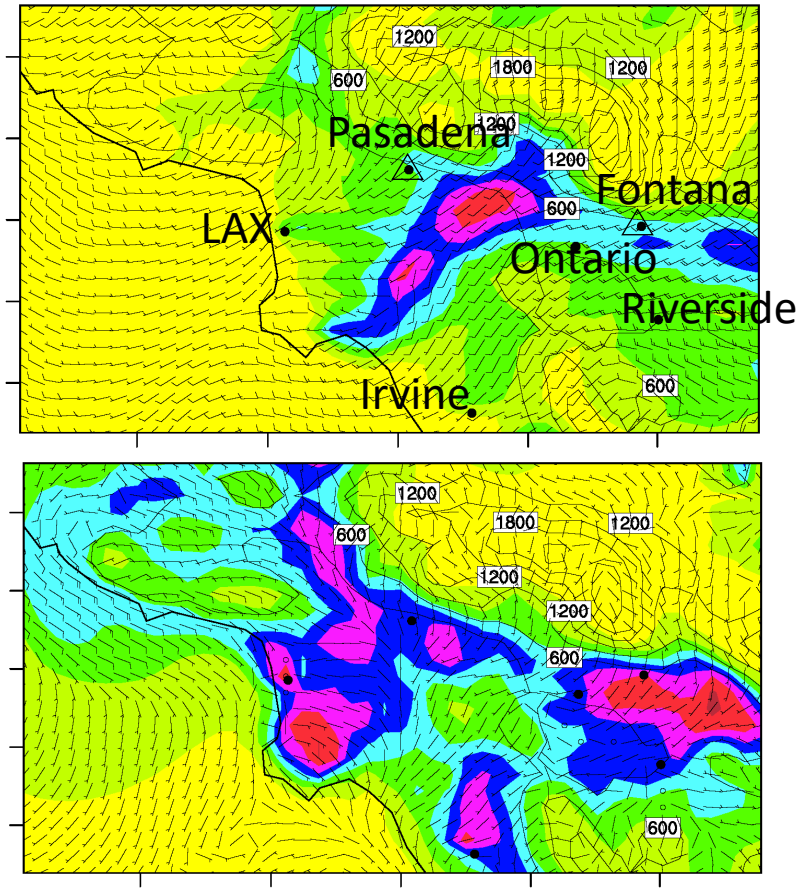
OMI provides regional-scale imagery:



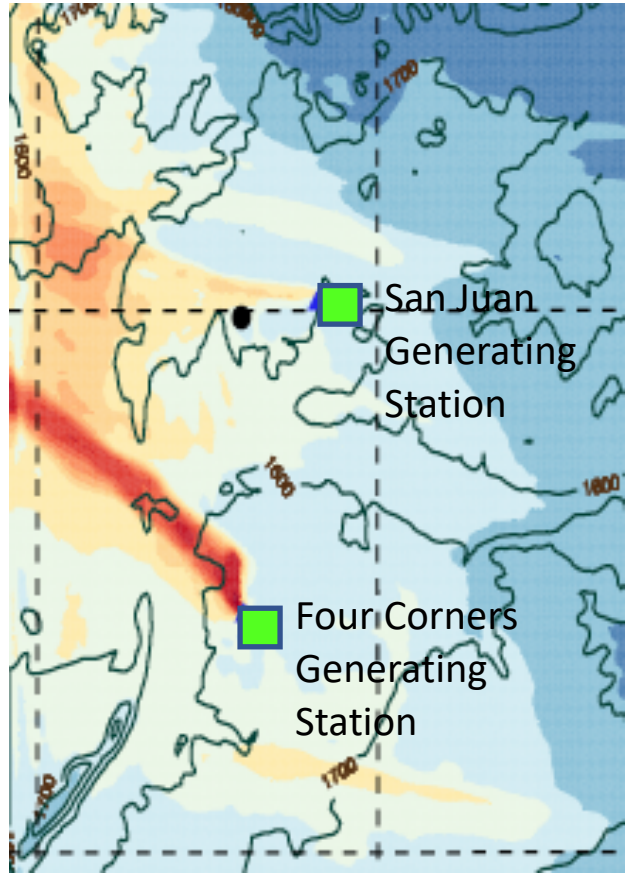
NASA OMI Image

NACHOS will provide local-scale imagery

…of urban areas



…or individual power plants

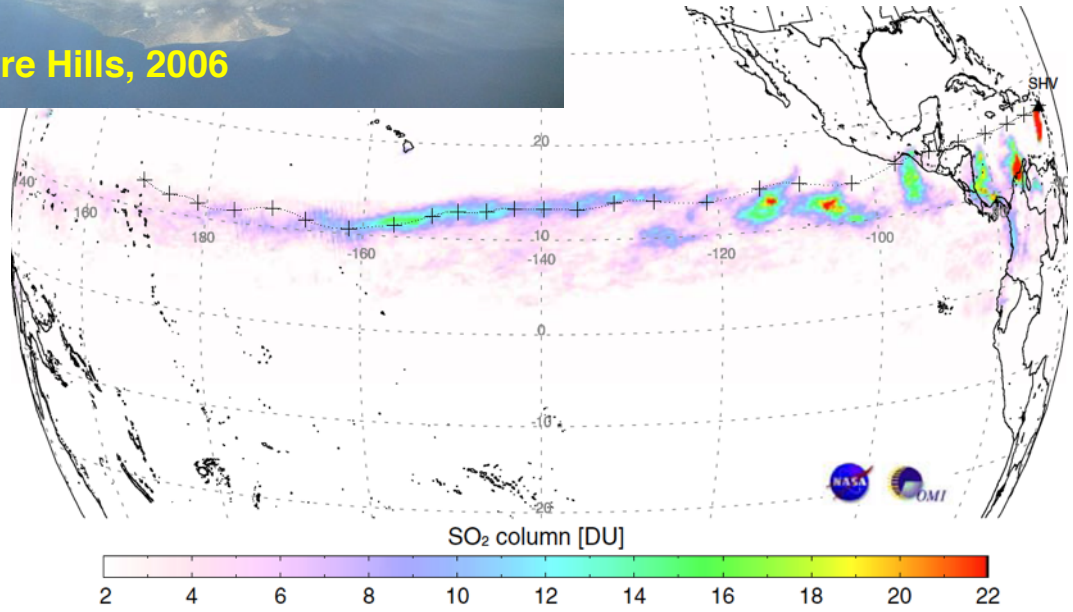


Modeled NO_2 images at roughly NACHOS spatial resolution

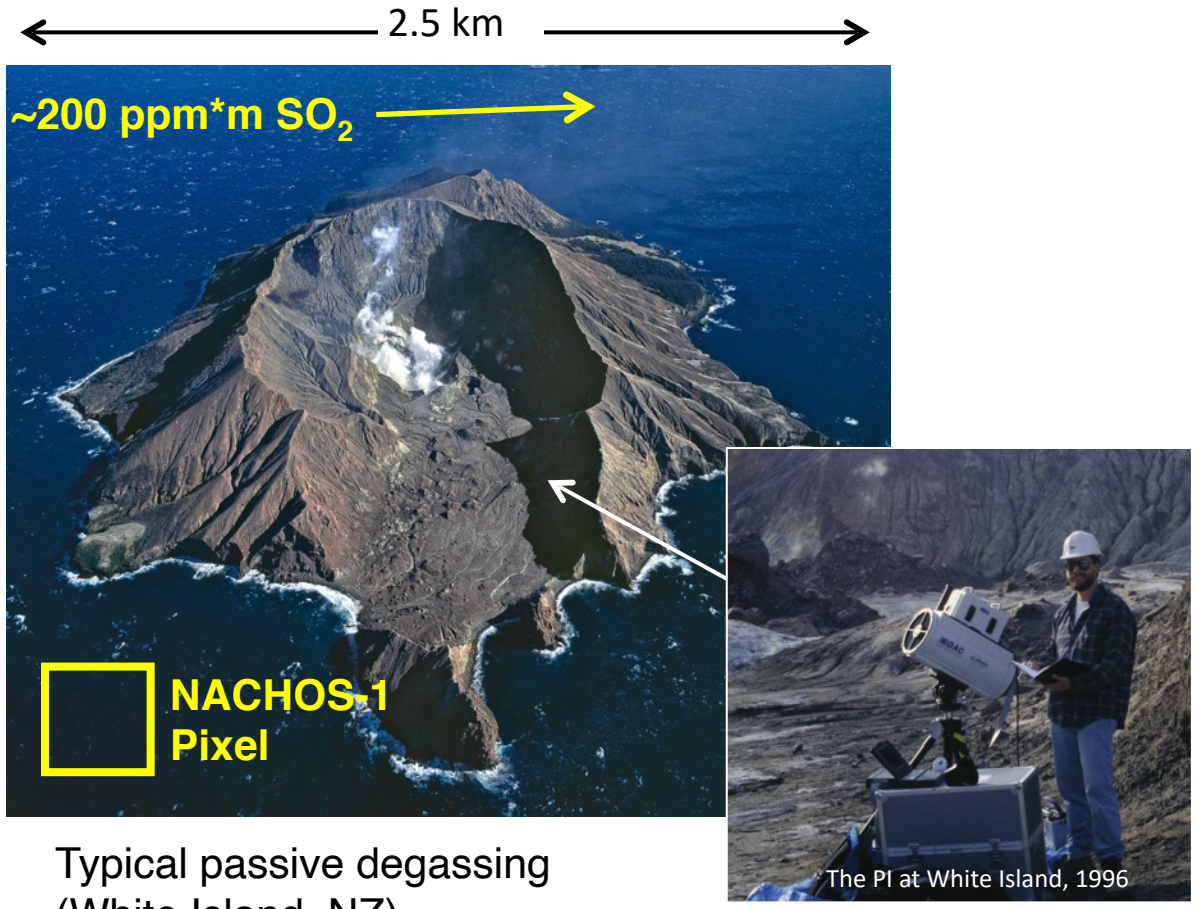
Science applications: SO_2 imaging for volcanology

OMI, etc. can image SO_2 plumes from LARGE events

OMI Image of globe-spanning SO_2 plume from Soufriere Eruption:



With NACHOS's high spatial resolution, can detect low-level passive degassing, new emissions at recently awakened volcanoes, map satellite vents, …

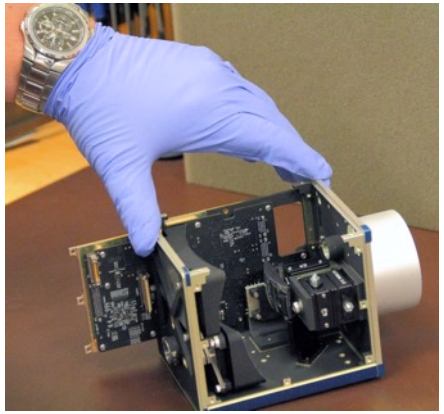


Typical passive degassing (White Island, NZ)

… and many more:

- Tropospheric ozone
- Formaldehyde from wildfires
- Aerosols, absorbing (black soot) vs. scattering – spectrally distinguishable in this region
- Additional volcanic gases, BrO, IO, OClO, etc.

- NACHOS engineering units are also very portable ground-based HSI's. Coordinated space- and ground-based measurements are planned.



