InVEST-17-0013

NACHOS: A 3U CubeSat for High-Resolution Hyperspectral Imaging of Atmospheric Trace Gases

Steven P. Love

Kirk W. Post, Logan A. Ott, Magdalena E. Dale, Claira L. Safi, Hannah D. Mohr, Kerry G. Boyd, Markus P. Hehlen, Christian R. Ward, Michael P. Caffrey, James A. Wren, Ryan L. Hemphill, Kristina G. McKeown, James Theiler, Bernard R. Foy, Manvendra K. Dubey

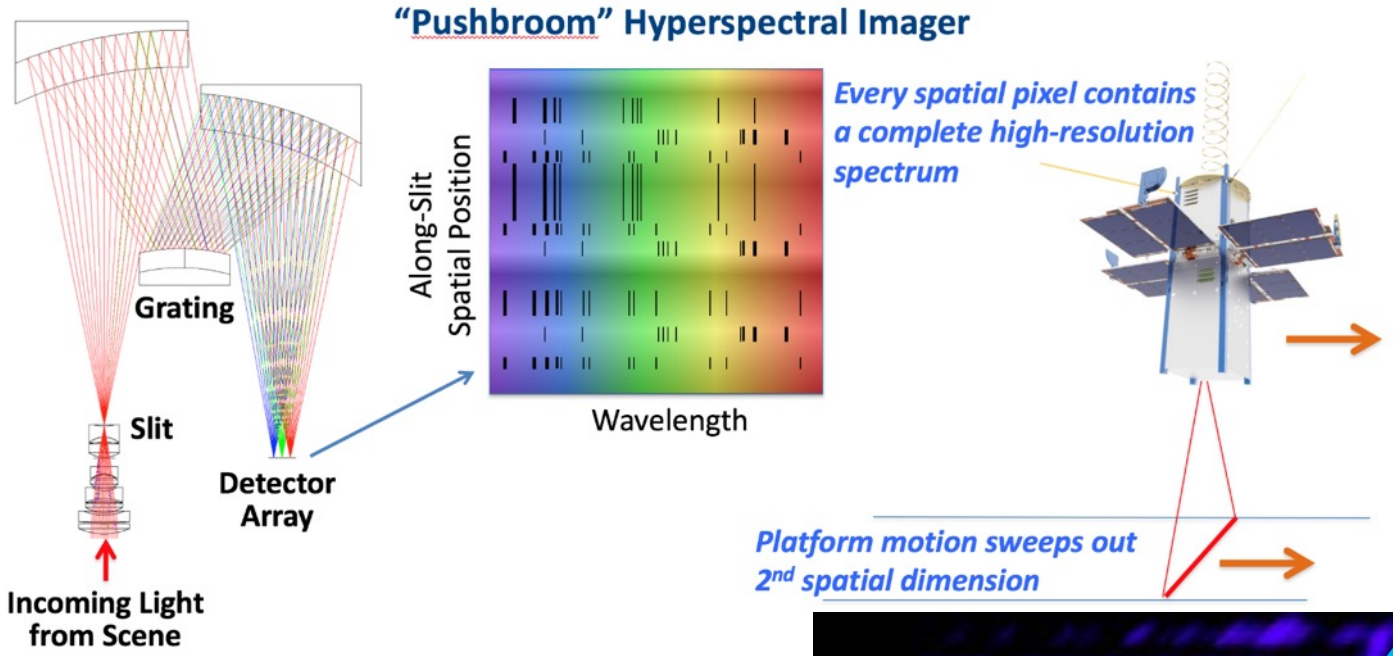
Los Alamos National Laboratory

Los Alamos NATIONAL LABORATORY

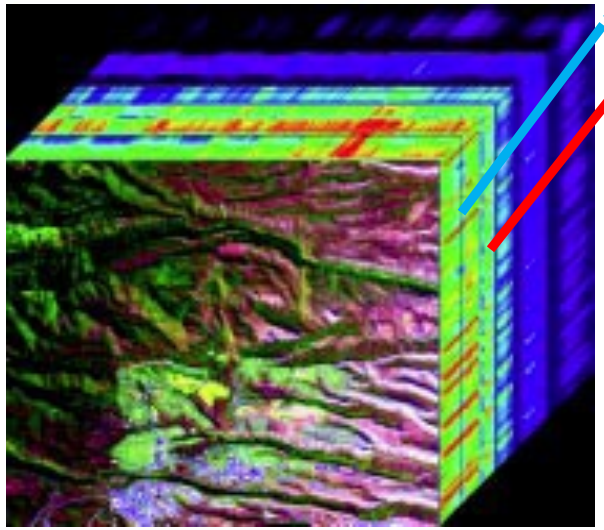
LA-UR-21-25547

NACHOS goal: High-resolution hyperspectral imaging of trace gases, with streamlined onboard gas retrieval processing

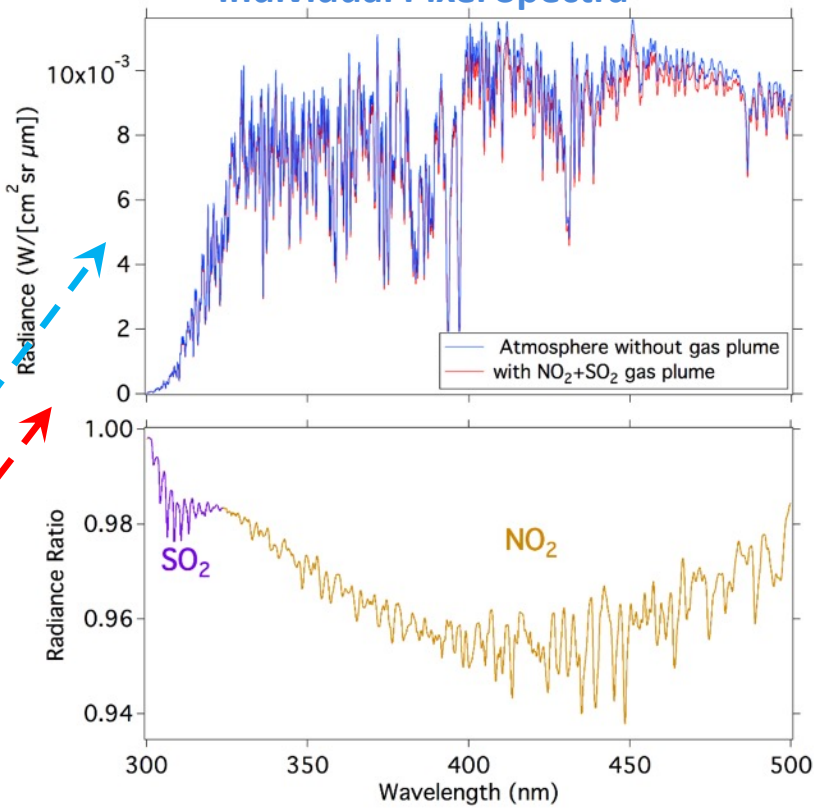
Hyperspectral Imaging: Each pixel contains a high-resolution spectrum



Hyperspectral Data Cube (~400 MB):



Individual Pixel Spectra



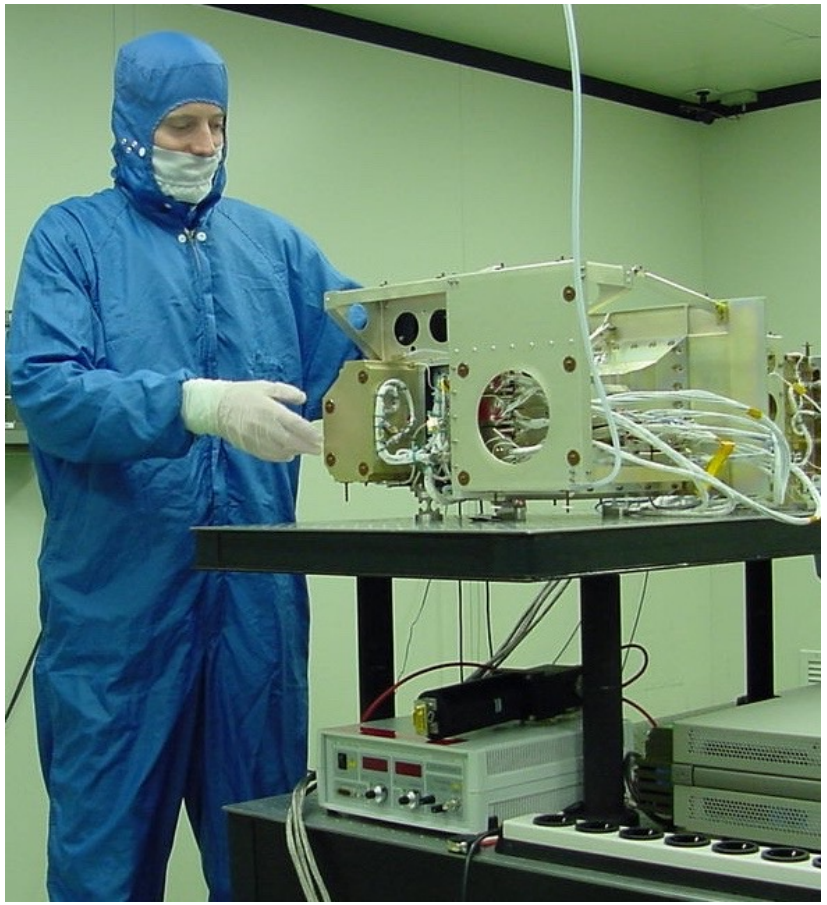
- Ground materials: mineralogy, vegetation, etc.
  - Relatively easy; requires only modest spectral resolution and sensitivity.

→ **Atmospheric trace gases**

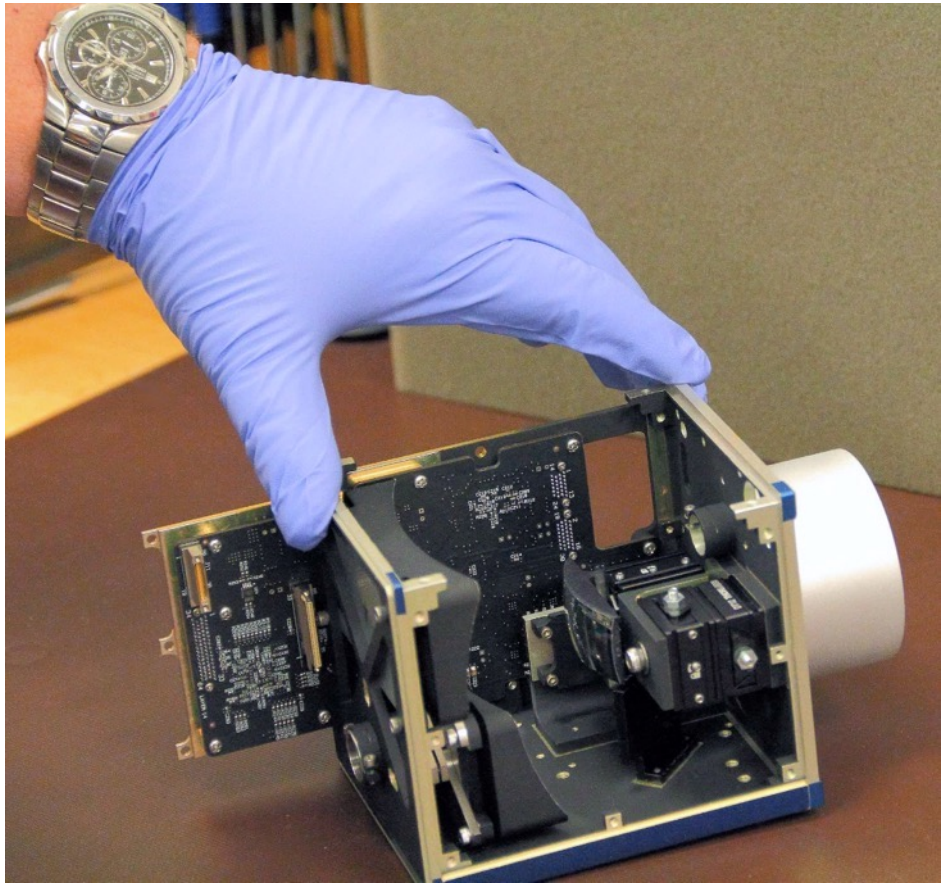
- Requires much higher spectral resolution and sensitivity. Traditionally has required a big, expensive, large-satellite instrument.

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

NASA Ozone Monitoring Instrument (OMI)
270-500 nm, 0.5-1.0 nm resolution
65 kg (instrument only)



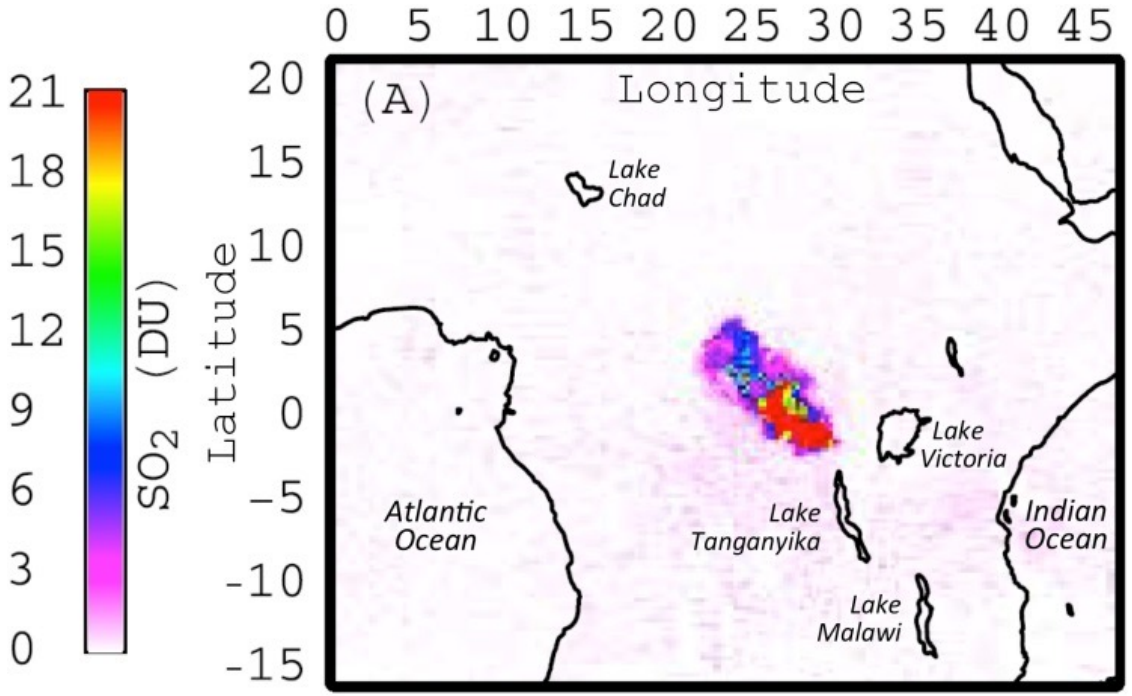
NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)
290-500 nm, 1.3 nm resolution, 0.6 nm sampling
4 kg (complete satellite)*



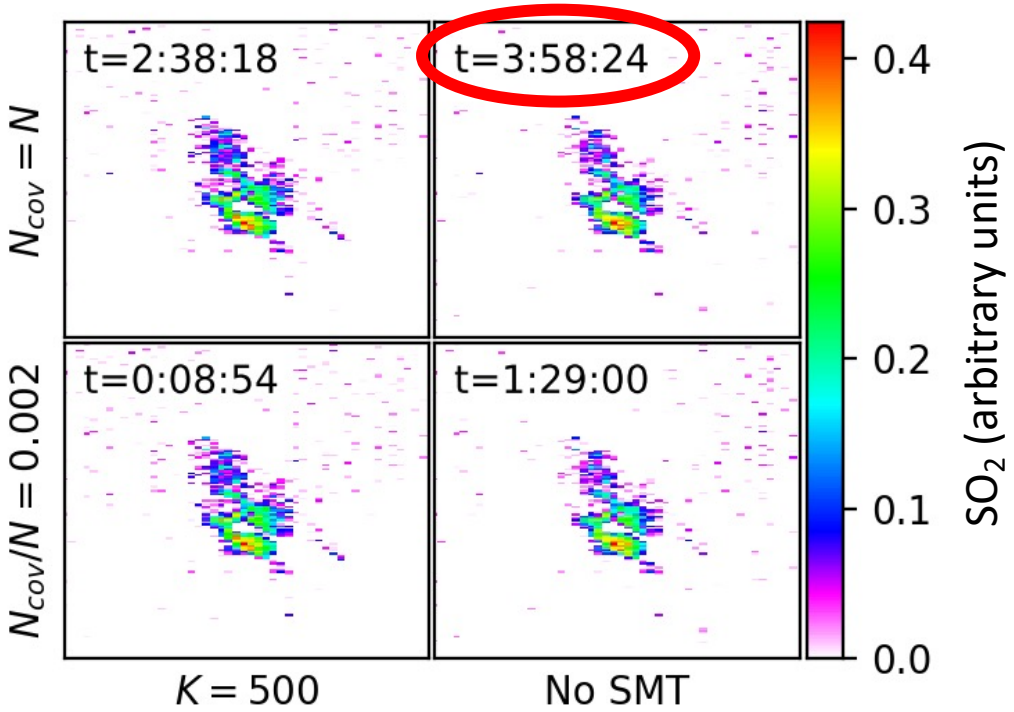
*** Now ballasted up to 6.25 kg to increase orbital lifetime**

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



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

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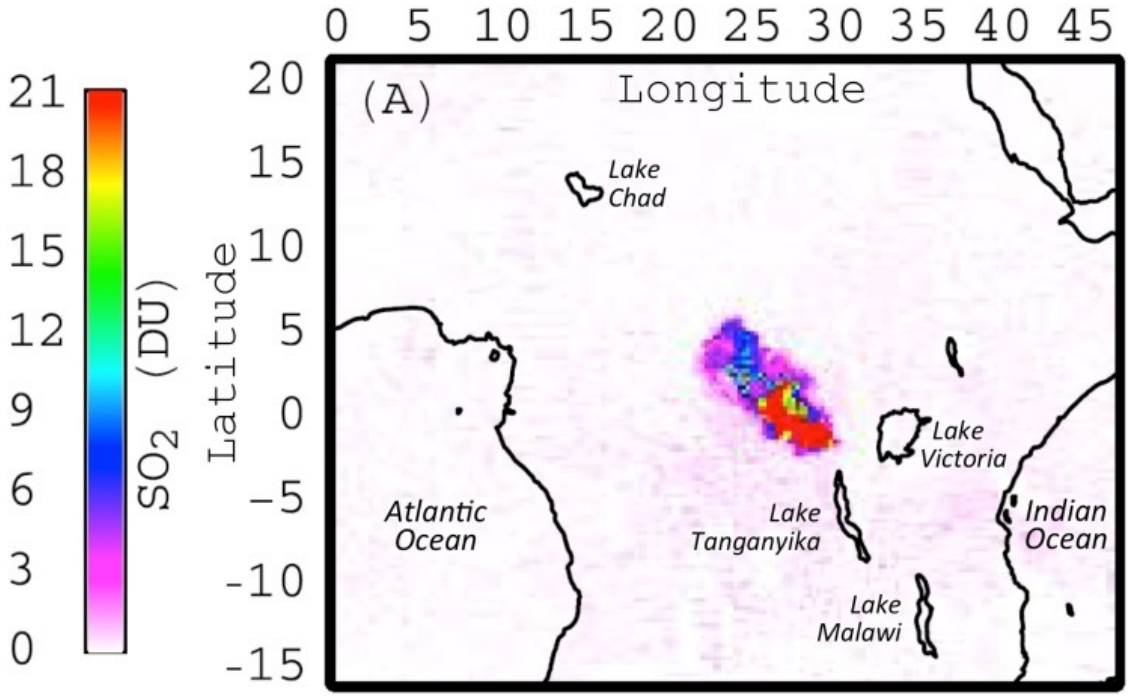