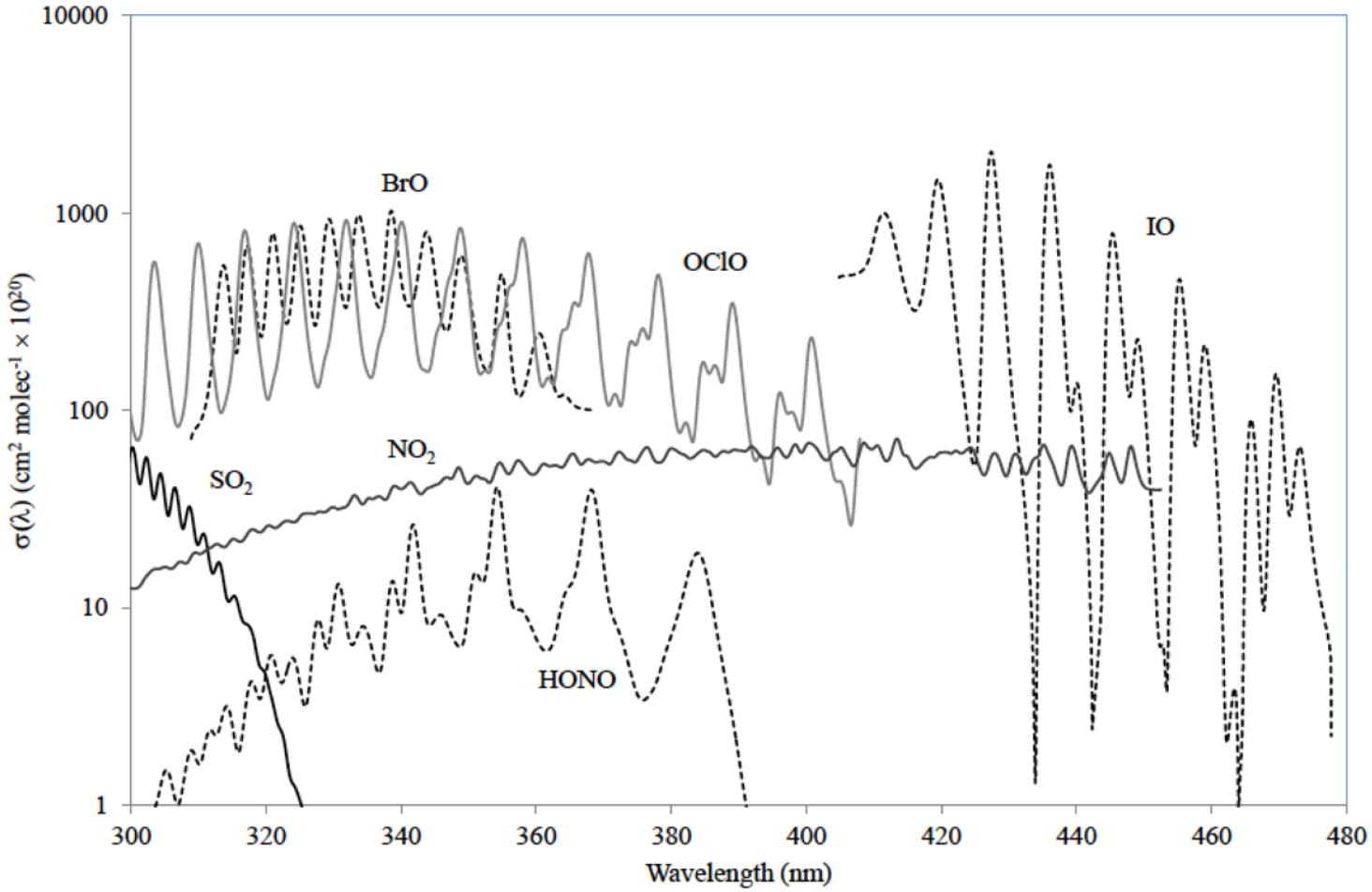
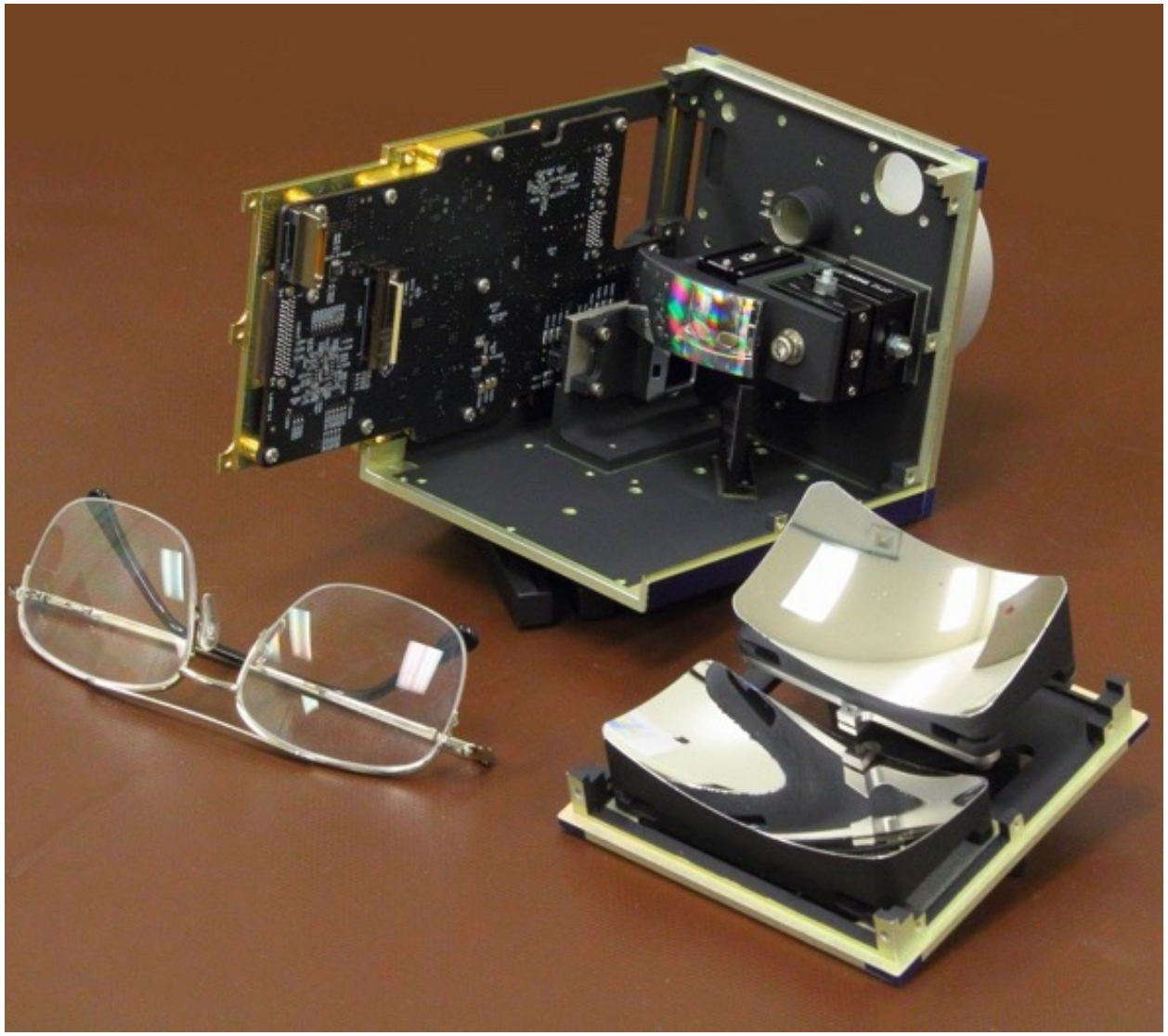
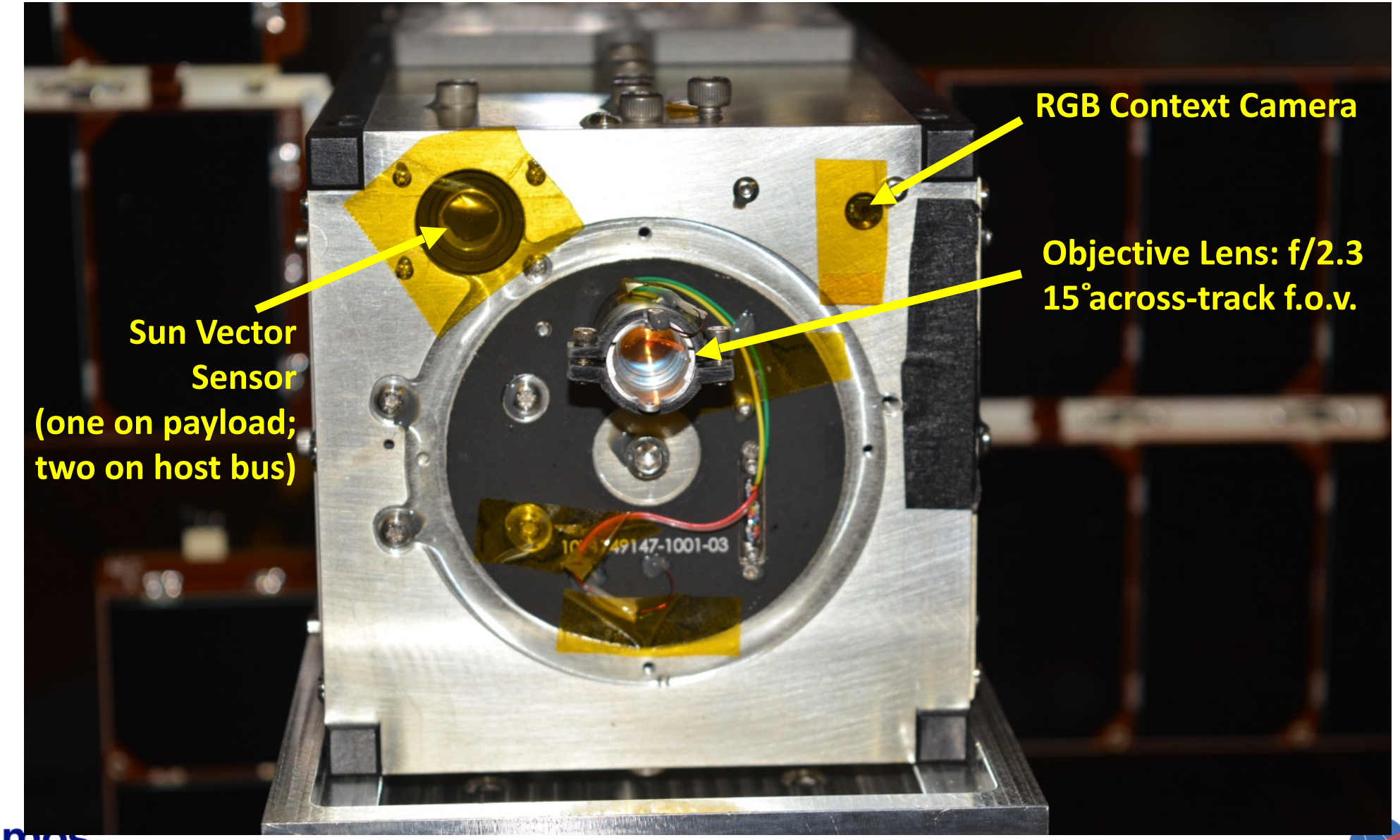


Figure from: C. Oppenheimer, B. Scaillet, and R. S. Martin, "Sulfur Degassing From Volcanoes: Source Conditions, Surveillance, Plume Chemistry and Earth System Impacts," *Reviews in Mineralogy & Geochemistry* **73,** 363-421 (2011).

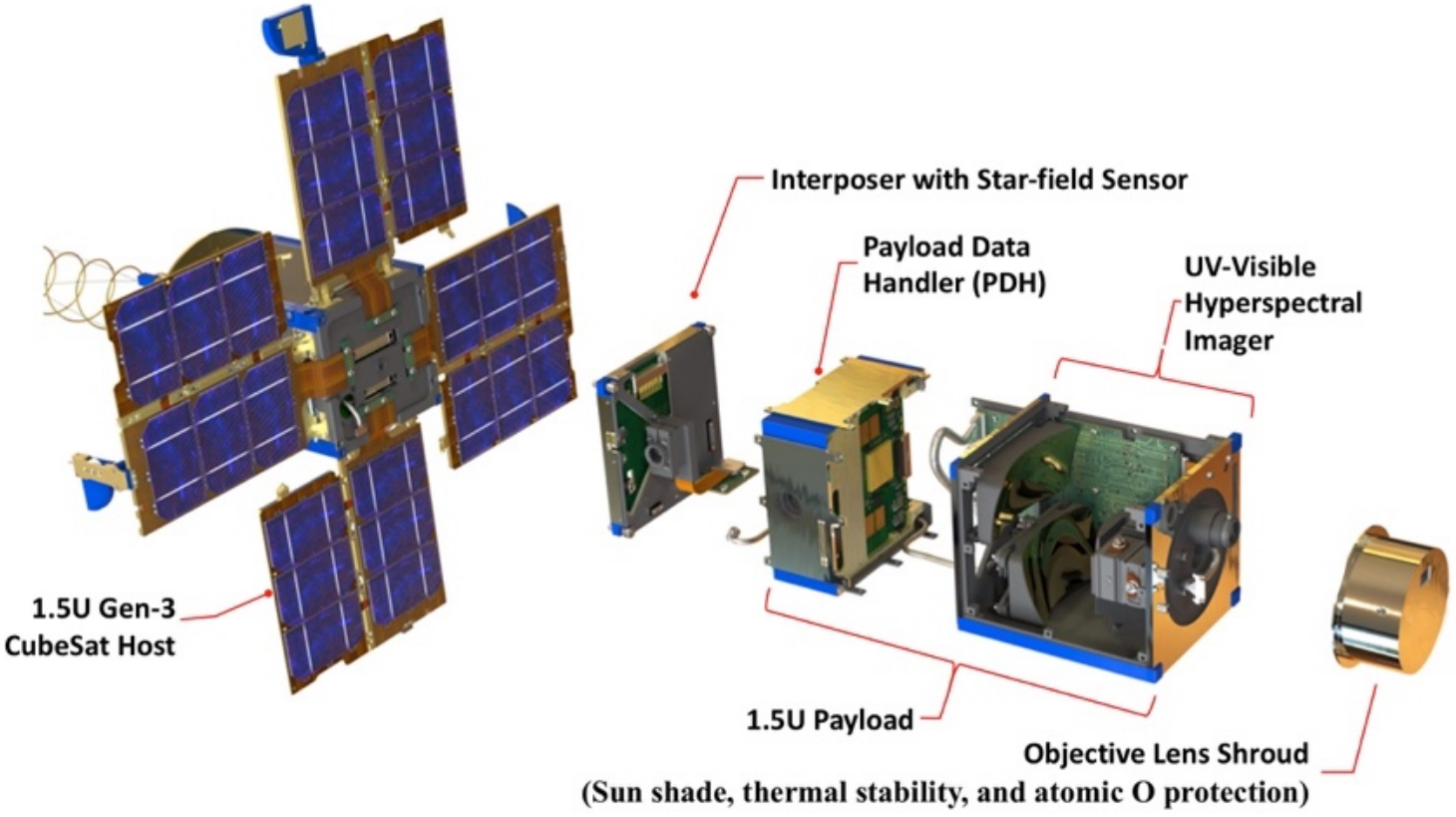
NACHOS optical payload assembly

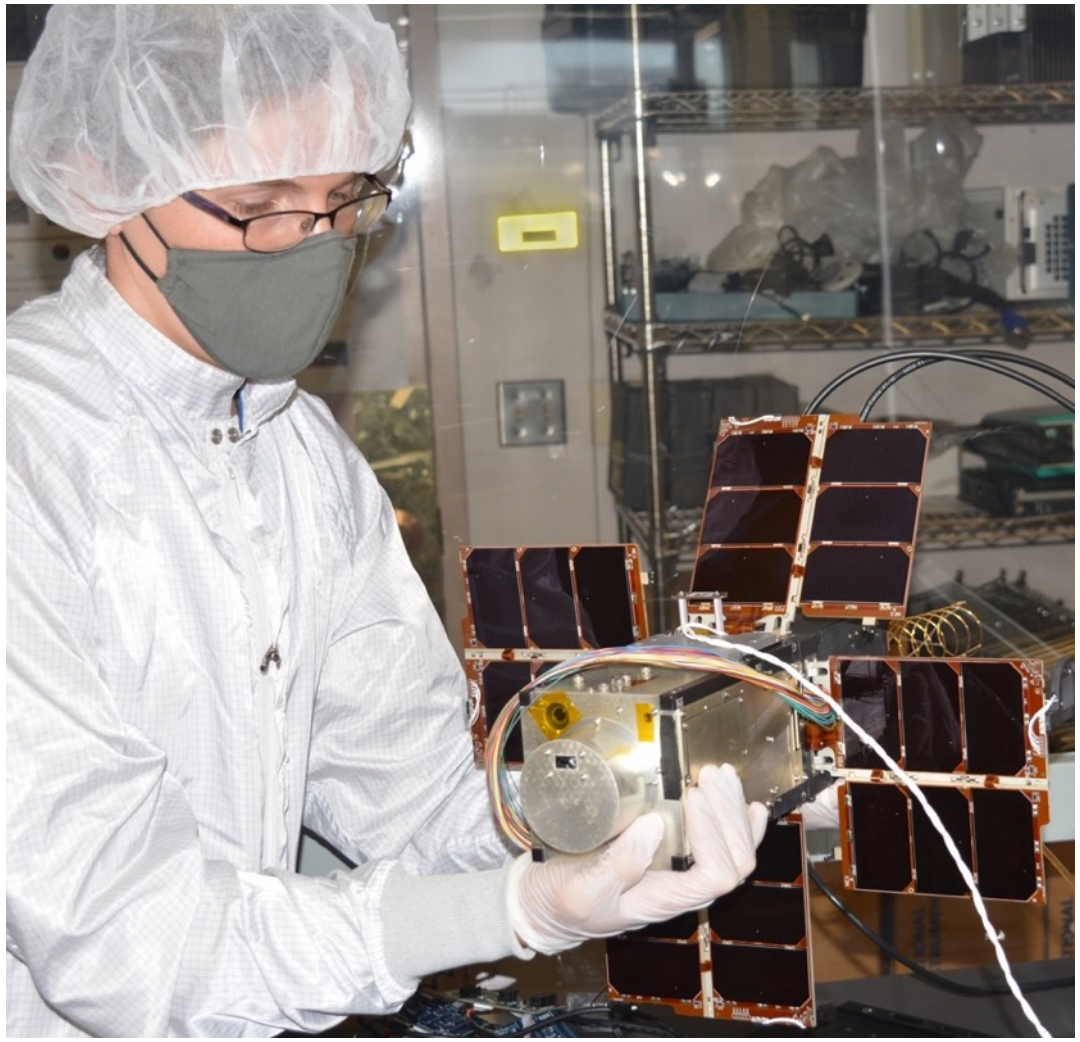


NACHOS business end (with thermistors added for TVAC test)



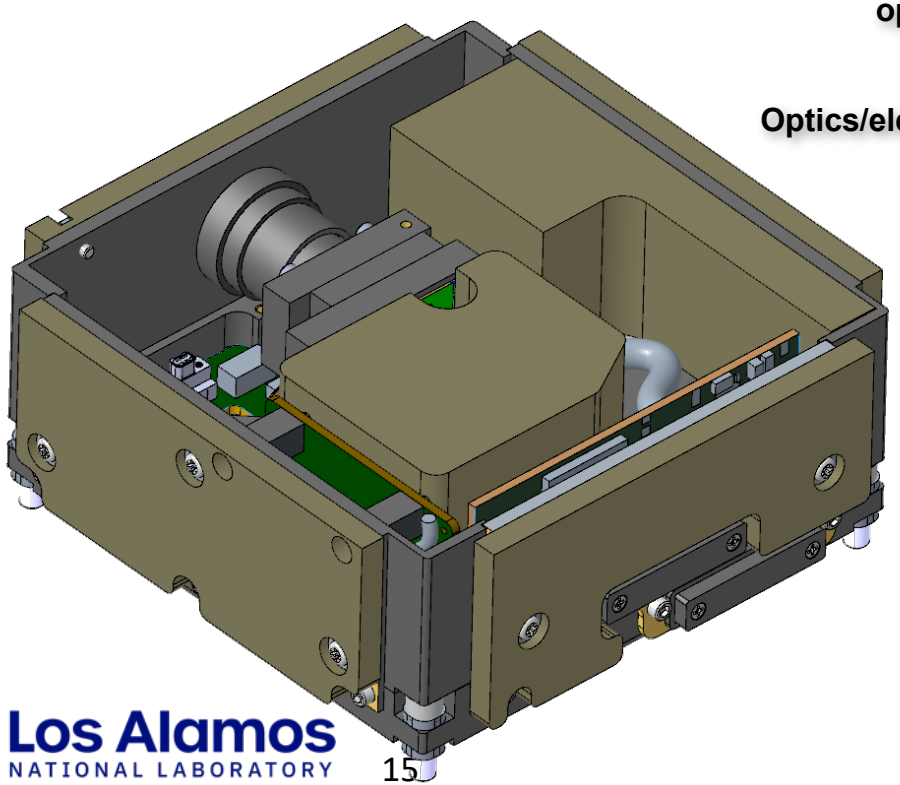
NACHOS Payload hosted on LANL's 3rd-Generation CubeSat bus

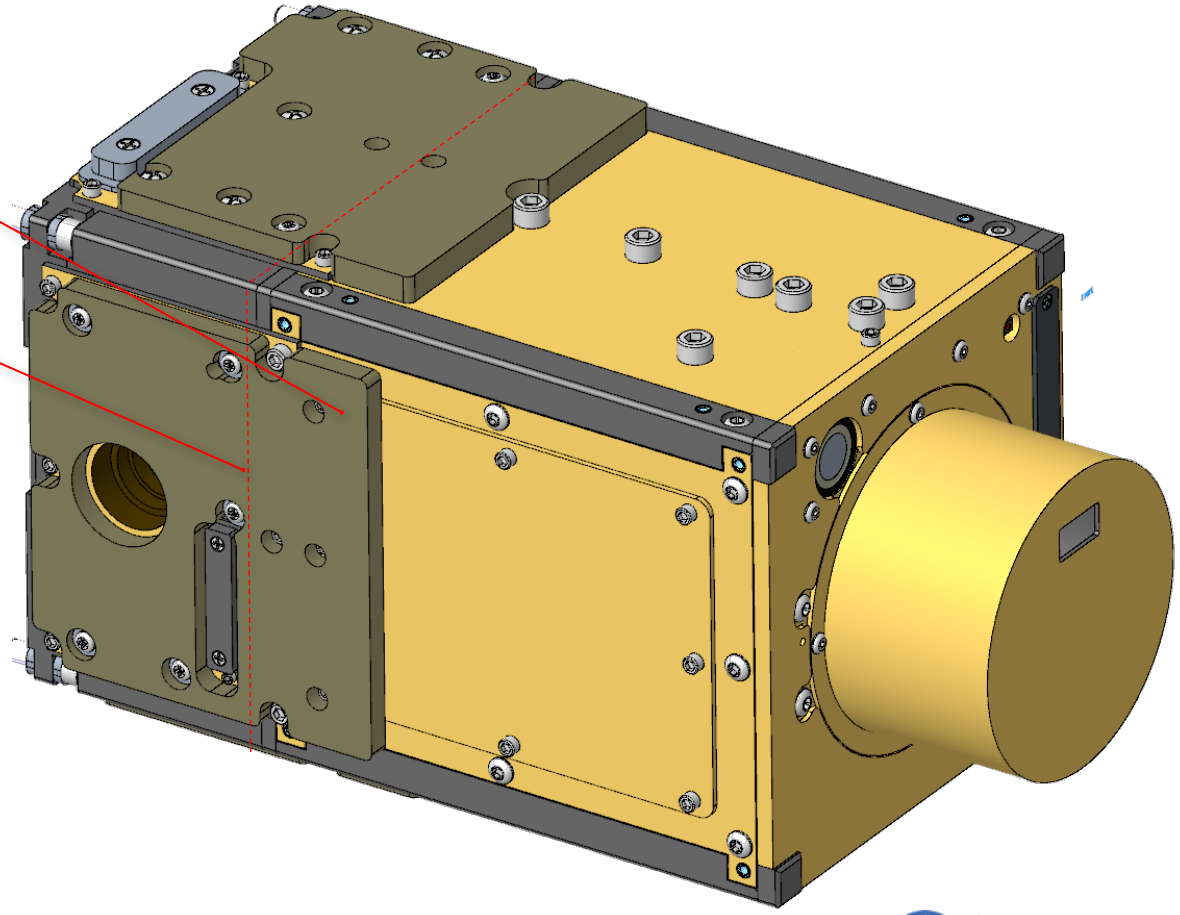




Addition of mass ballast to increase orbital lifetime

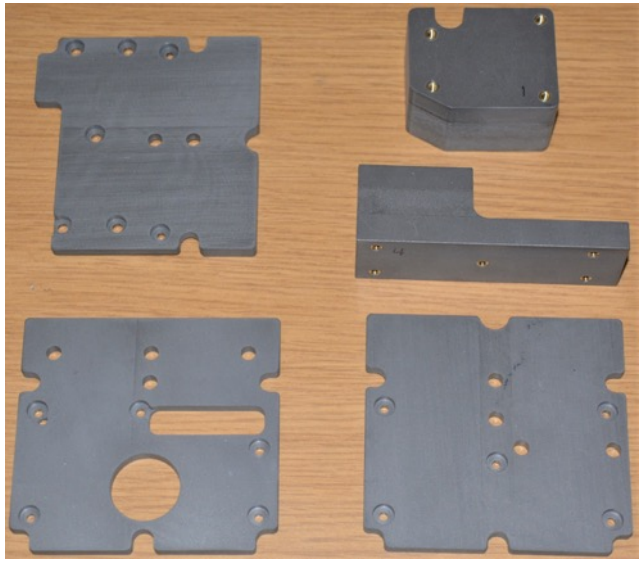
- Our deployable solar panels are great for providing lots of power, but the their large surface area creates greater drag in low earth orbit than is typical for a 3U CubeSat. With the advancing solar cycle, this becomes significant.
- Improving the mass/area ratio by adding ~2 kg of ballast, increasing total mass to 6.25 kg, provides an acceptable ~1 year or better lifetime.

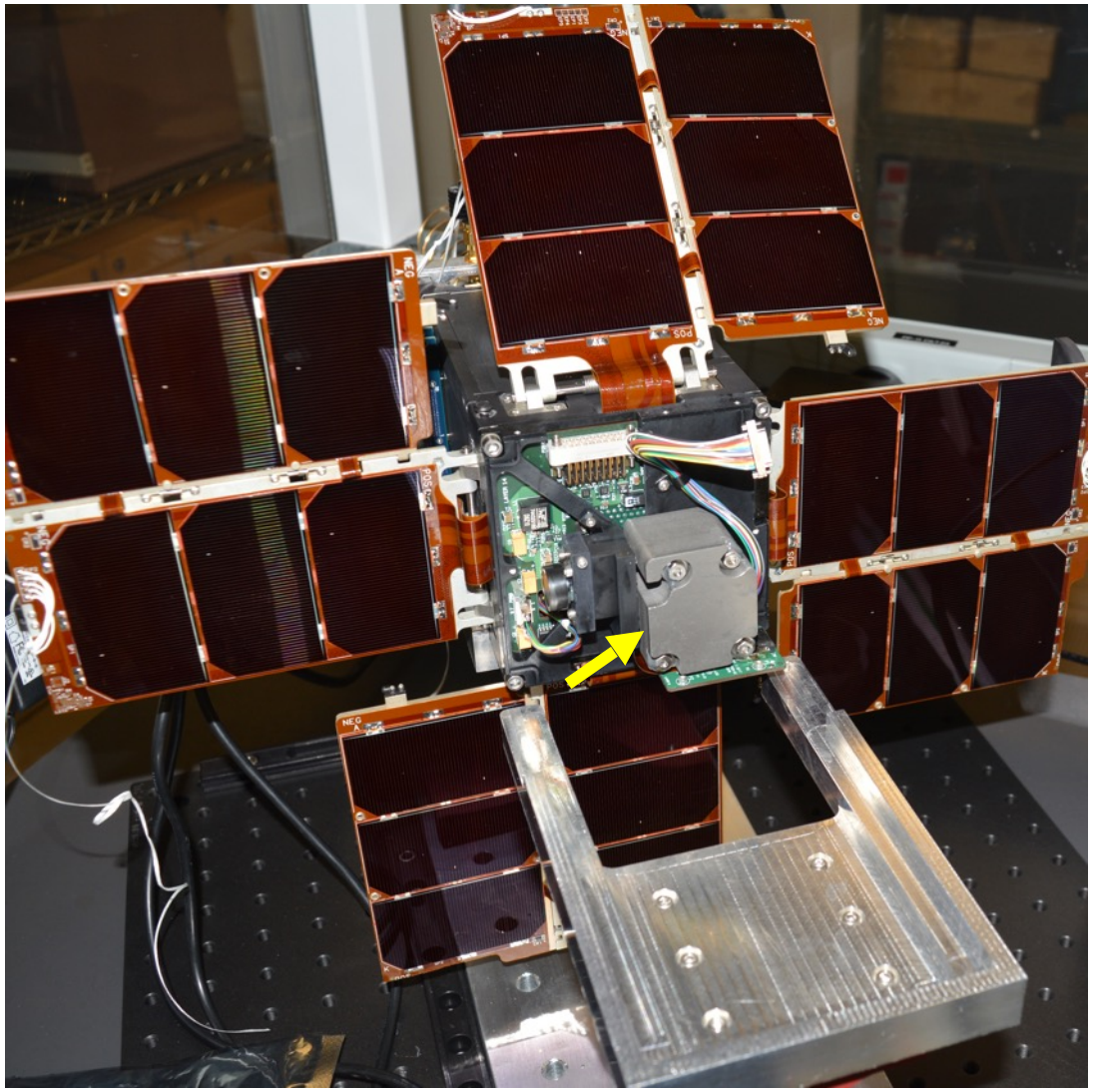




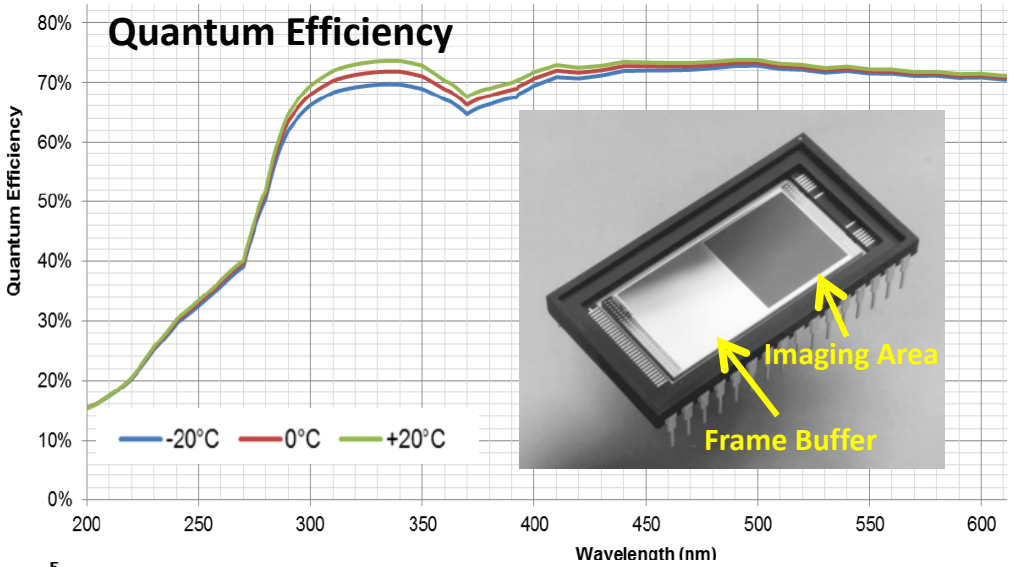
Tungsten Polymer Ballast

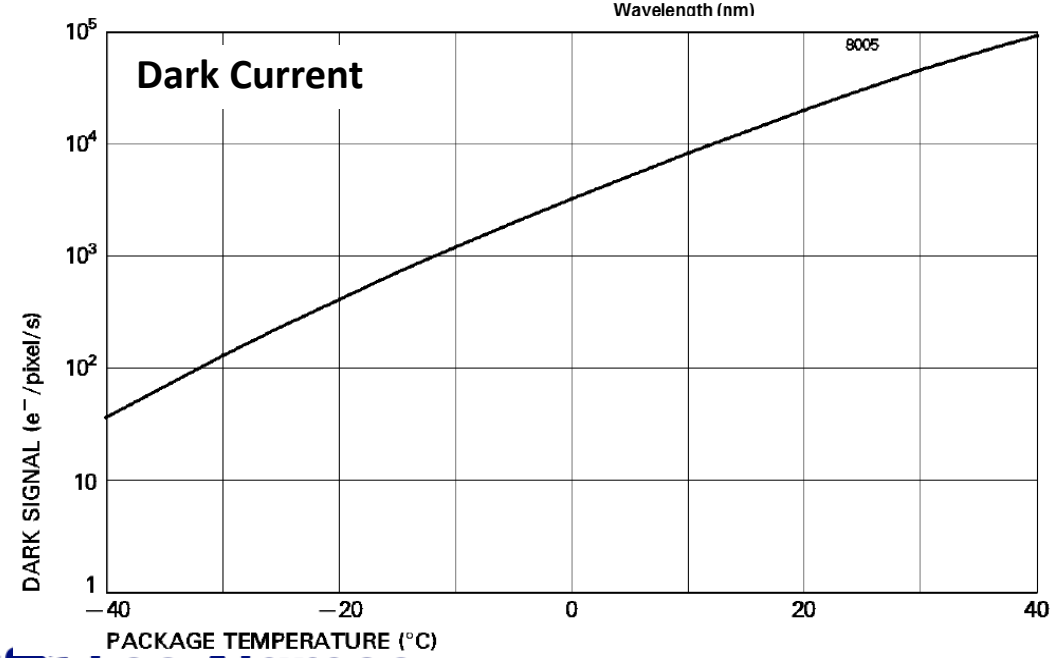
- **Thanks to Rick Kohnert of CU, who pointed us towards this material**
- **Ecomass Technologies, Austin TX**
  - Compound 1700TU96
  - 30% PA12 nylon, 70% Tungsten powder (by mass)
  - Meets ODAR requirements
- **Low Outgassing**
- **Highly Machinable**