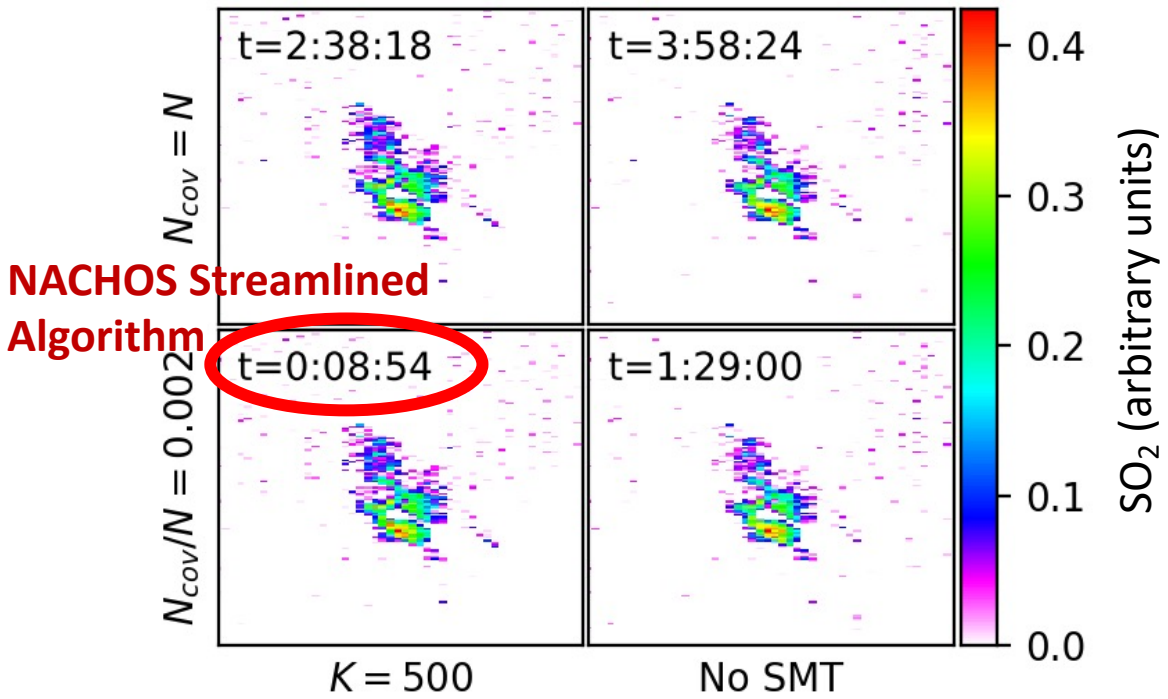

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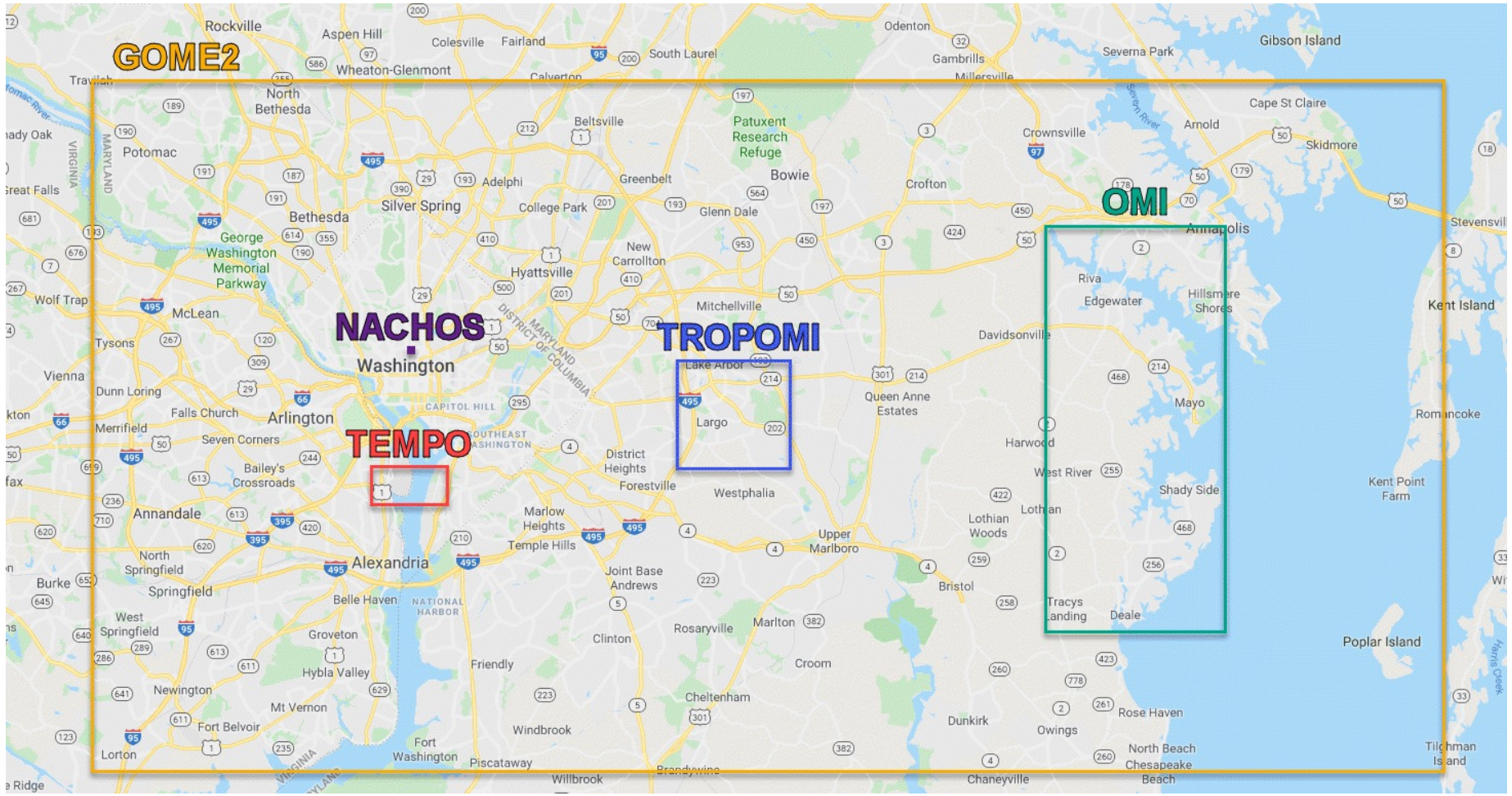
NACHOS Niche: Targeted, high spatial resolution gas imaging

Ground pixel size comparison:
NACHOS *vs.* current & planned gas imaging satellite instruments



NACHOS pixel: ~0.4 km at 500 km altitude

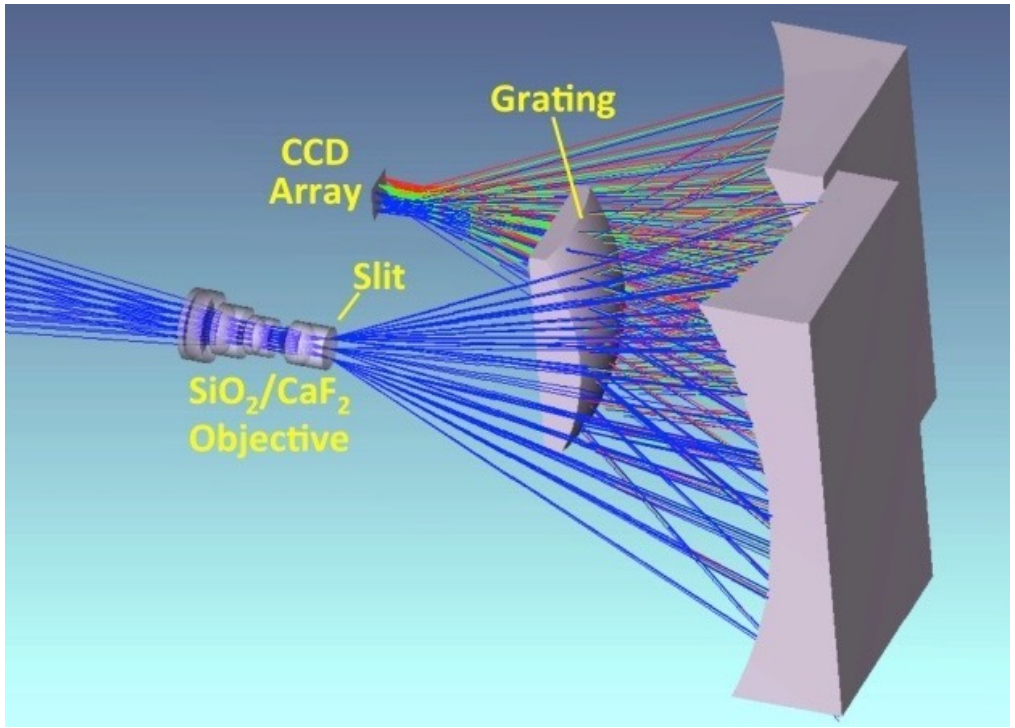
NACHOS 350-pixel swath width corresponds to a ~140 km swath at 500 km altitude

Envisioned NACHOS constellation would provide frequent target revisits

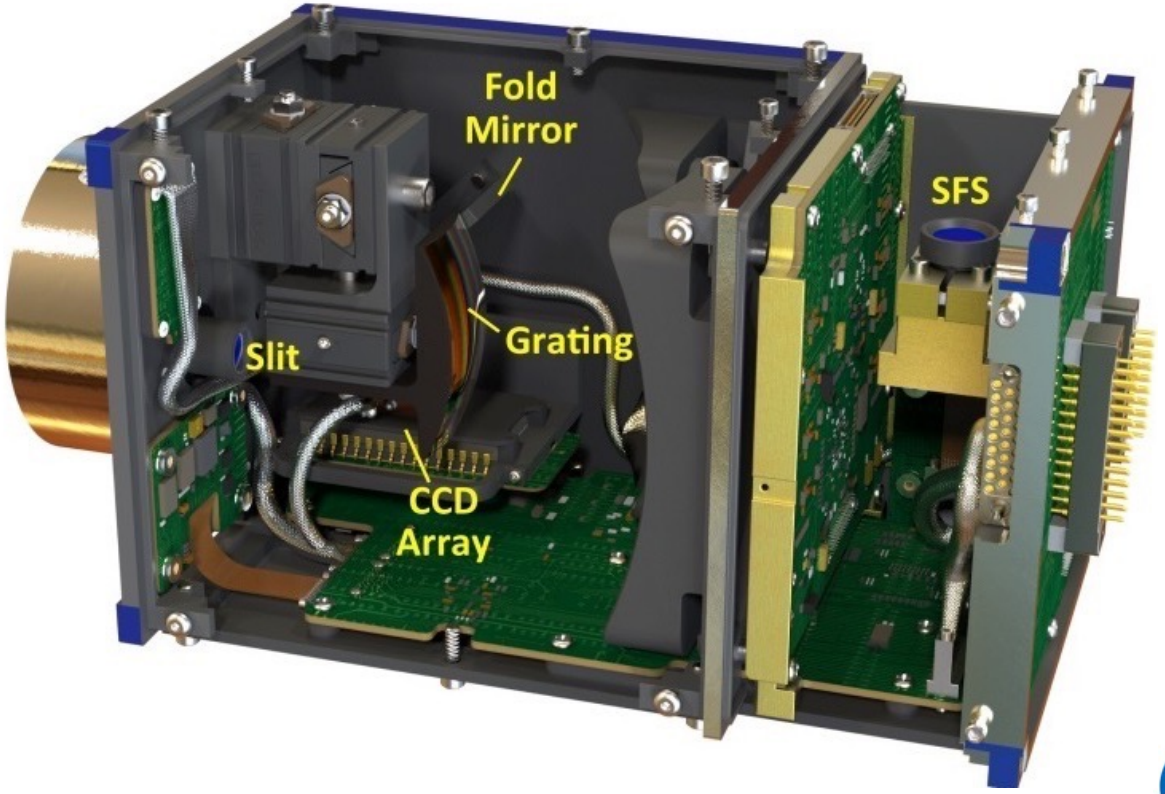
Challenge: Miniaturization to CubeSat scale while maintaining performance

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 (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