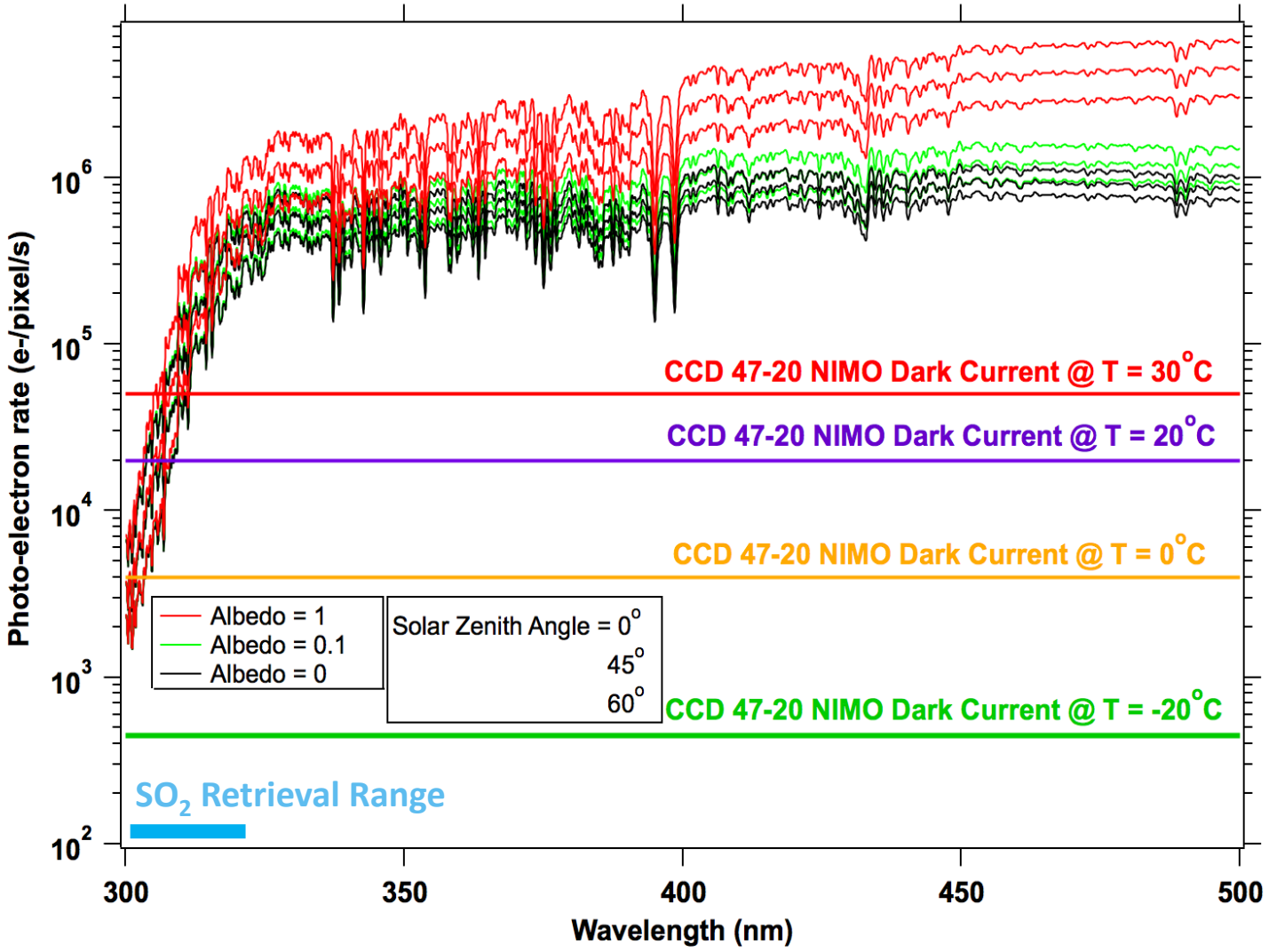


CCD Sensor: Teledyne/e2v CCD42-20 NIMO, Back-illuminated, UV AR-coated – Excellent quantum efficiency, ~70%; Substantial dark current for T>0℃



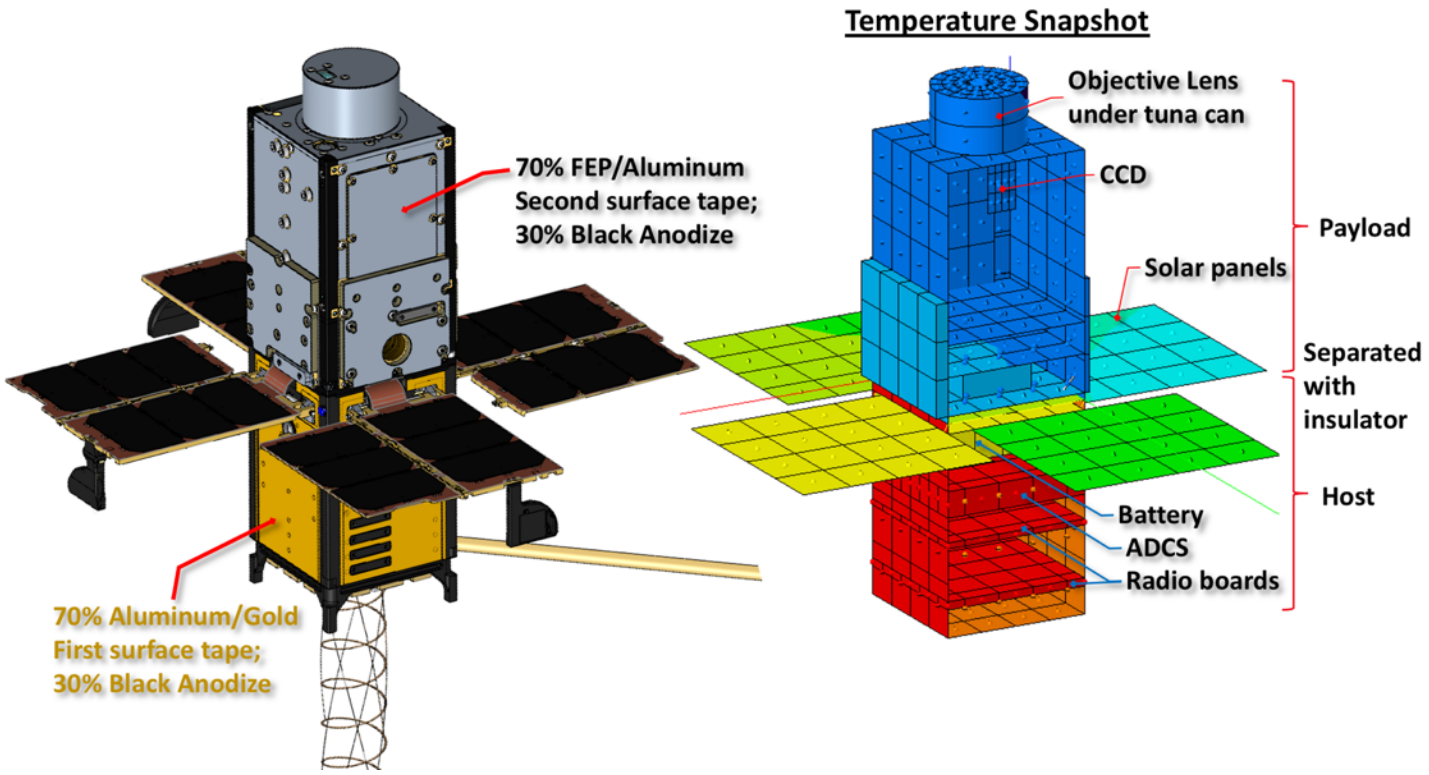


Modeled signal compared to dark current

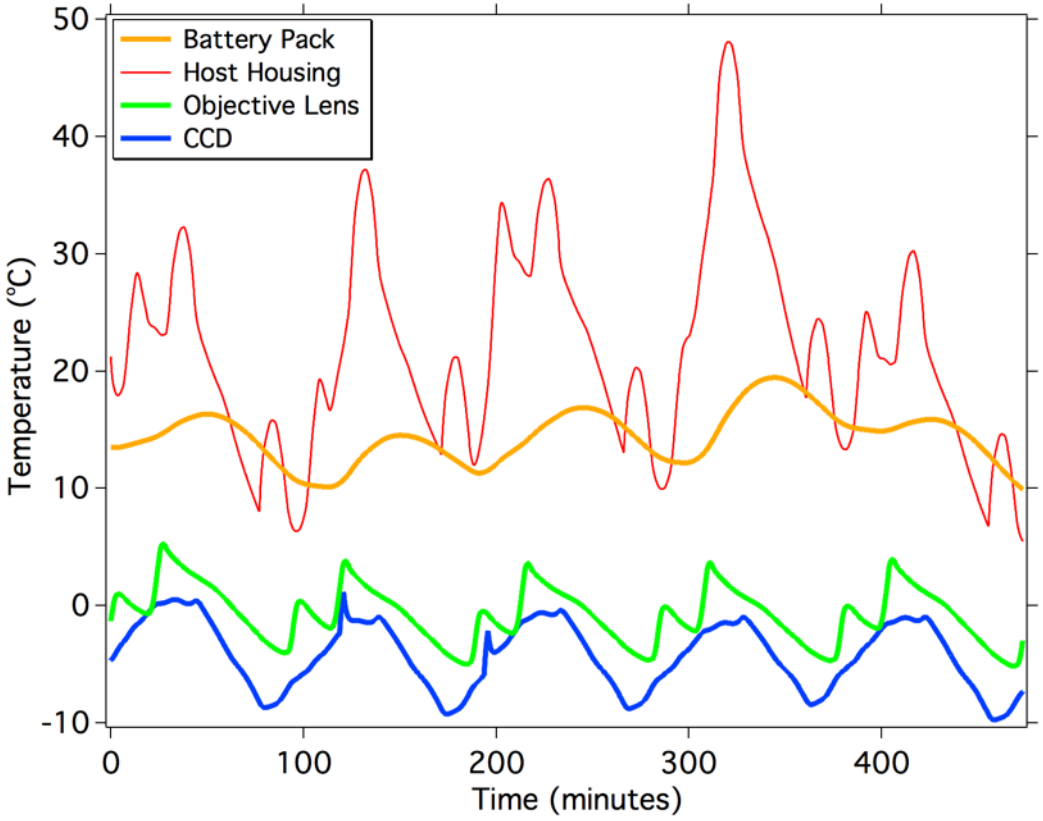


→ Want CCD temperature < ~5℃, preferably < 0℃

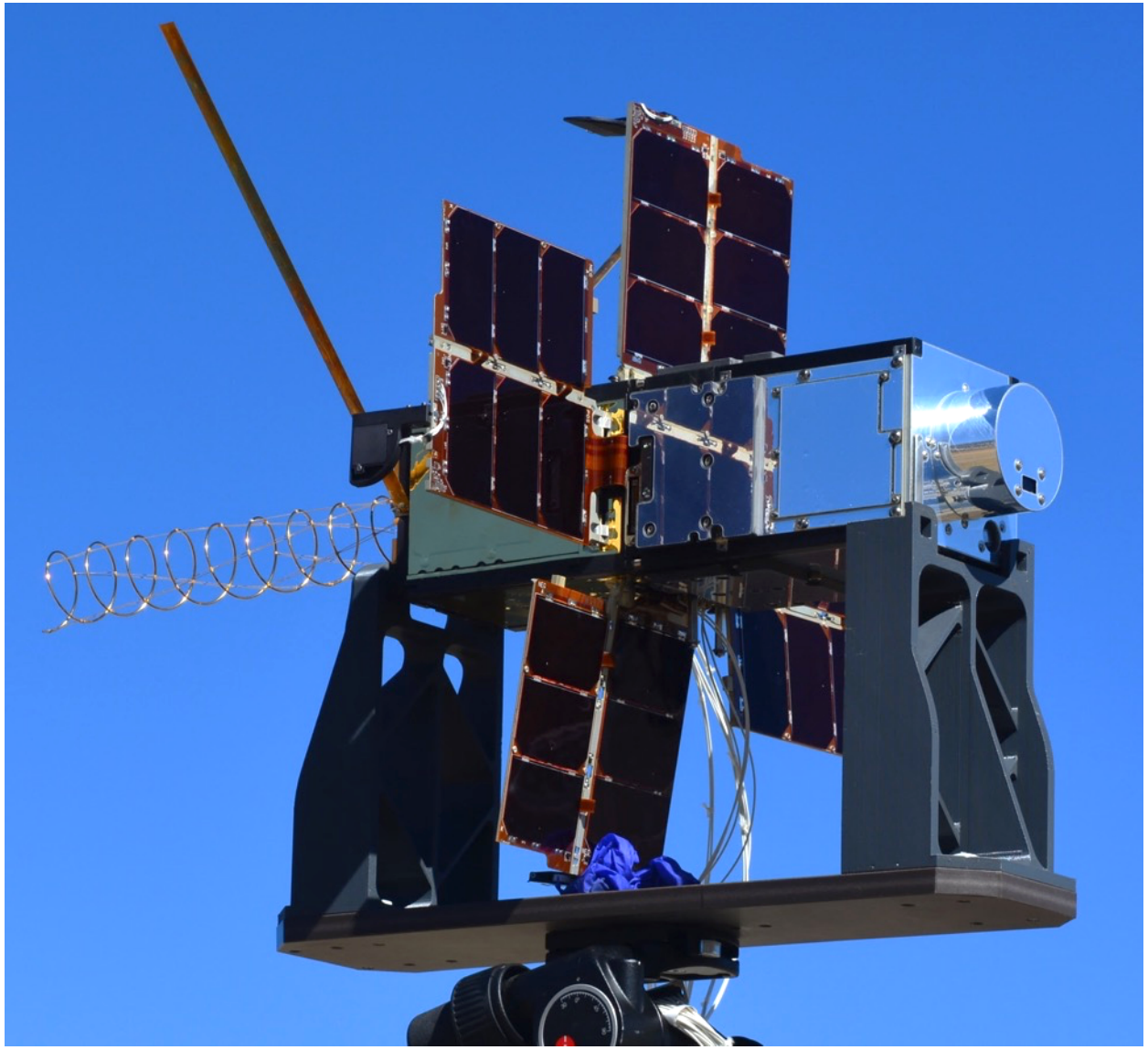
Passive management of CCD, optics, and battery temperatures



Modeled temperatures over five orbits:

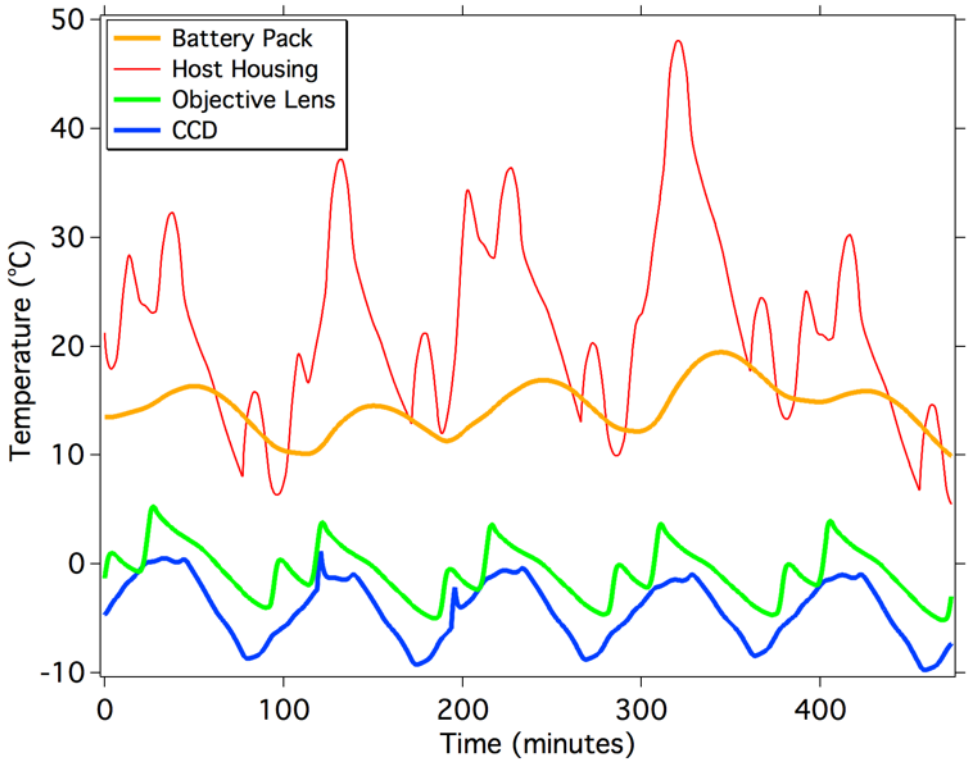


NACHOS thermal management surface treatments

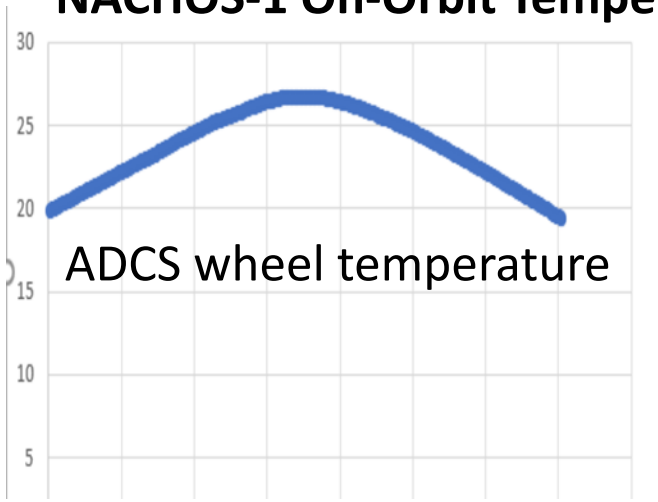


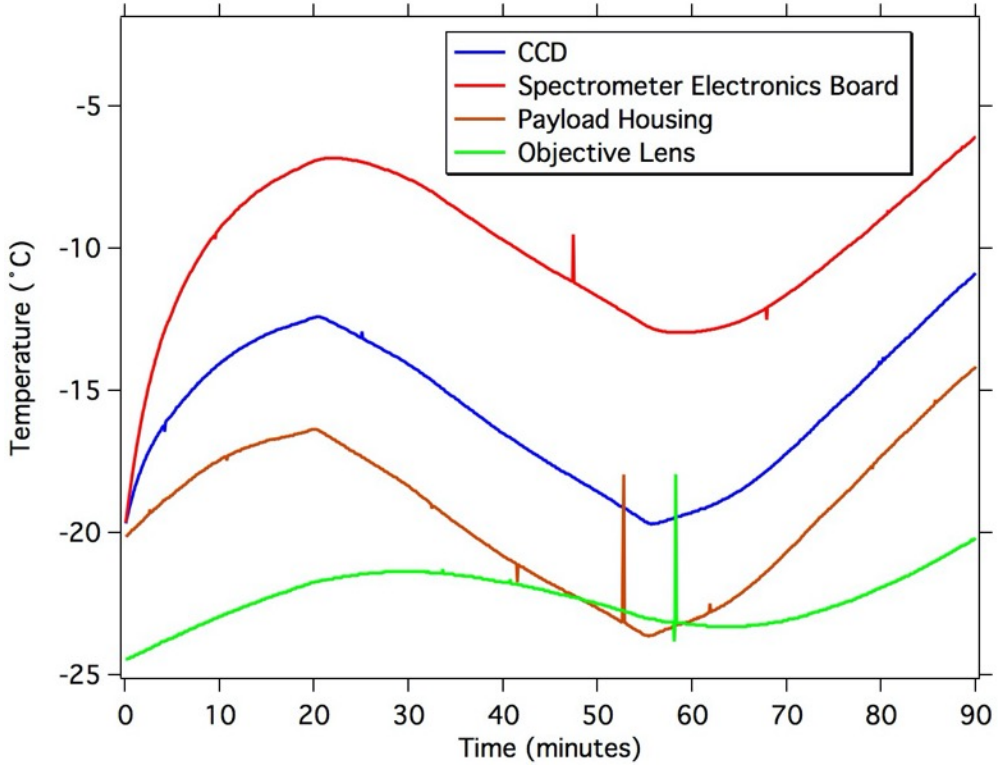
NACHOS-1 On-Orbit T Data *vs.* Model

Modeled temperatures over five orbits:



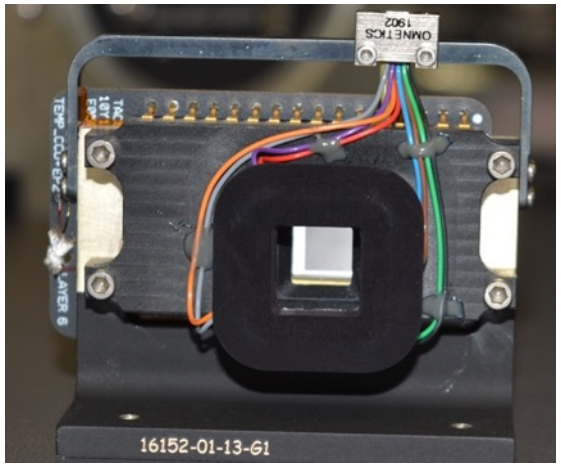
NACHOS-1 On-Orbit Temperatures

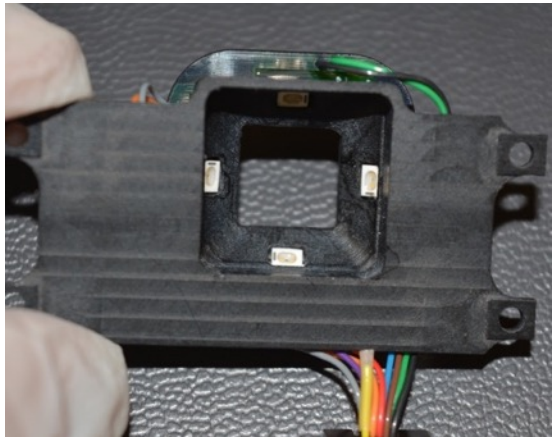




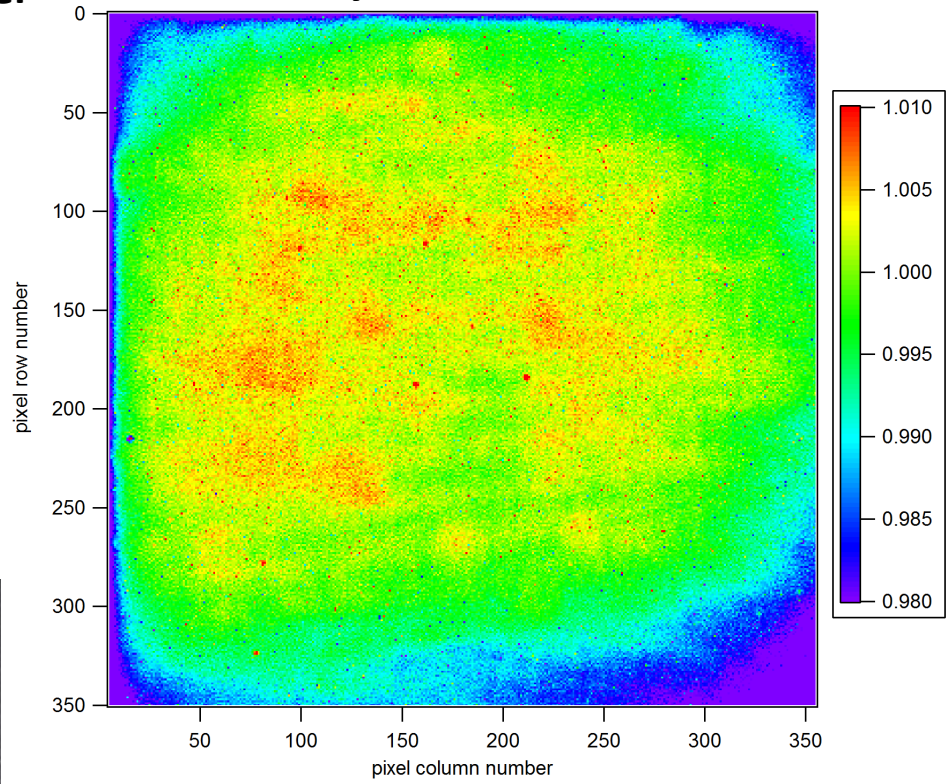
LED-based onboard CCD non-uniformity calibration

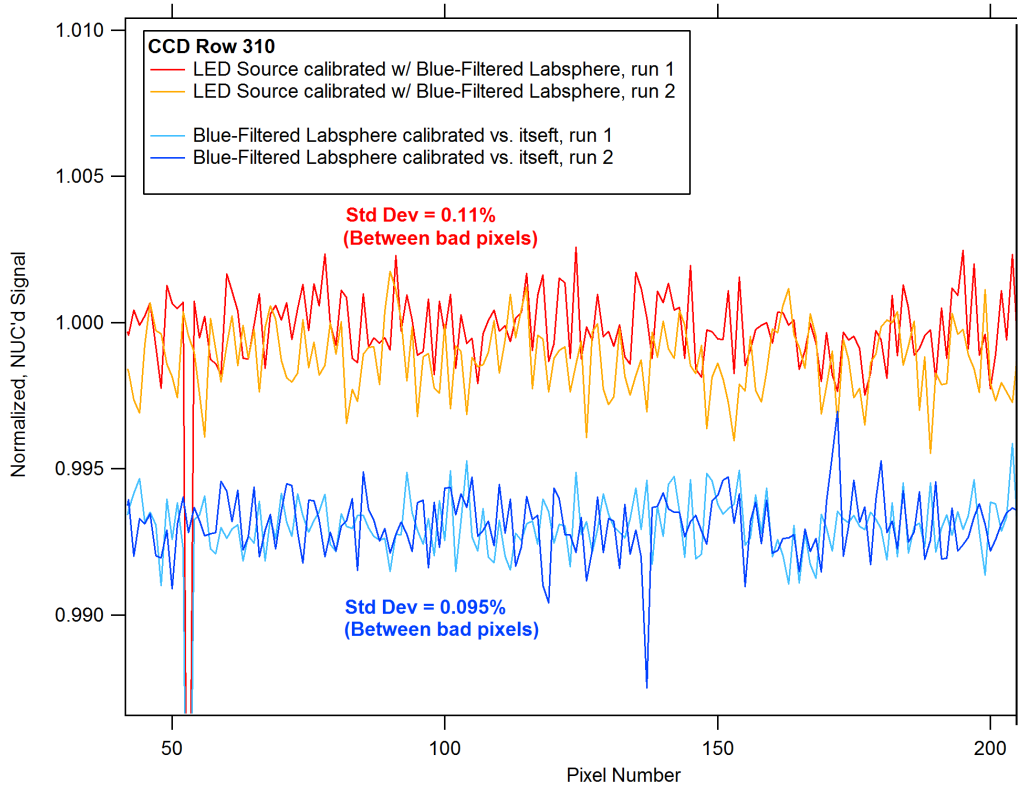
CCD module, with zero-order baffle and calibration LEDs:

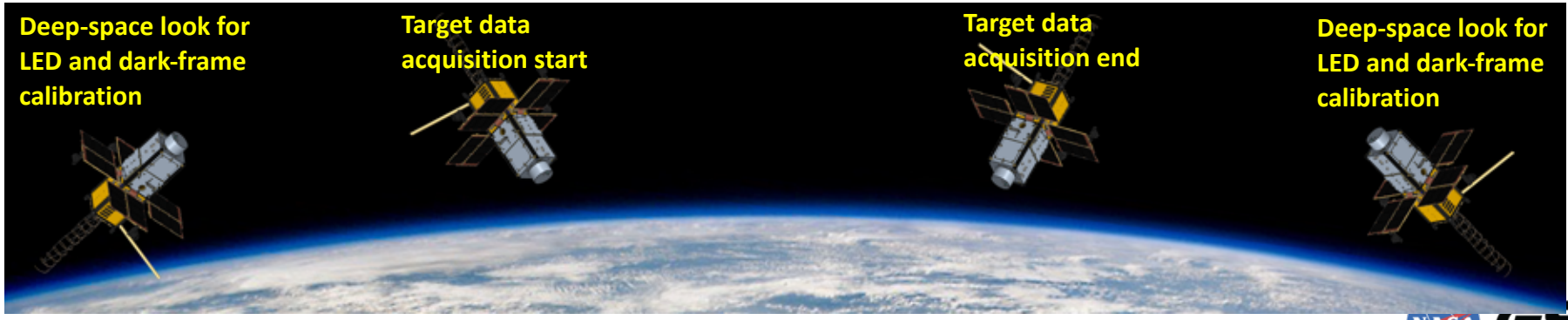




Uniformity of LED illumination, calibrated against external uniform source (Labsphere):