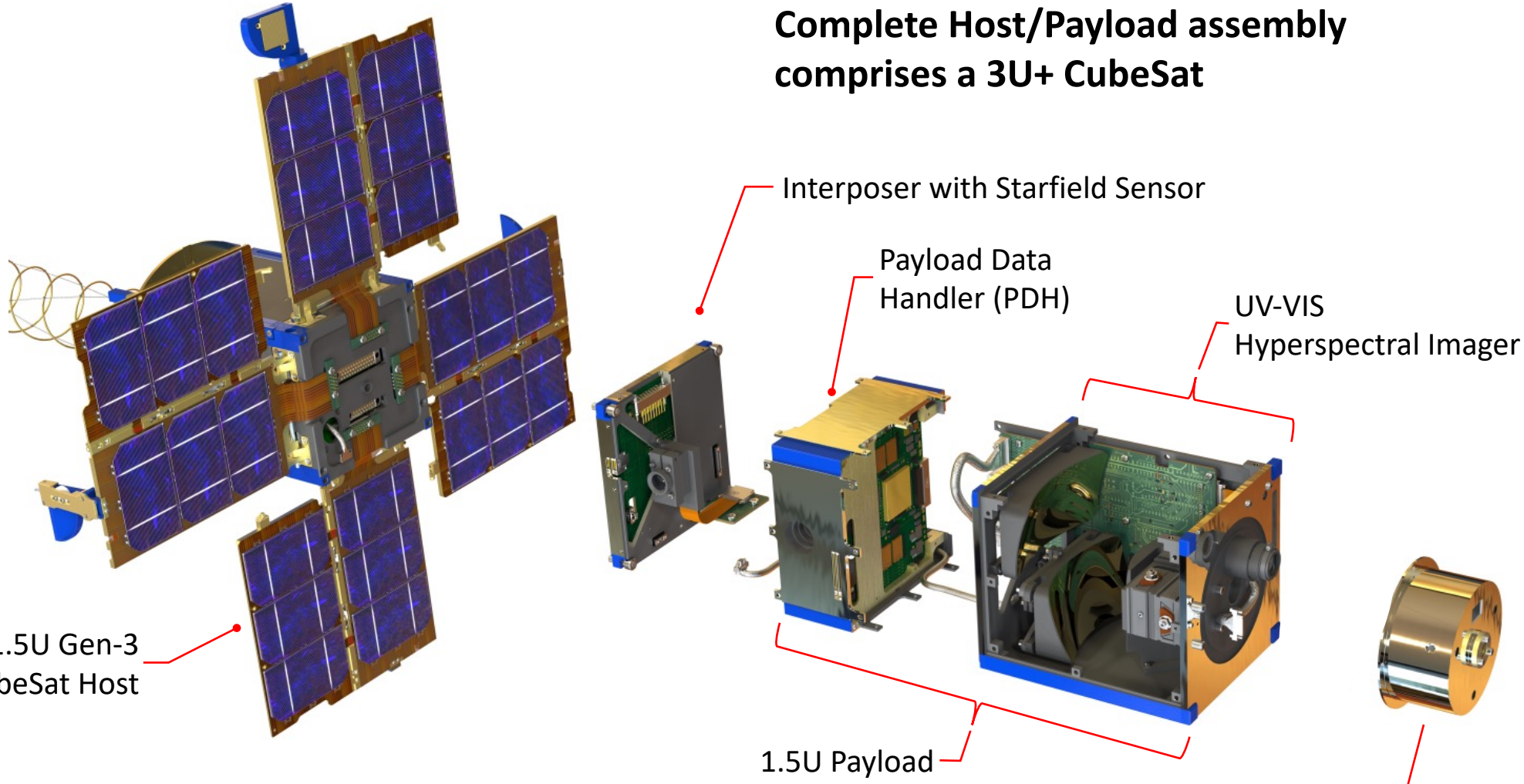


Spectrometer & Electronics comprise a 1.5U+ package



NACHOS Payload Hosted on LANL's 3rd-Geneation CubeSat Bus

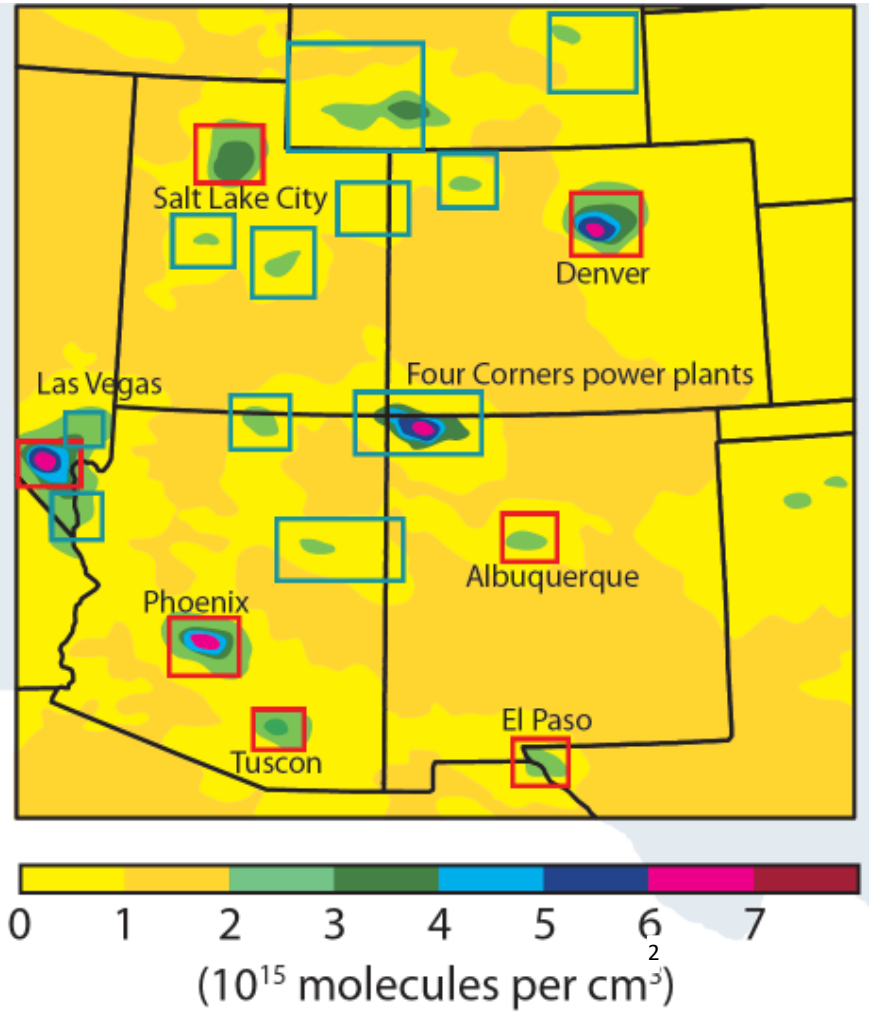
Complete Host/Payload assembly comprises a 3U+ CubeSat



(sun shade, thermal stability, and atomic O protection)

Science applications: (1) NO_2 as marker of fossil fuel burning

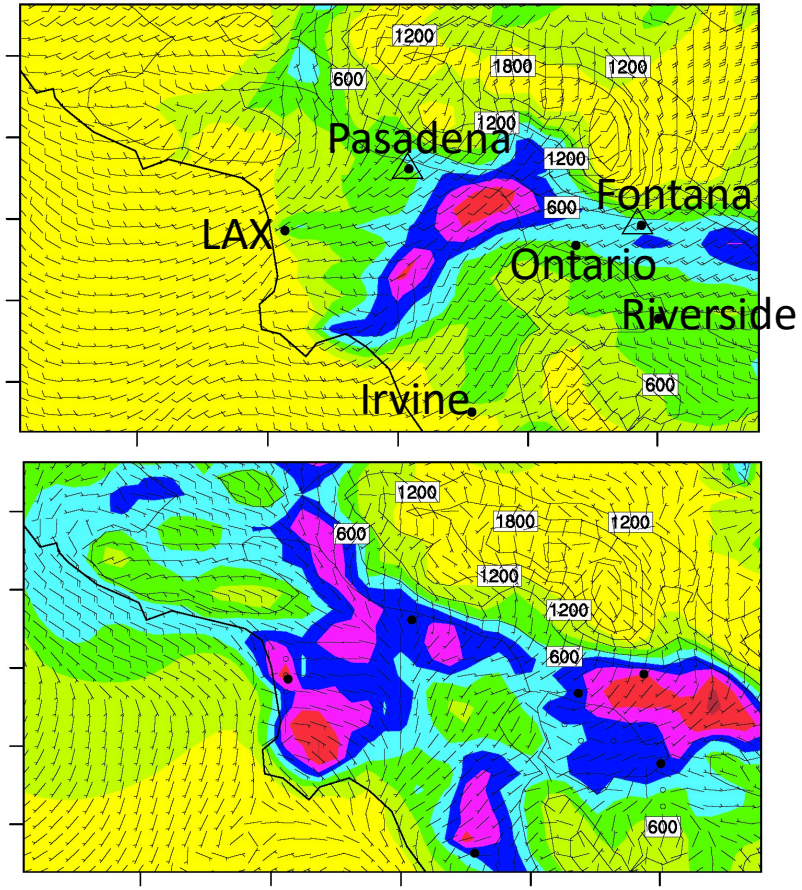
OMI provides regional-scale imagery:



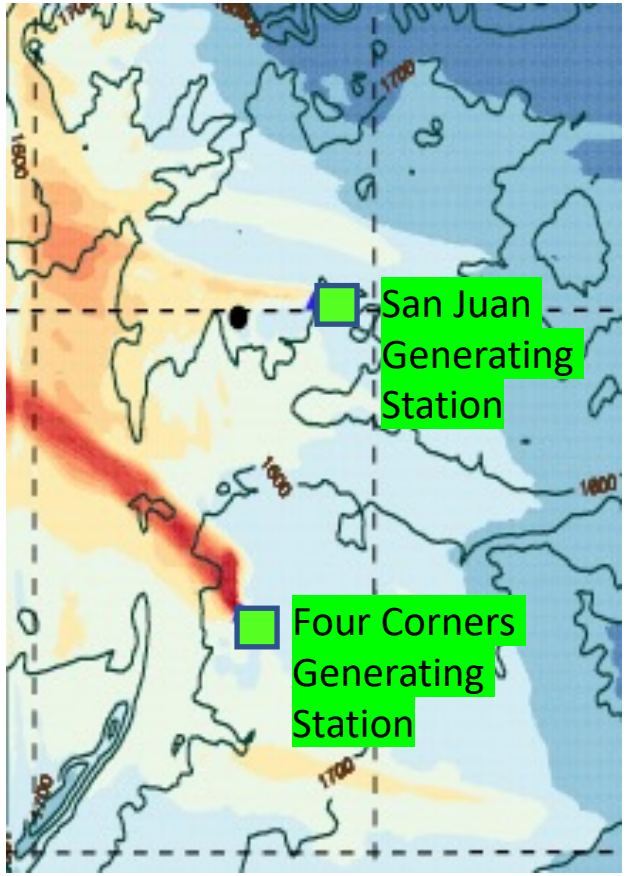
NASA OMI Image

NACHOS will provide local-scale imagery

…of urban areas



…or individual power plants

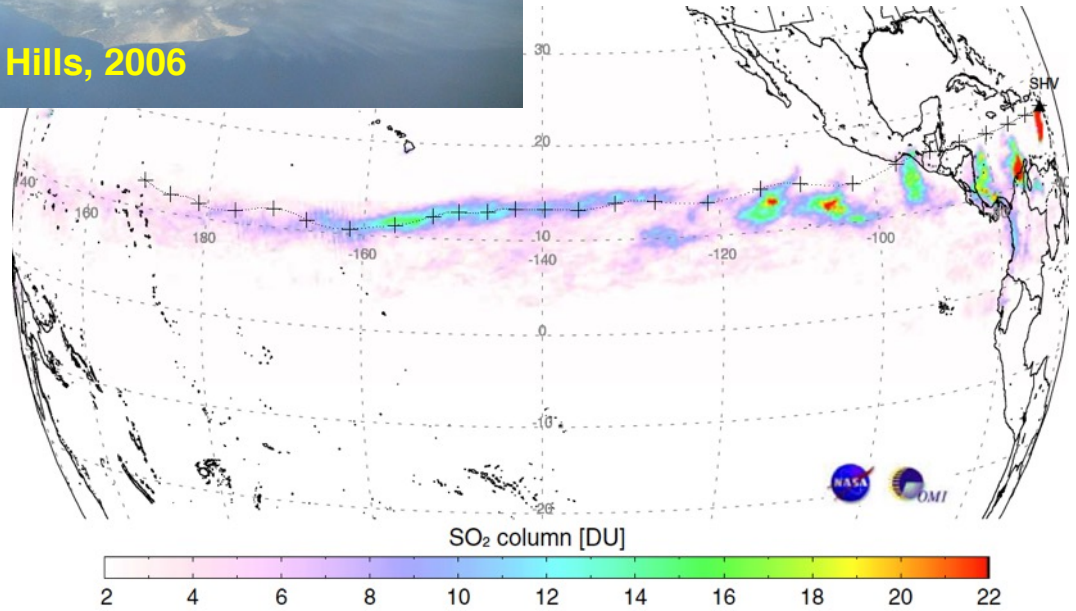


Modeled NO_2 images at roughly NACHOS spatial resolution

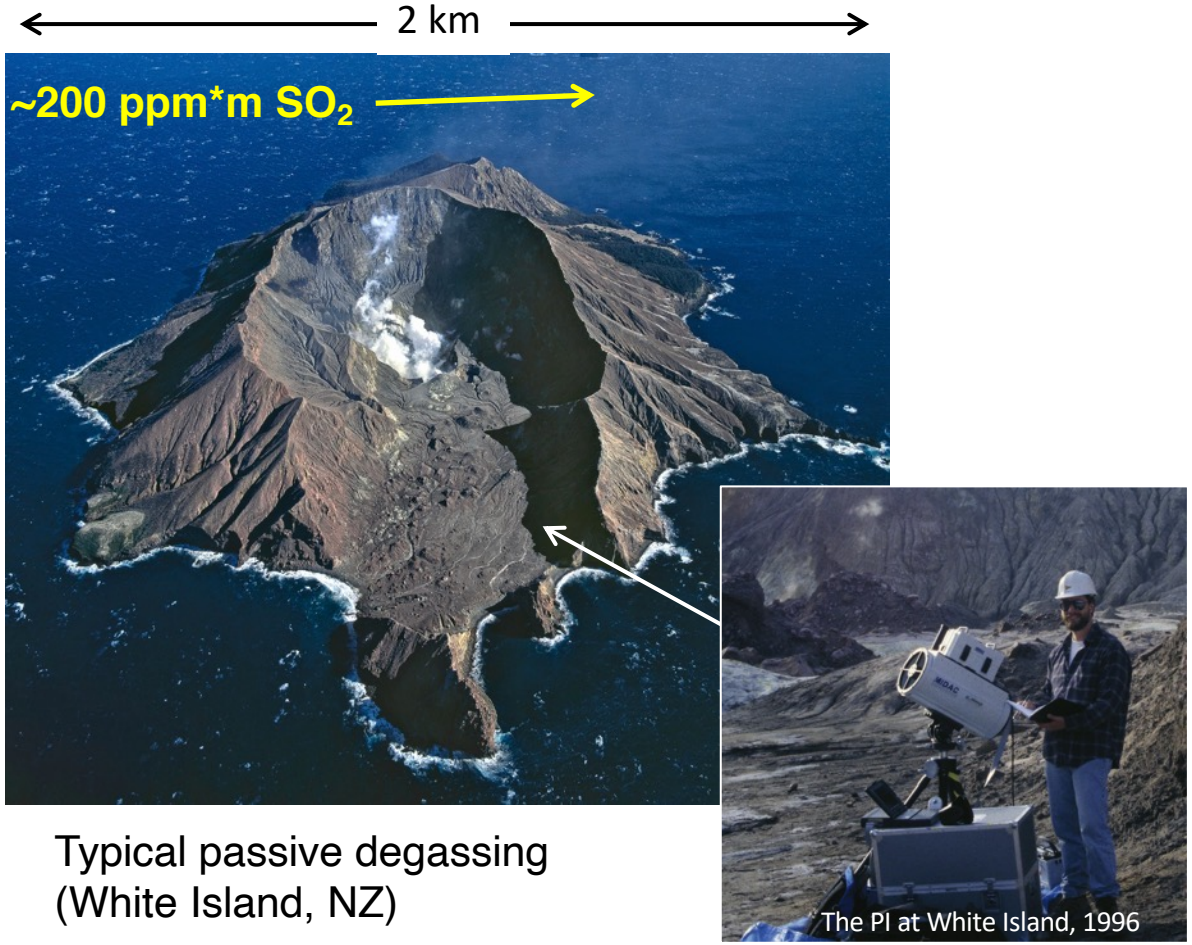
Science applications: (2) SO_2 imaging for volcanology

OMI, etc. can image SO_2 plumes from large events

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



NACHOS is aimed at monitoring low-level passive degassing at recently awakened volcanoes



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.

…

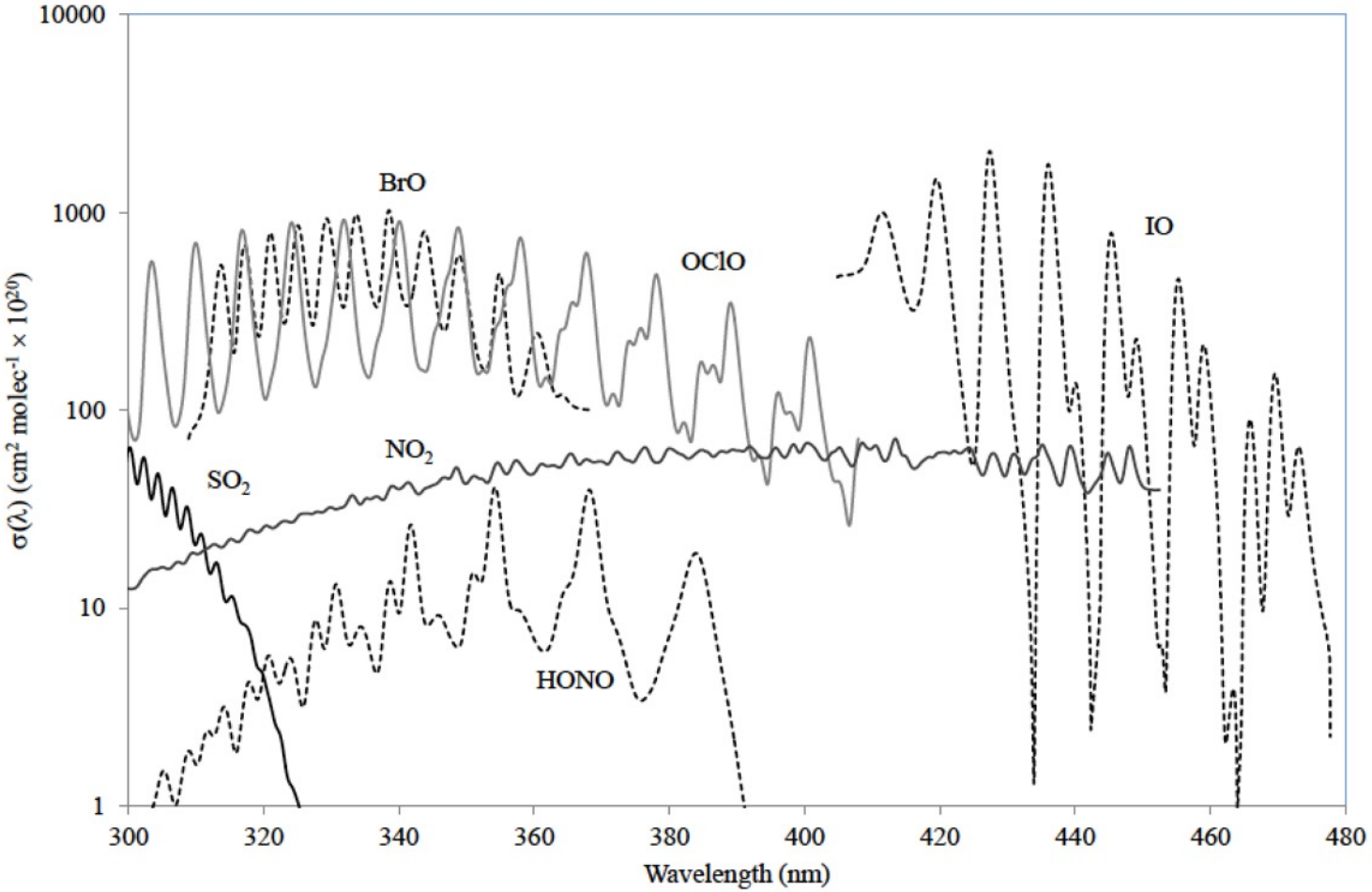
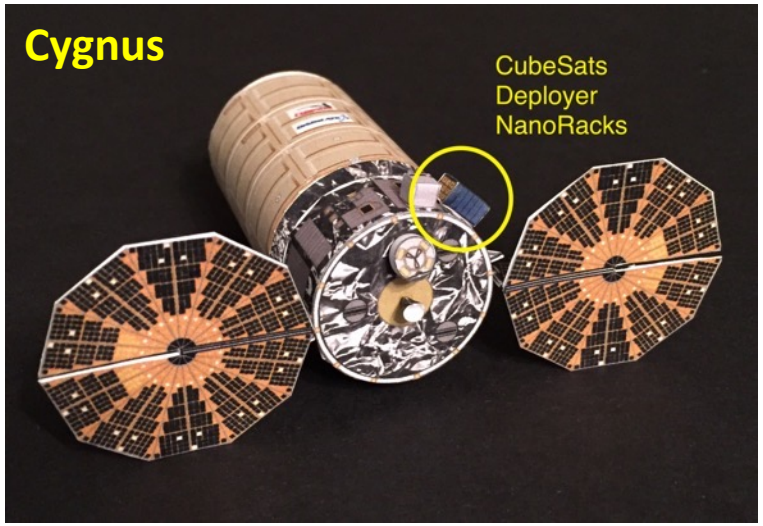


Figure from: C. Oppenheimer, B. Scaillet, and R. S. Martin, "Sulfur Degassing From Volcanoes: Source Conditions, Surveillance, Plume Chemistry and Earth System Impacts," *Reviews in Mineralogy & Geochemistry* **73,** 363-421 (2011).

Two NACHOS satellites are being built. We are hoping to fly both.

Primary NASA InVEST Flight Unit

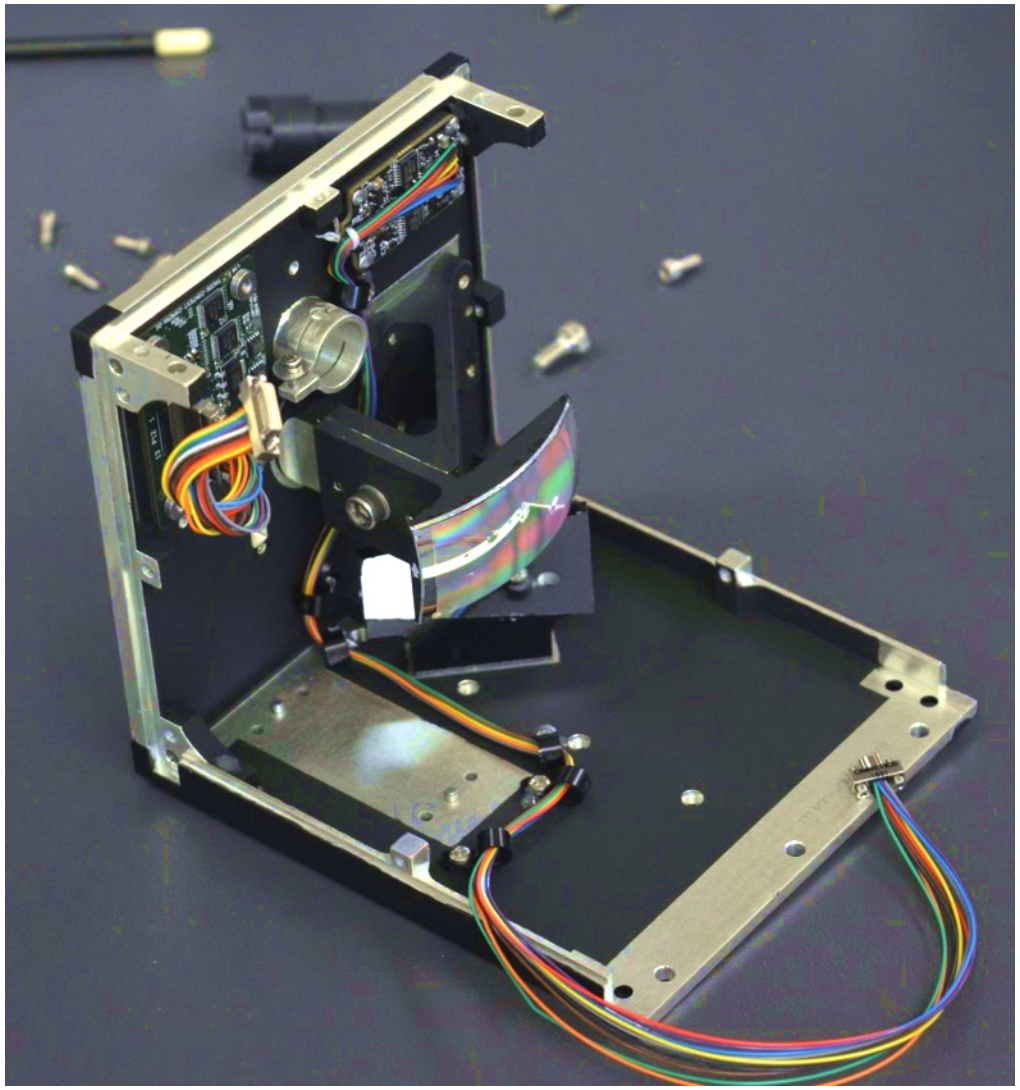
- All subassemblies ready; final assembly awaiting results of QM TVAC and Vibration tests; planned for mid- to late July
- TVAC and Vibration in Aug.-Sept.
- Launch under NASA CSLI program aboard Cygnus ISS resupply vehicle (flight NG-17); launch integrator NanoRacks.
  - Delivery: Dec. 1, 2021
  - Launch to ISS: Feb., 2022
  - Undock from ISS and deploy to 485 km orbit: ~April-May, 2022