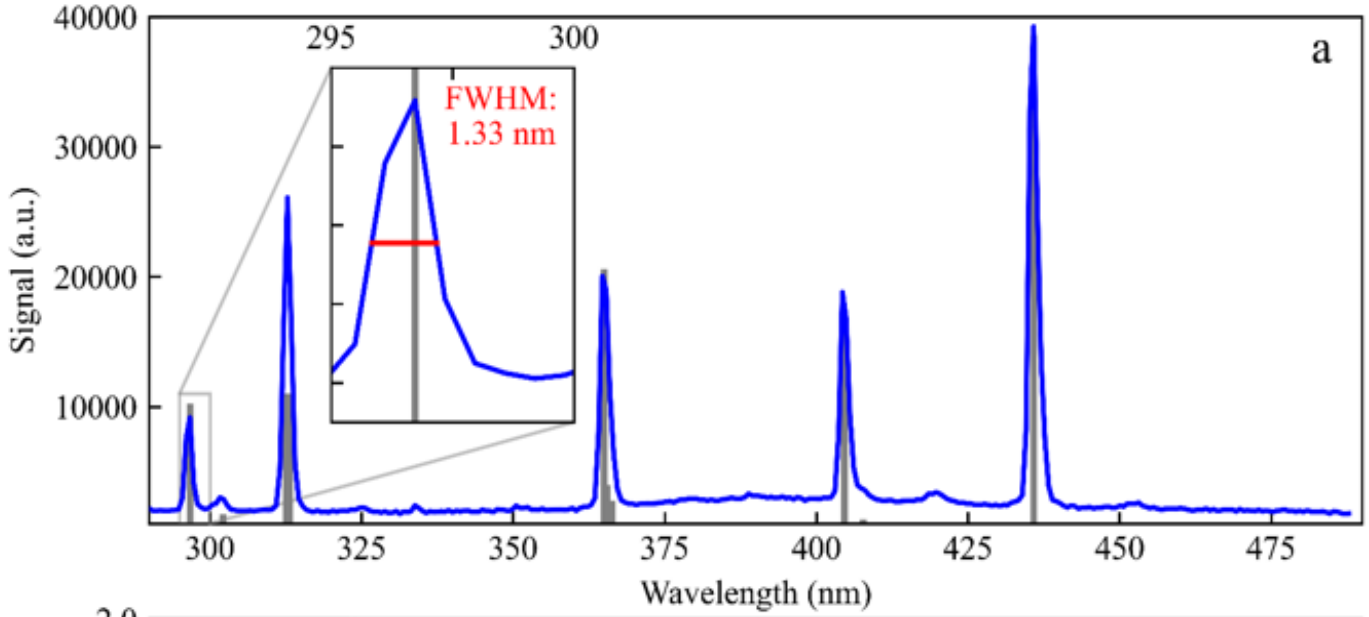




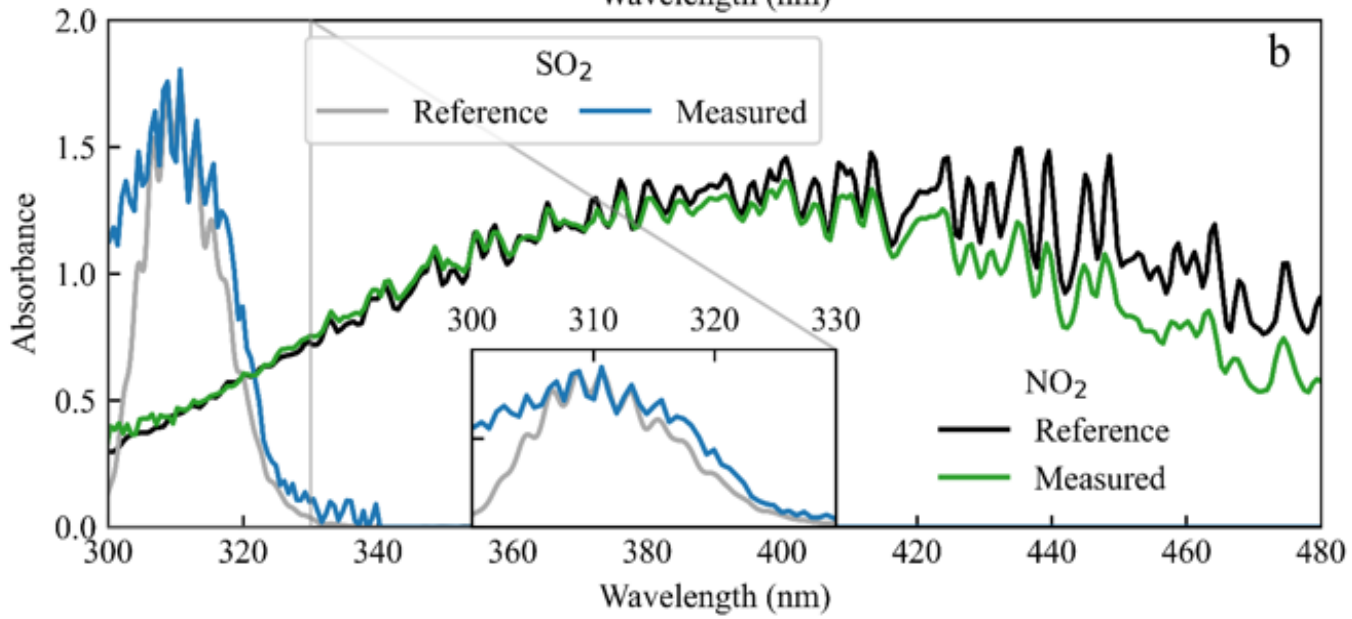


NACHOS test spectra

Hg-vapor Calibration Lamp:

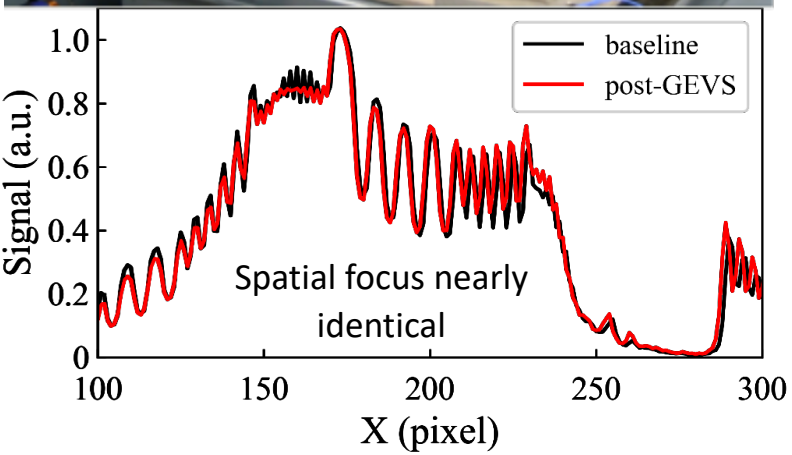


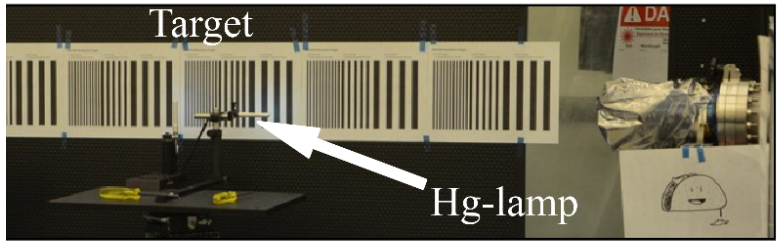
SO_2 and NO_2 gas-cell spectra:

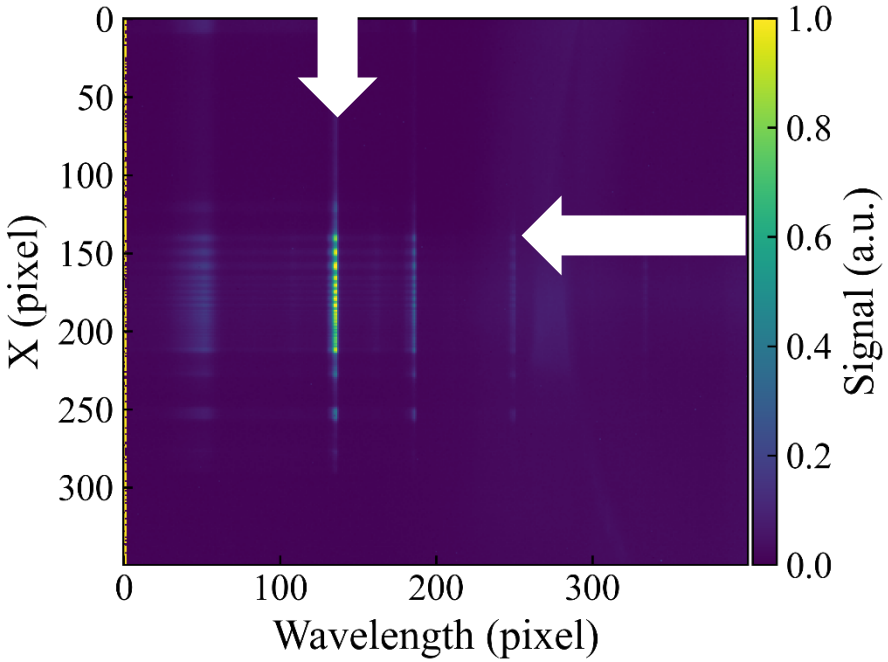


Environmental Testing

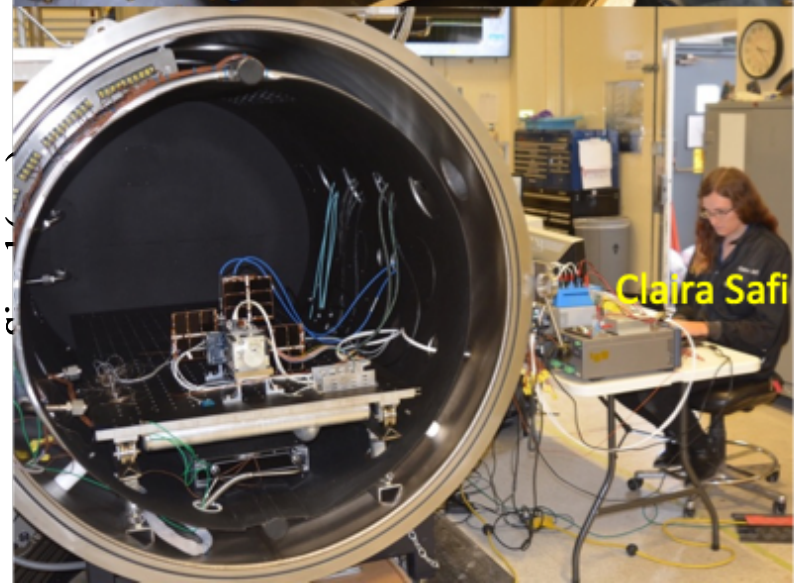
Vibration



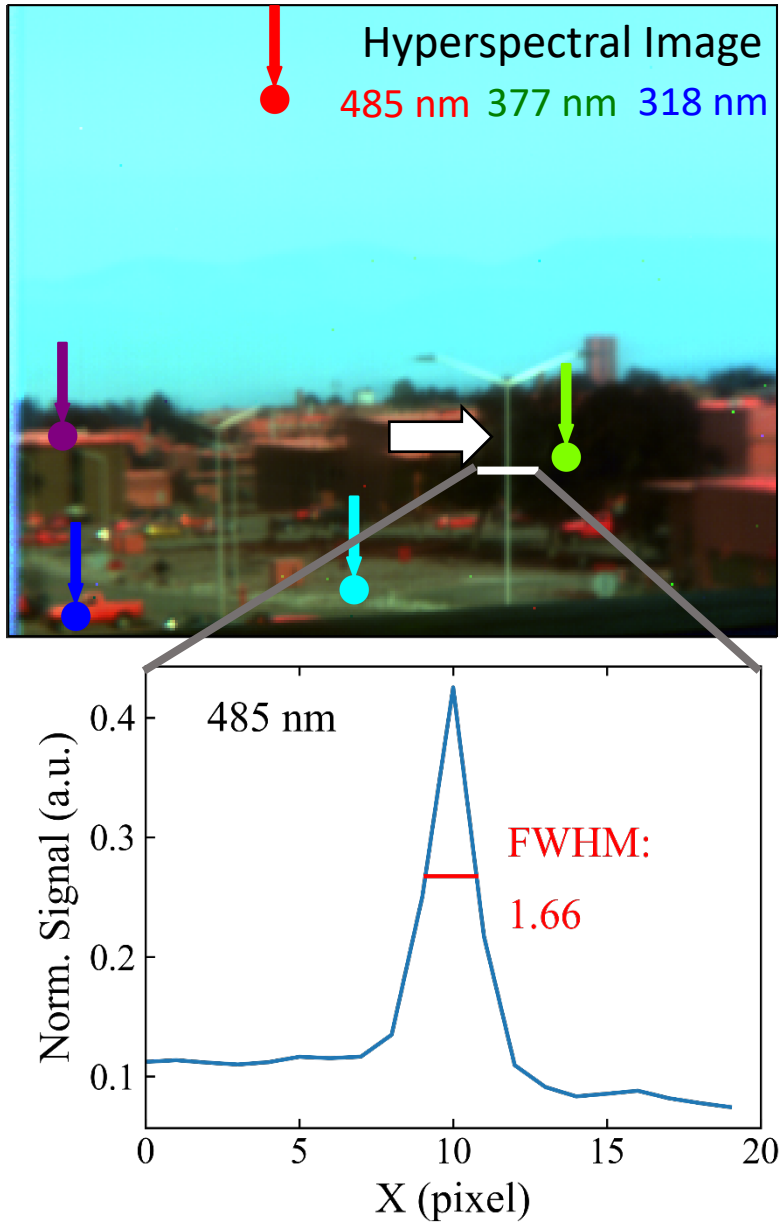


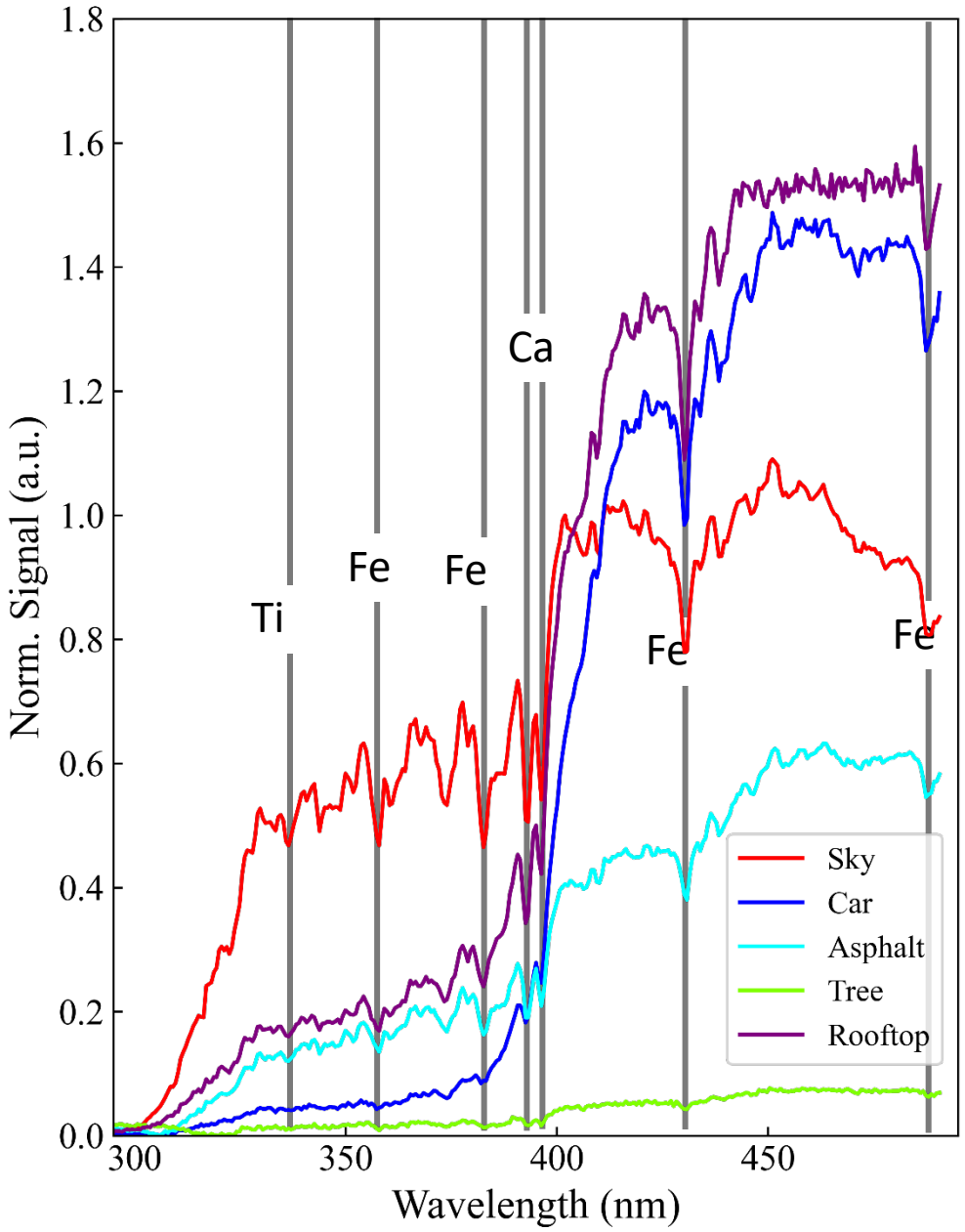


Thermal Vacuum



Outdoor Testing



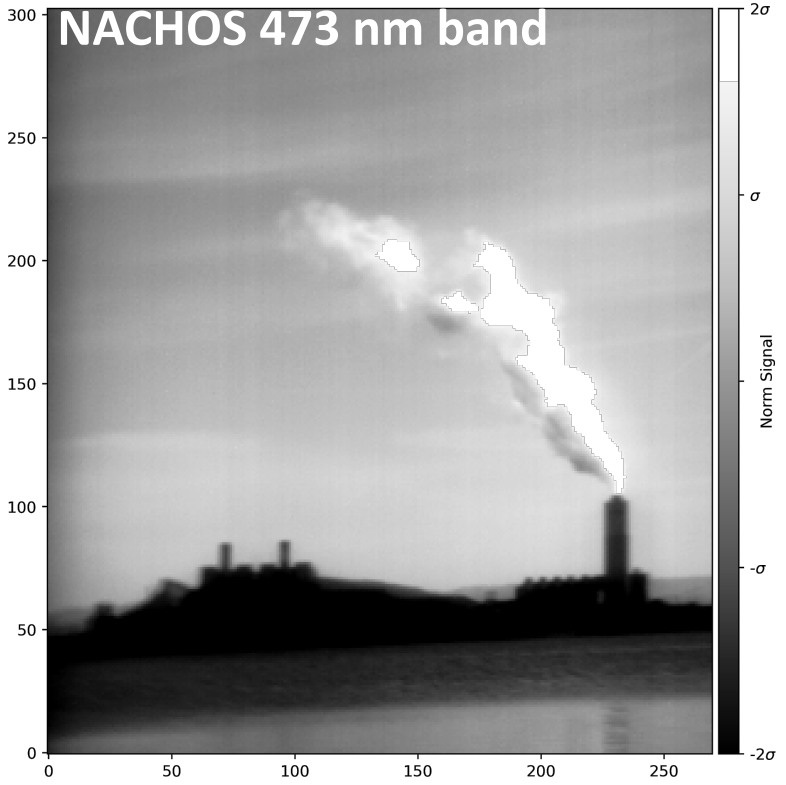


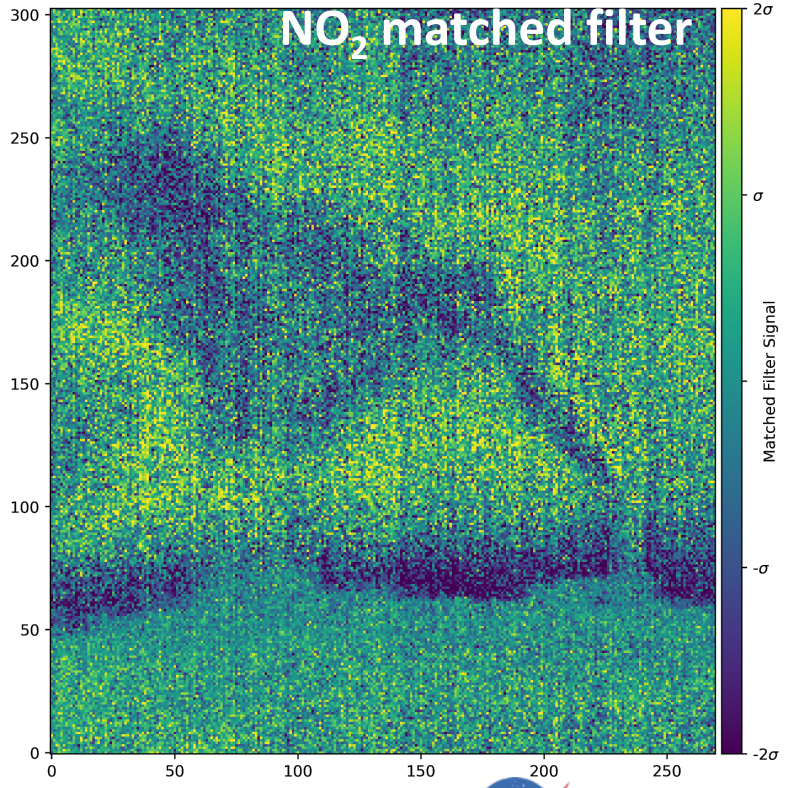
Most of the sharp spectral features seen here arise from the solar spectrum.

This ubiquitous solar spectrum will be used for on-orbit spectral calibration

Ground-based gas measurements with NACHOS engineering units:

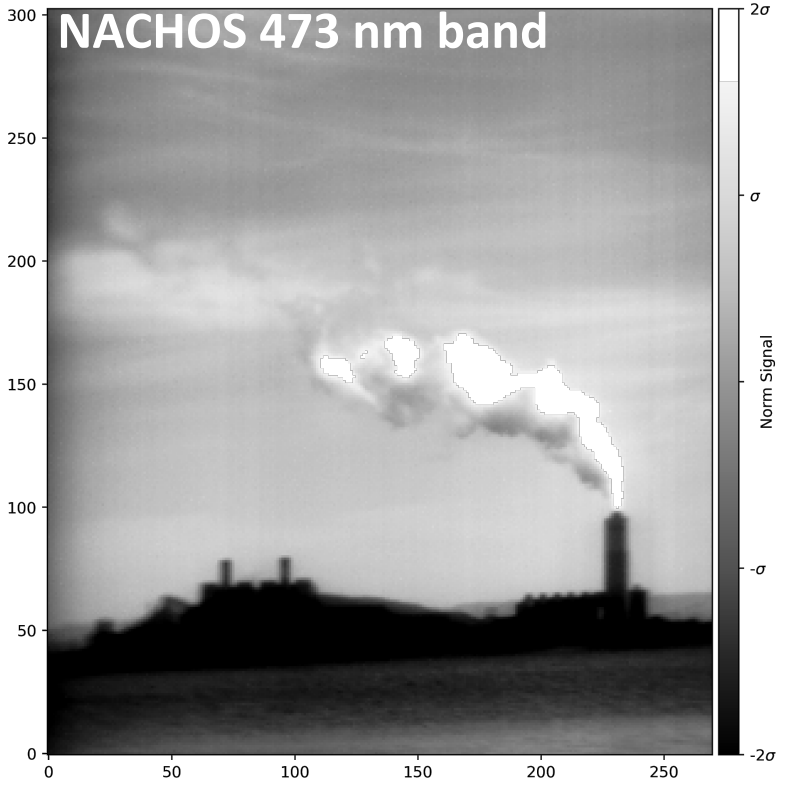
Coal-fired power plants near Farmington, NM

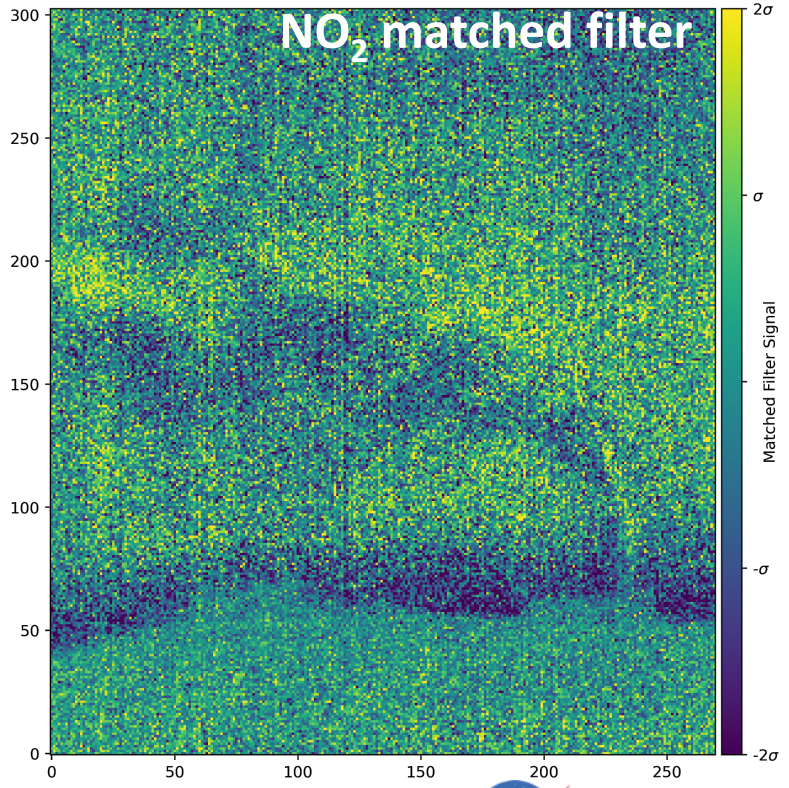




Ground-based gas measurements with NACHOS engineering units:

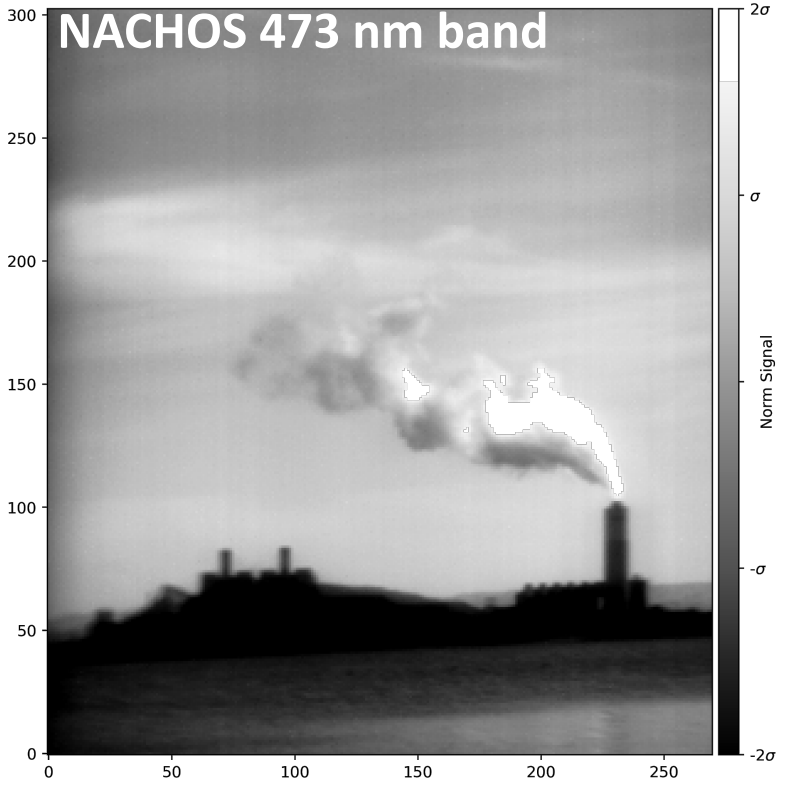
Coal-fired power plants near Farmington, NM

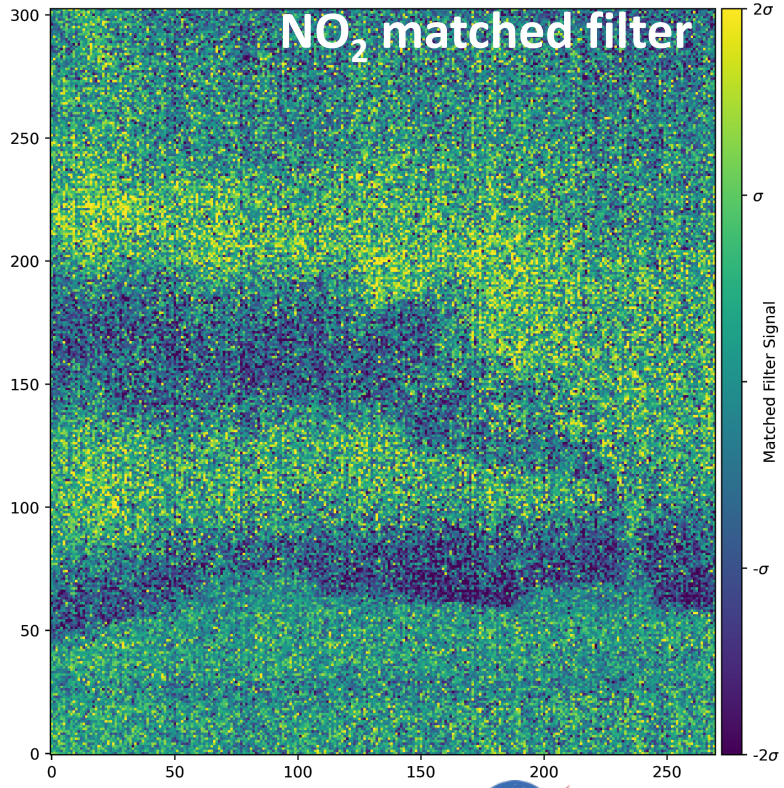




Ground-based gas measurements with NACHOS engineering units:

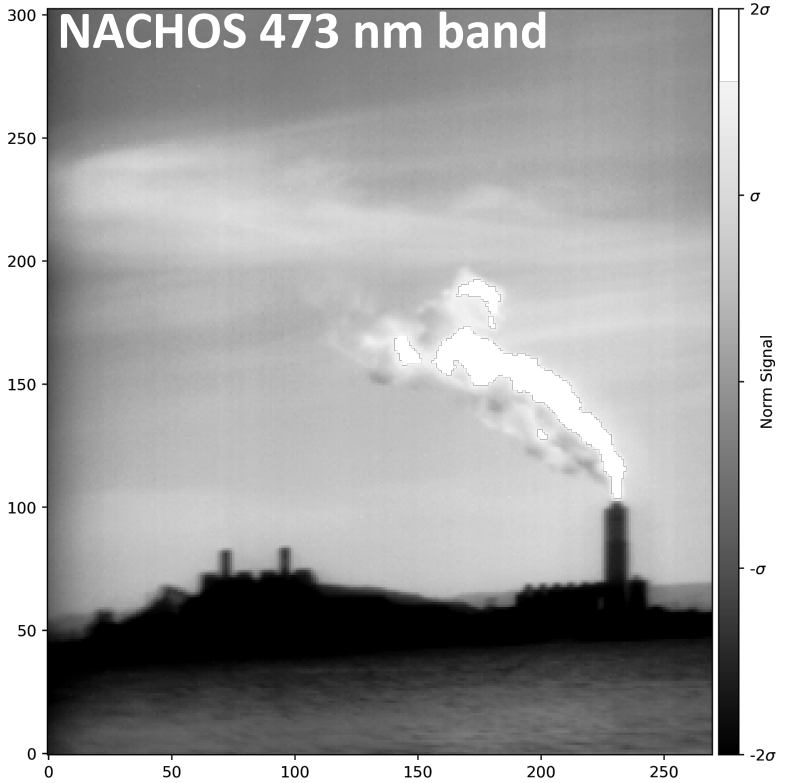
Coal-fired power plants near Farmington, NM

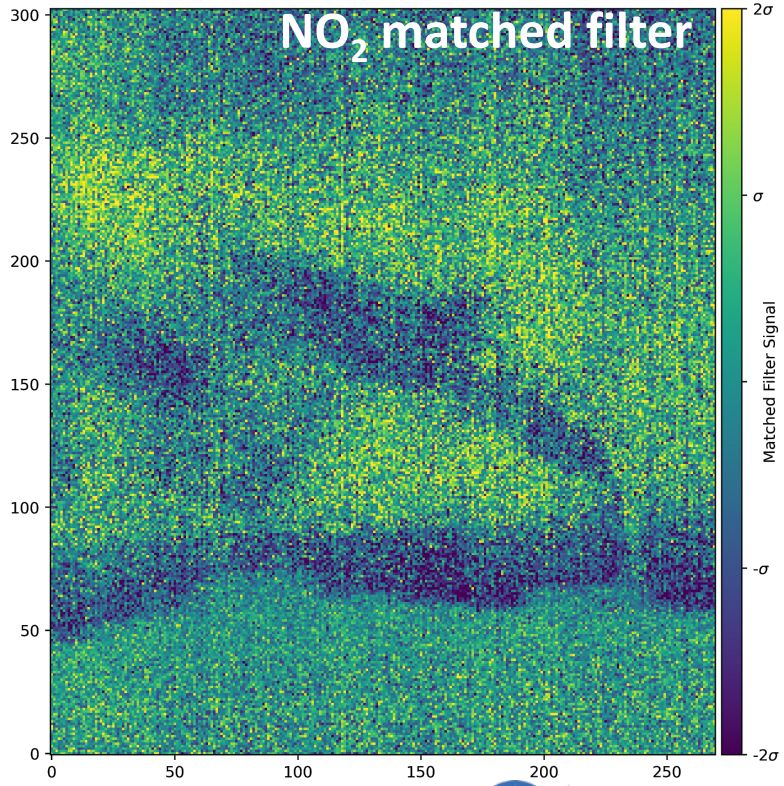




Ground-based gas measurements with NACHOS engineering units:

Coal-fired power plants near Farmington, NM





Ground-based gas measurements with NACHOS engineering units:

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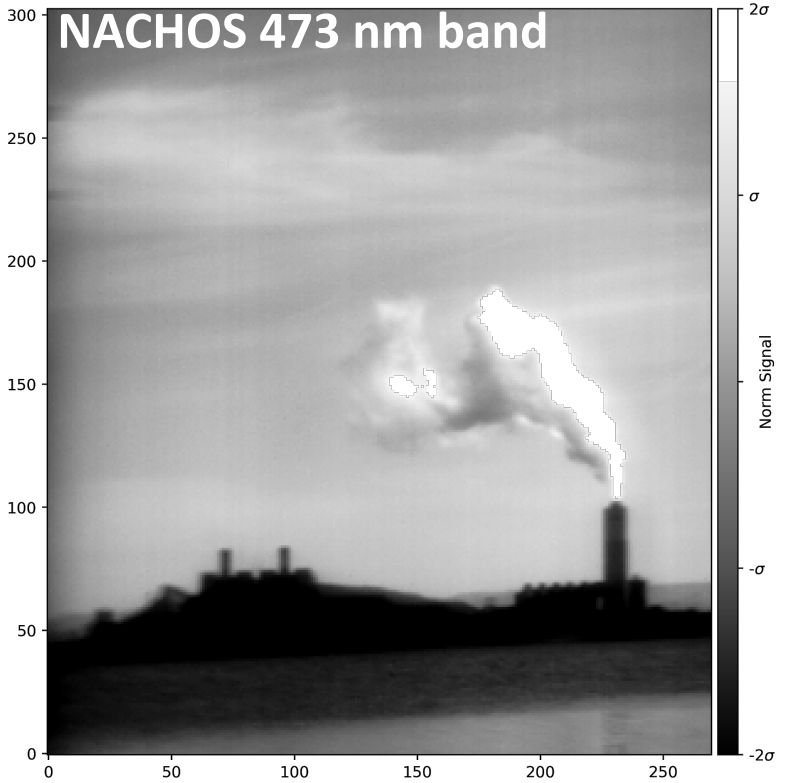
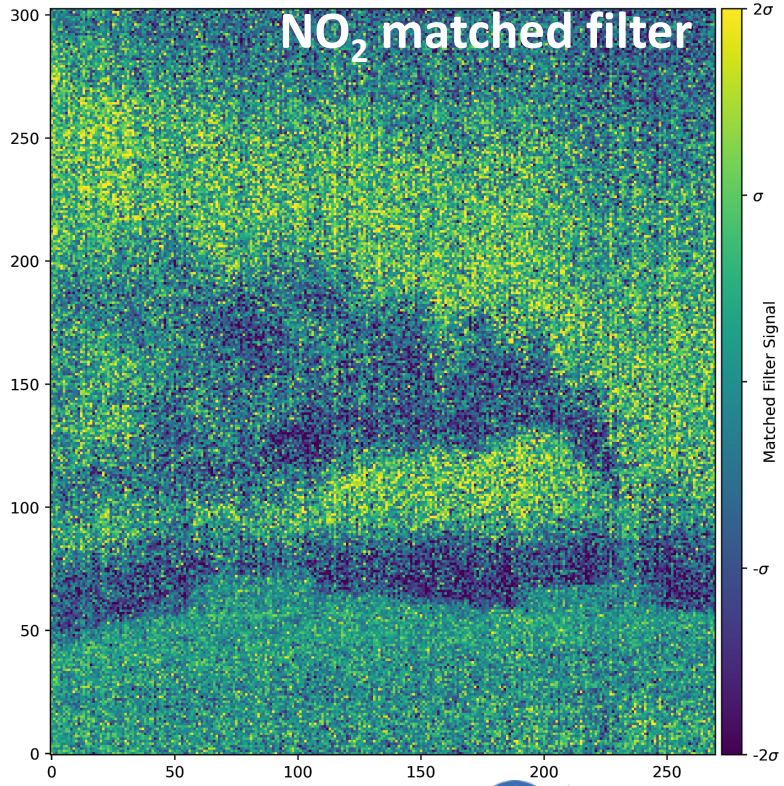
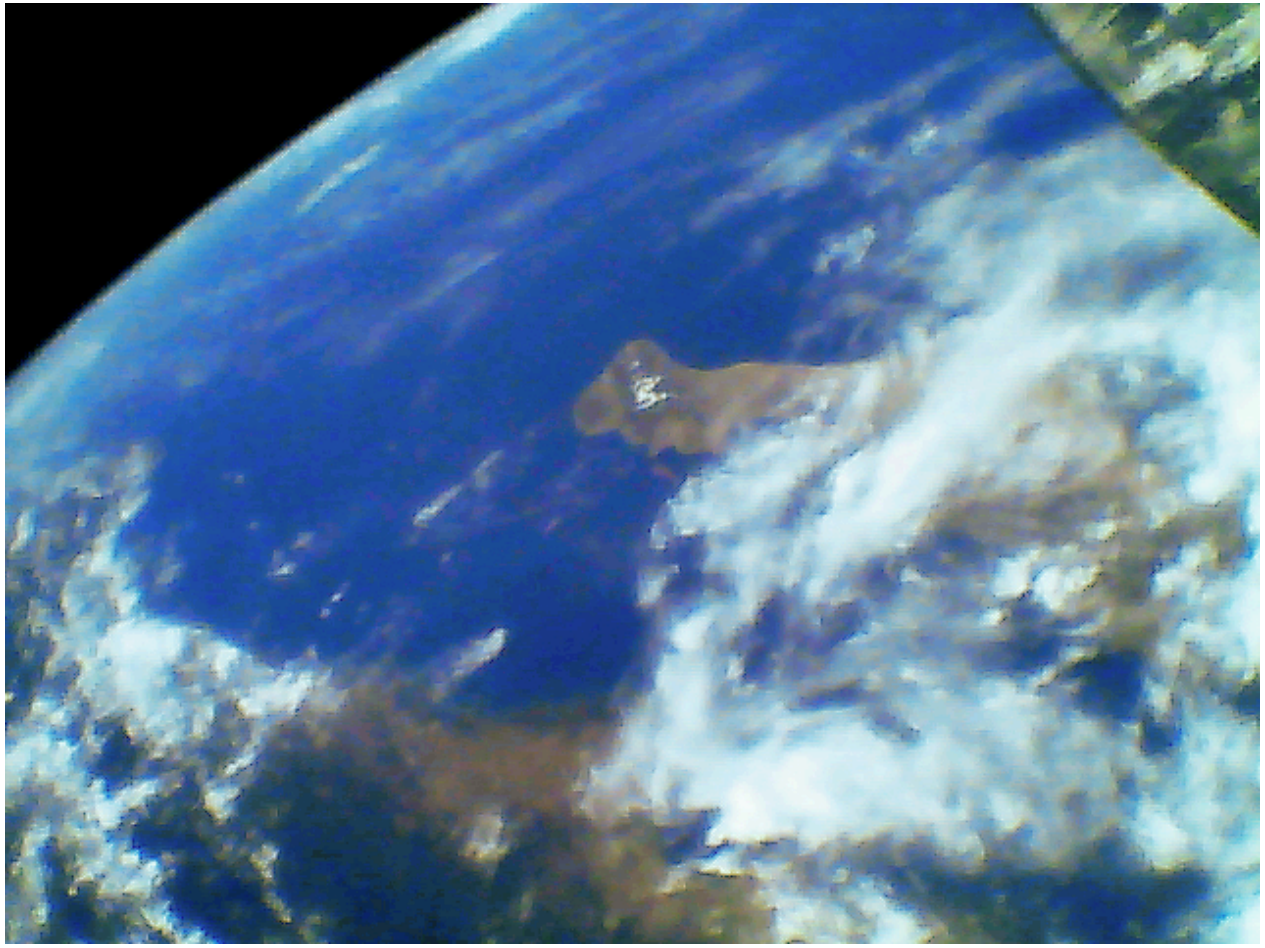




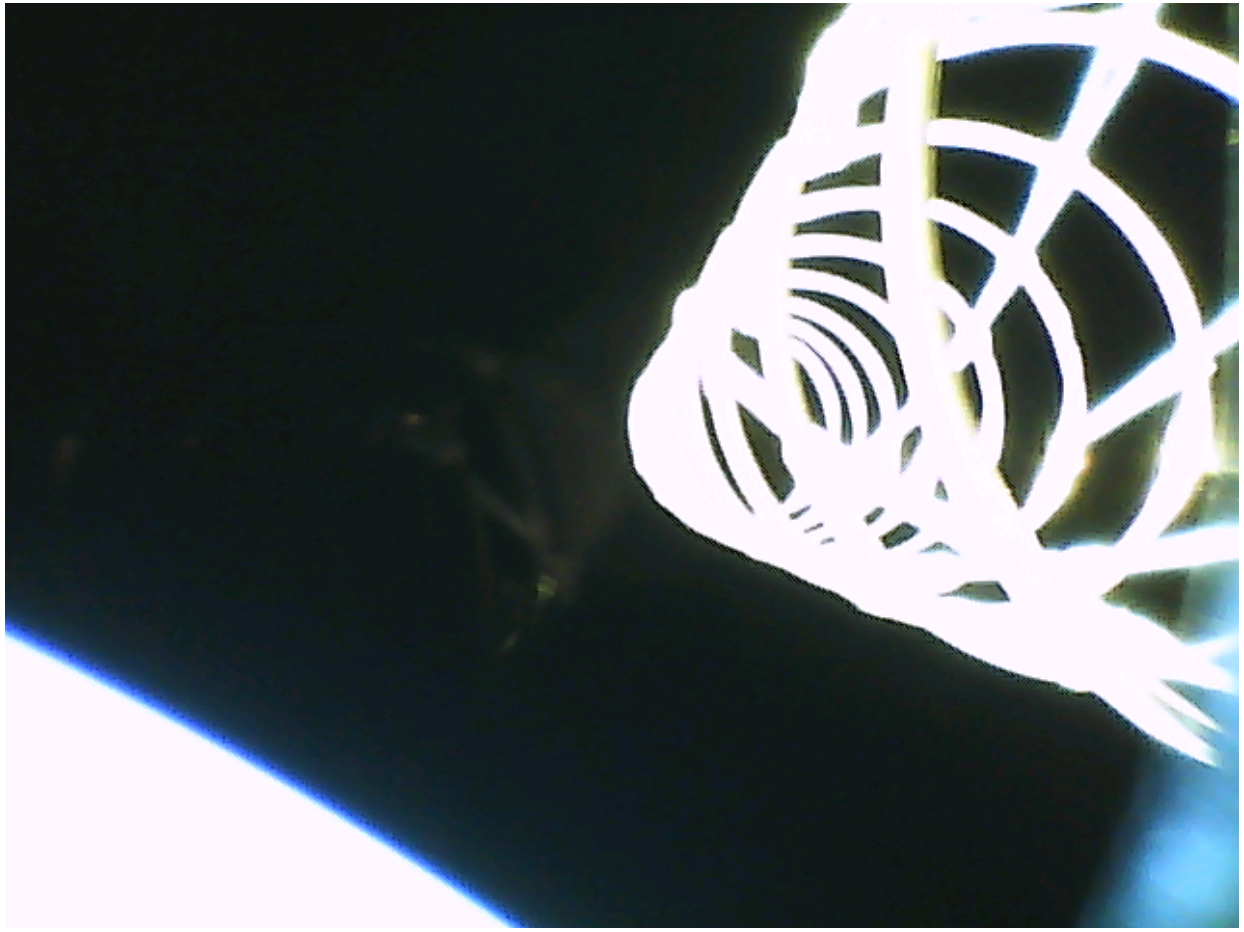
On-orbit operations are just beginning

NACHOS-2 Context Camera Images

Payload-end camera:



Host-end camera:



First-Light NACHOS-2 spectrum (uncalibrated, random targeting) – Downlinked August 7, 2022

- Solar Fraunhofer lines appear as they should
- Excellent spectrometer focus and alignment, virtually unchanged from pre-launch