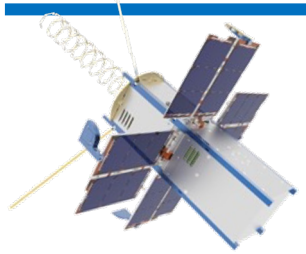
Qualification Model

- Integrated satellite complete
- Currently beginning Thermal Vacuum testing
- Vibration testing in early July
- Hope to launch under DoD's Space Test Program aboard VOX LauncherOne vehicle.
  - Launch to 500 km, 45˚ orbit: No earlier than Feb. 2022
- If this independent "bonus mission" goes forward, will be known as "NACHOS-2"

NACHOS Qualification Model assembly

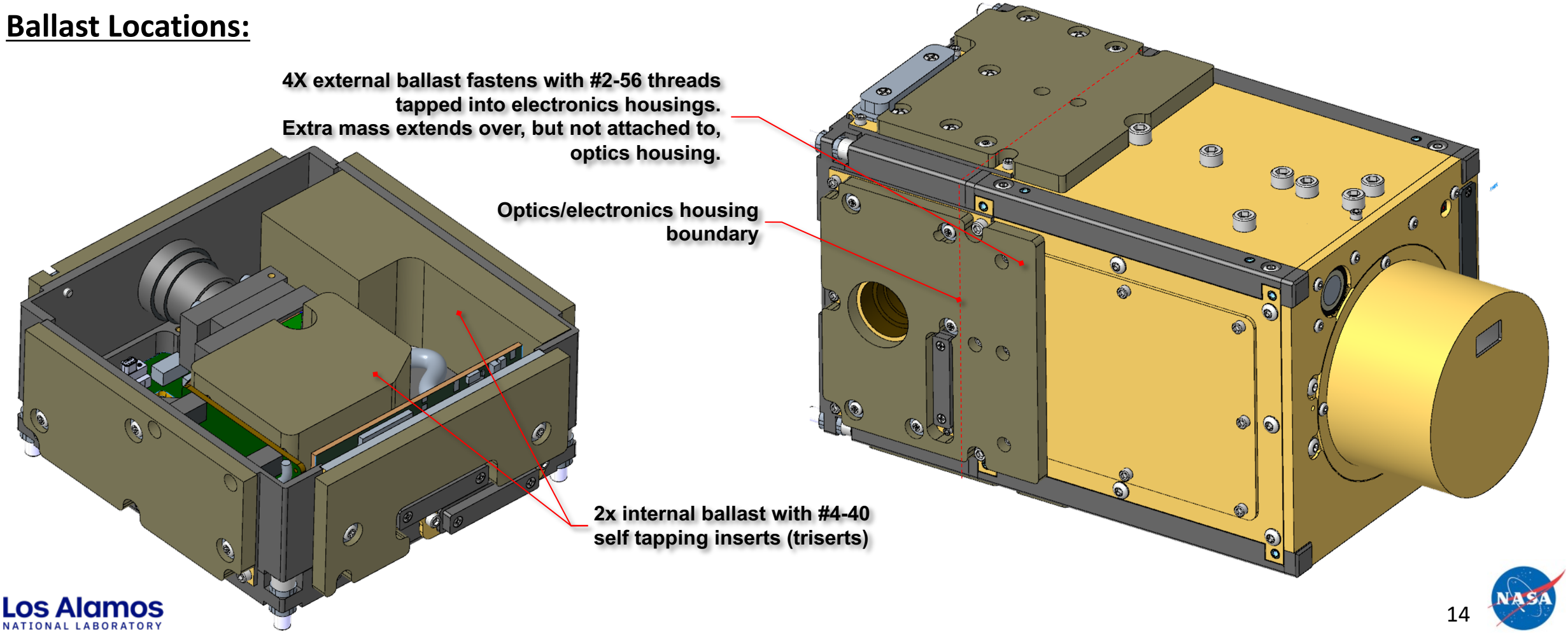


Addition of mass ballast to increase orbital lifetime



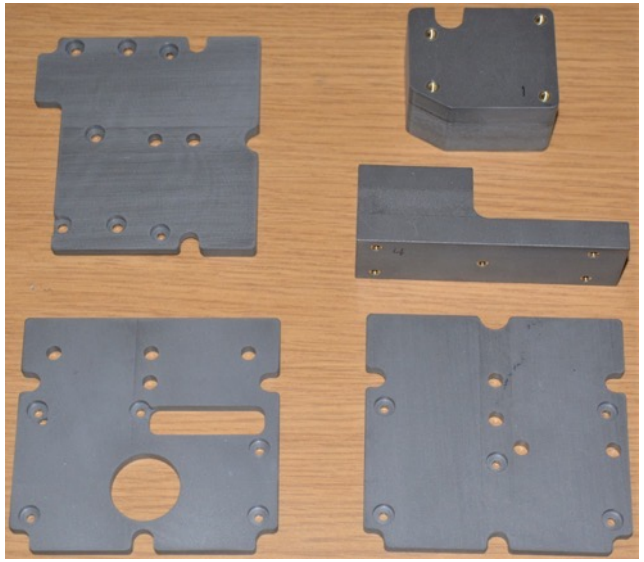
- Our deployable solar panels are great for providing lots of power, but the their large surface area creates greater drag in low earth orbit than is typical for a 3U CubeSat. With the advancing solar cycle, this becomes significant, even for the ~485 km Cygnus orbit.
- Improving the mass/area ratio by adding ~2 kg of ballast, increasing total mass to 6.25 kg, provides an acceptable ~1 year or better lifetime in our ~485 km orbit.

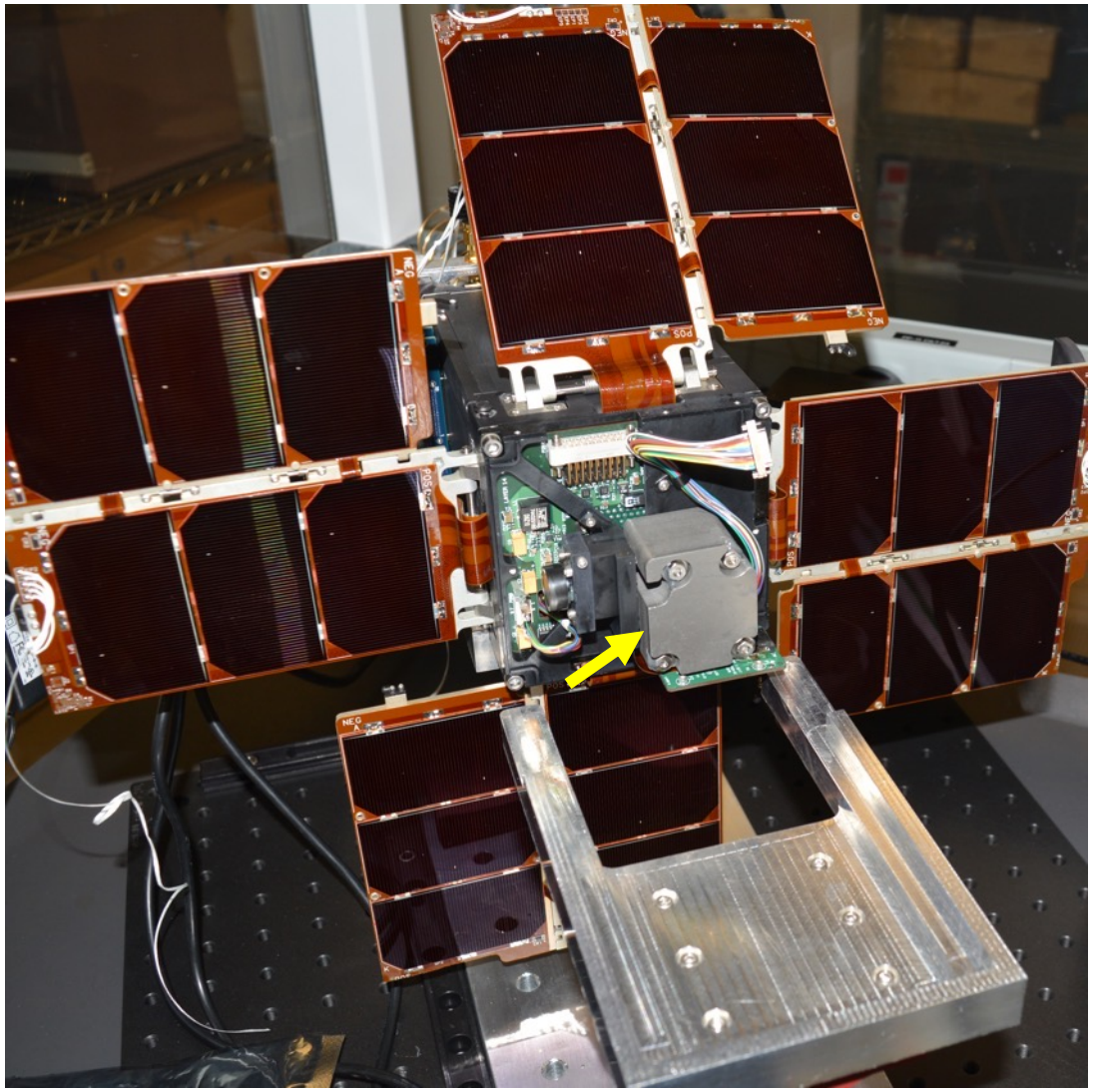
Ballast Locations:



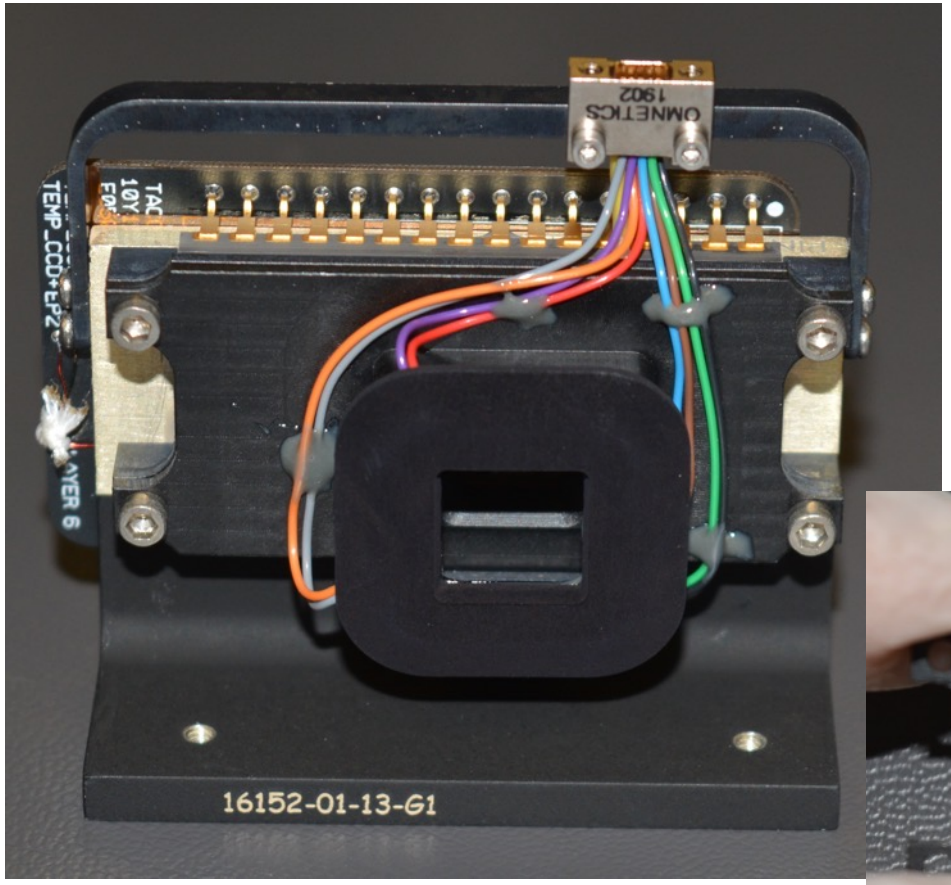
Tungsten Polymer Ballast

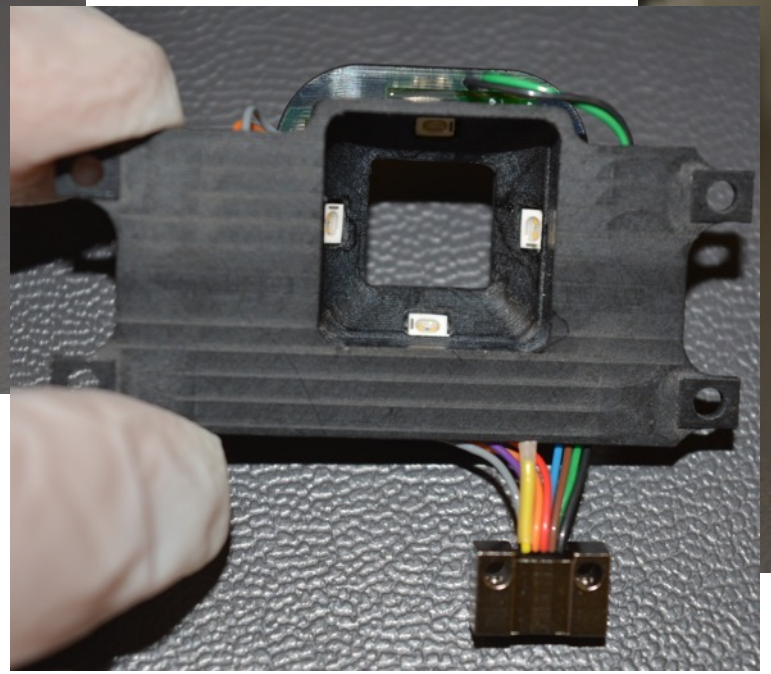
- **Thanks to Rick Kohnert of CU, who pointed us towards this material**
- **Ecomass Technologies, Austin TX**
  - Compound 1700TU96
  - 30% PA12 nylon, 70% Tungsten powder (by mass)
  - Meets ODAR requirements
- **Outgassing**
  - outgassing.nasa.gov indicates this type of nylon meets 'low outgassing' requirements after bakeout
- **Highly Machinable**
- **Good epoxy adhesion**
- **Full strength threaded inserts**

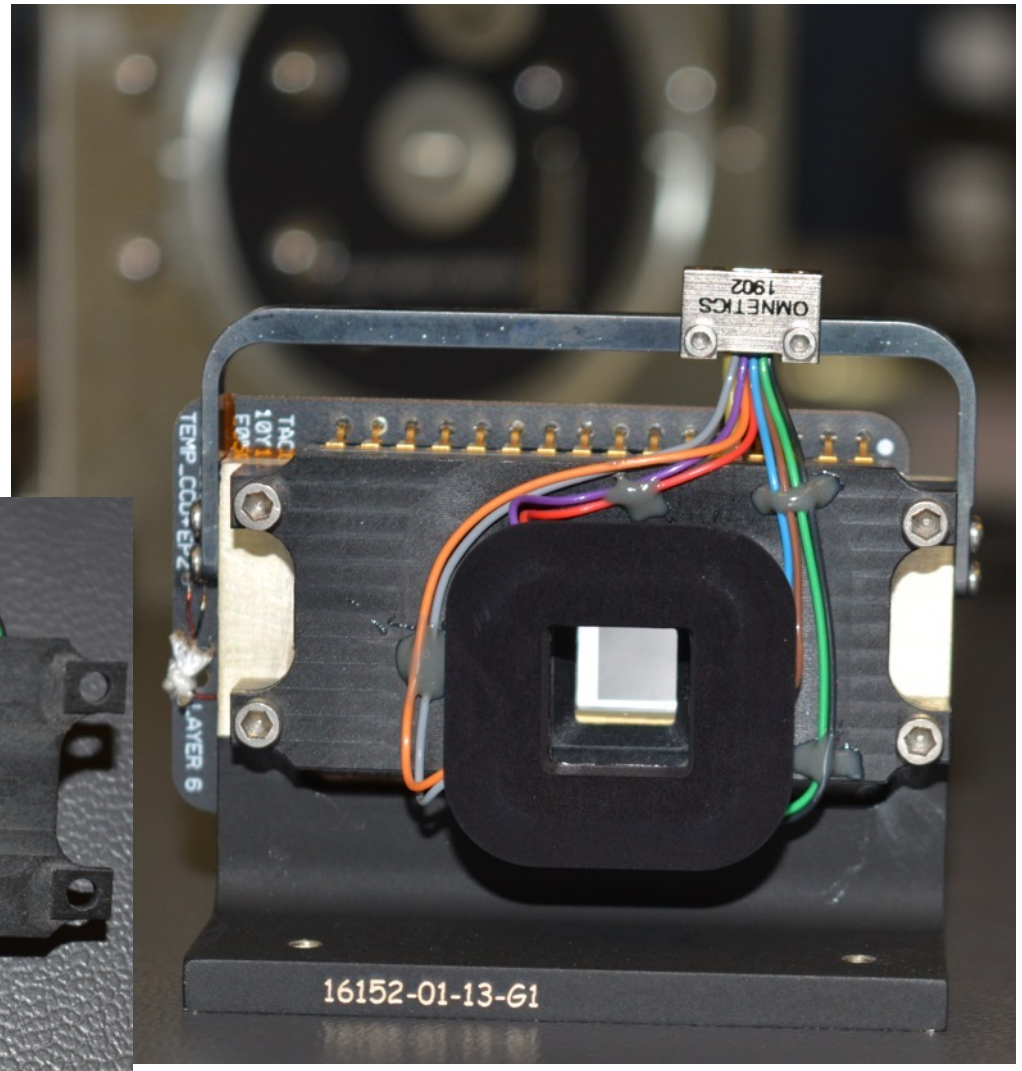




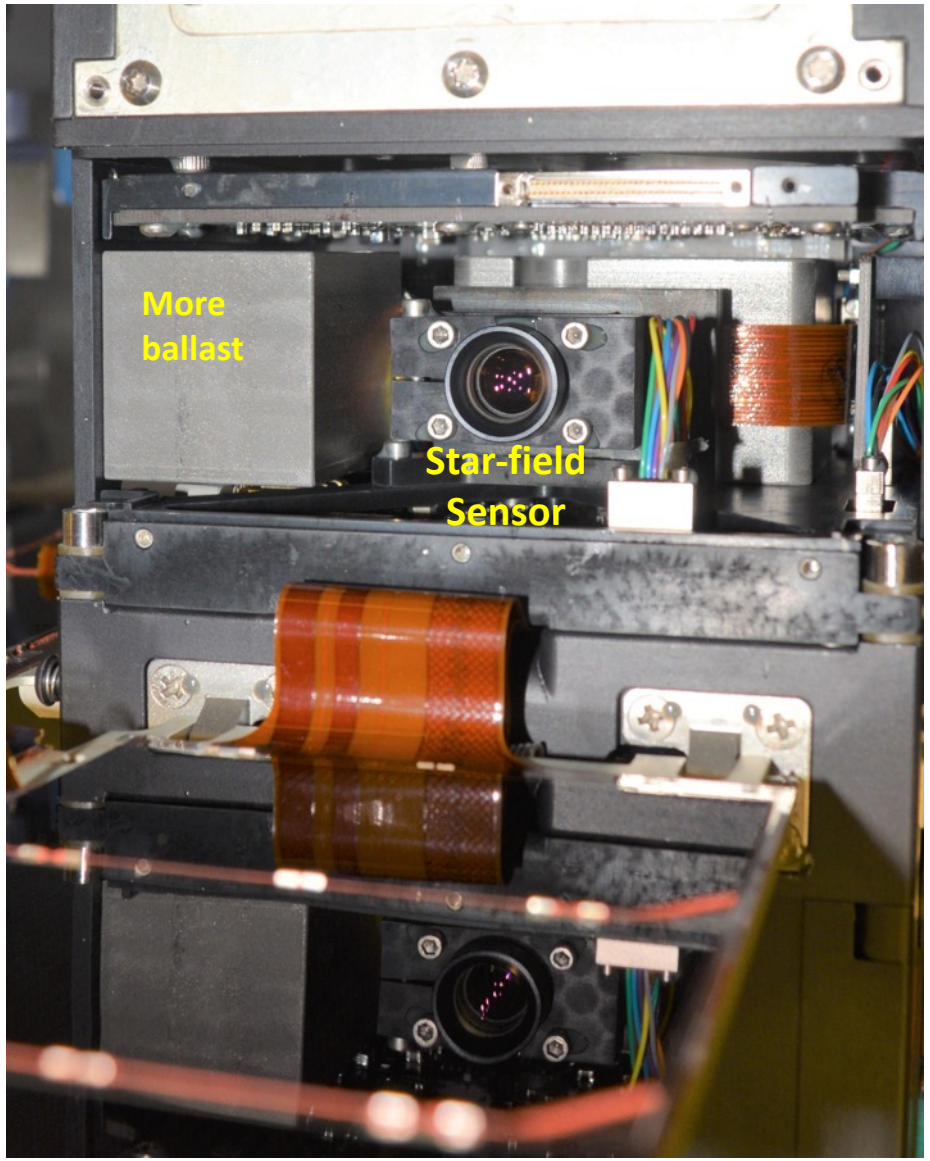
CCD Module, with stray light baffle and calibration LEDs

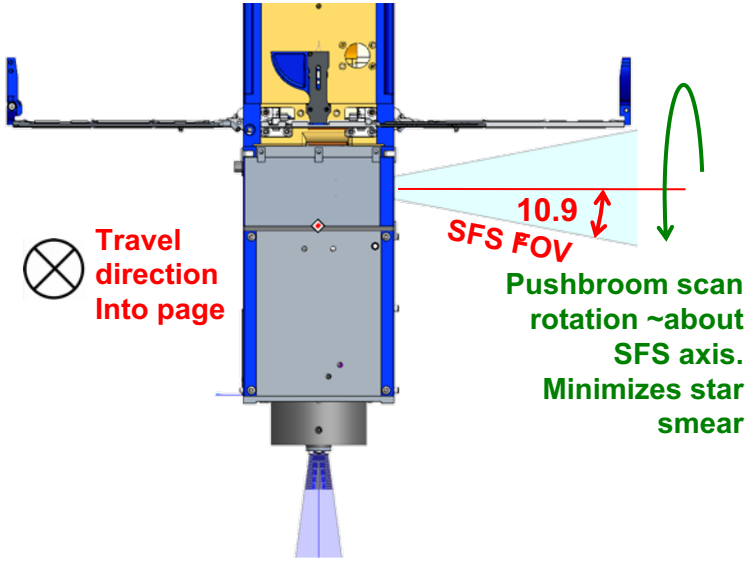


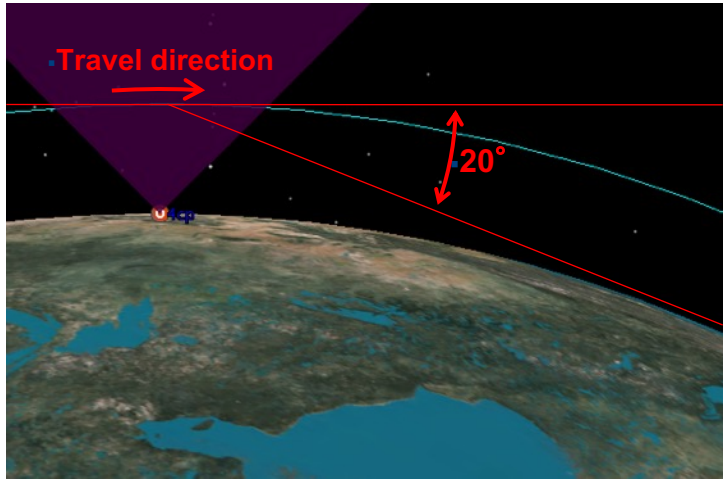




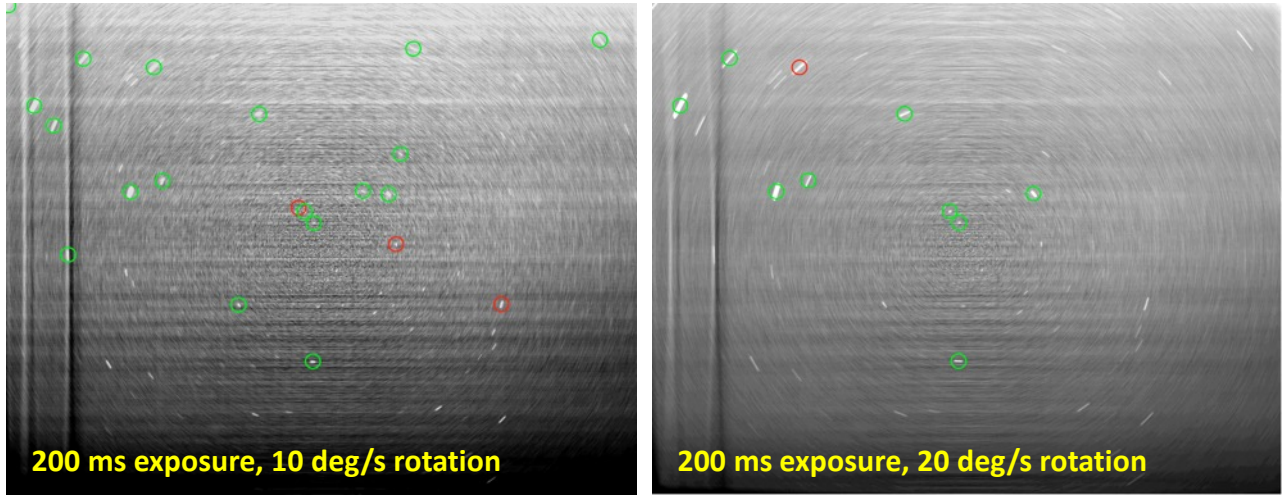
Star-field Sensor: A first for LANL's series of CubeSats







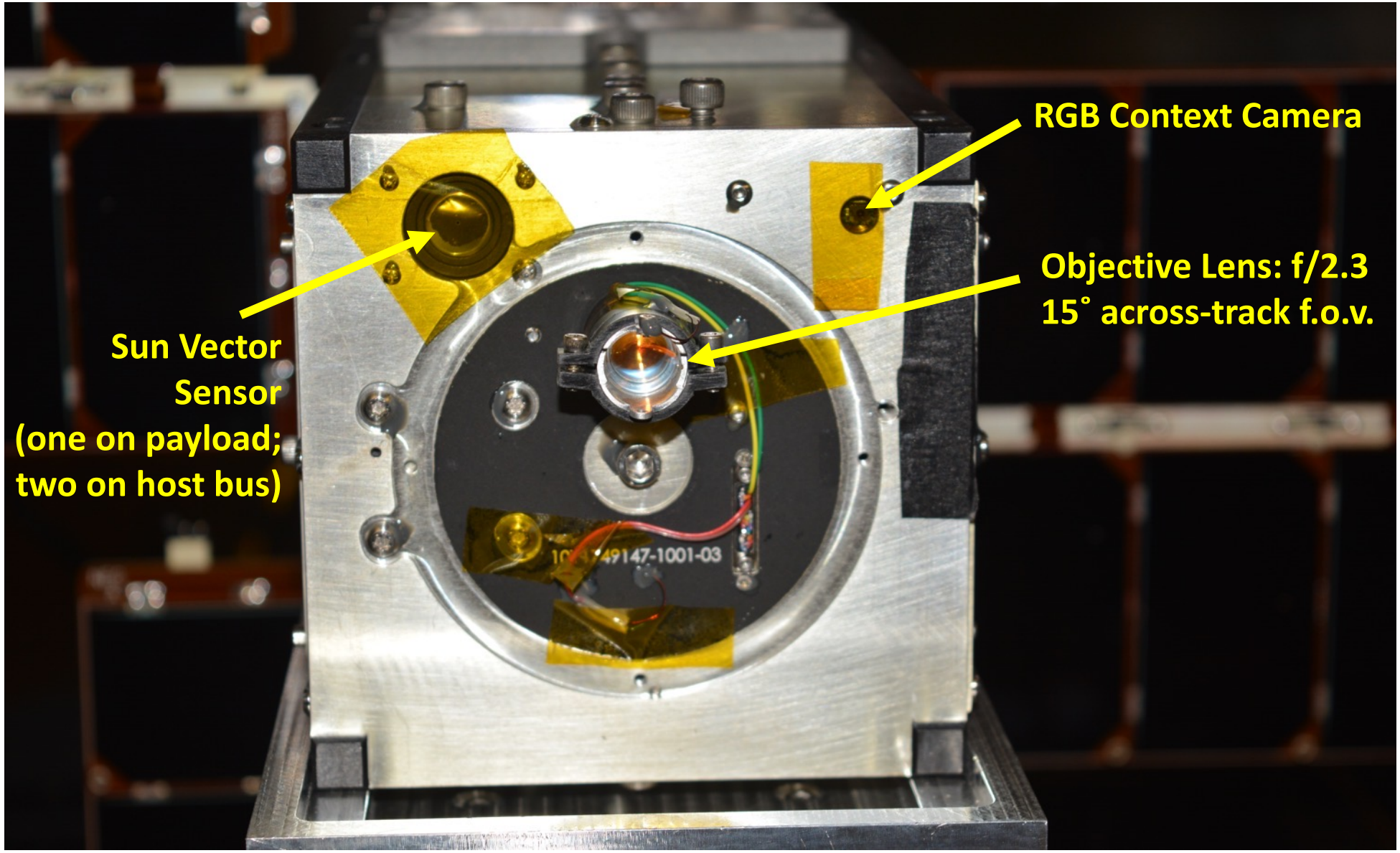
This orientation ensures accurate position fix even at high rotation rates:



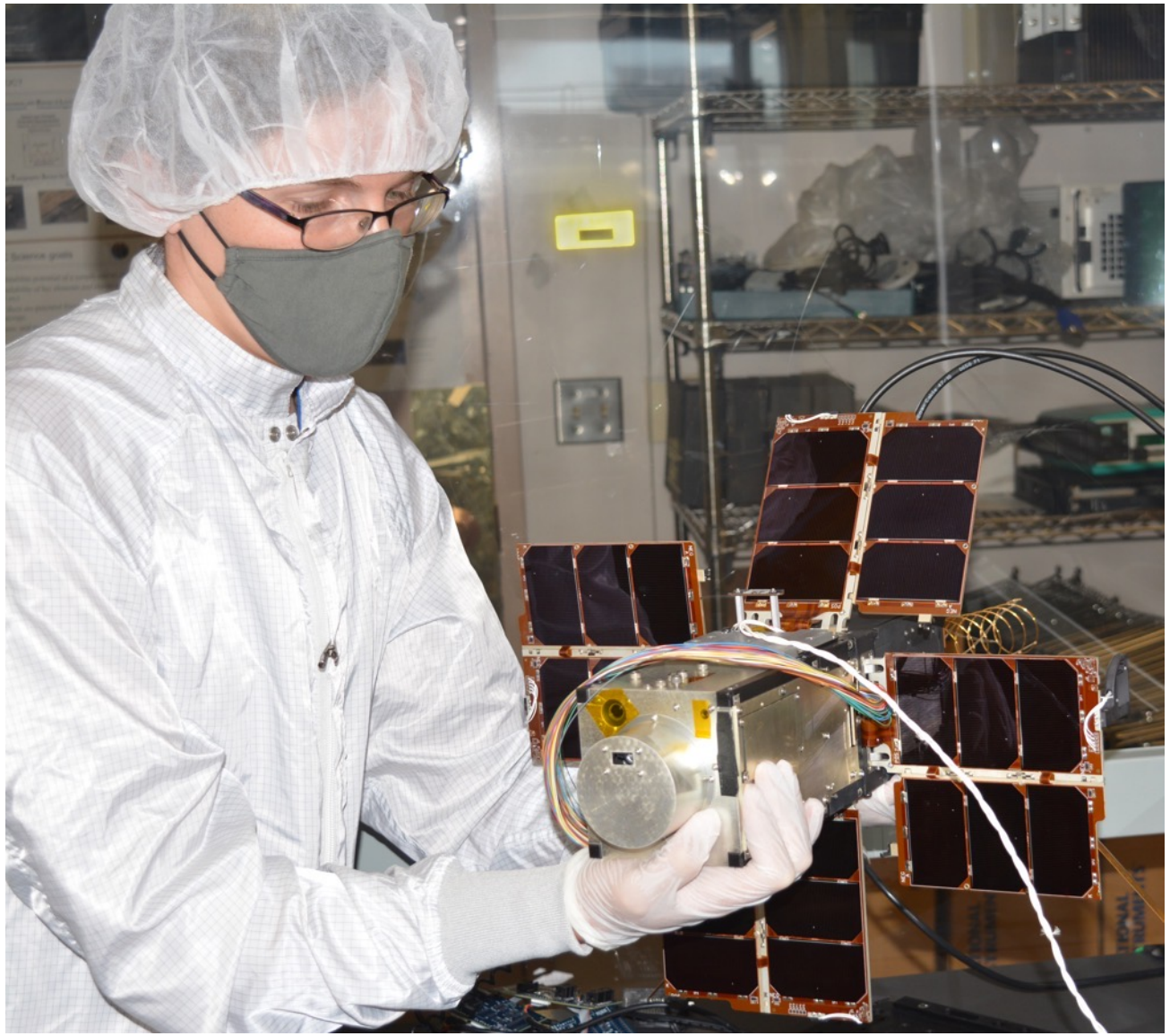
- Successful star catalog match (5 needed for fix)
- Failed star catalog match

- Raw SFS pointing solution accuracy: ~0.01 degree, but must be transferred to satellite in motion, with some extrapolation. Resulting final satellite pointing accuracy TBD.
- 10-200 sec for initial "lost in space" solution; <10 sec for subsequent solutions

NACHOS business end (with thermistors added for TVAC test)

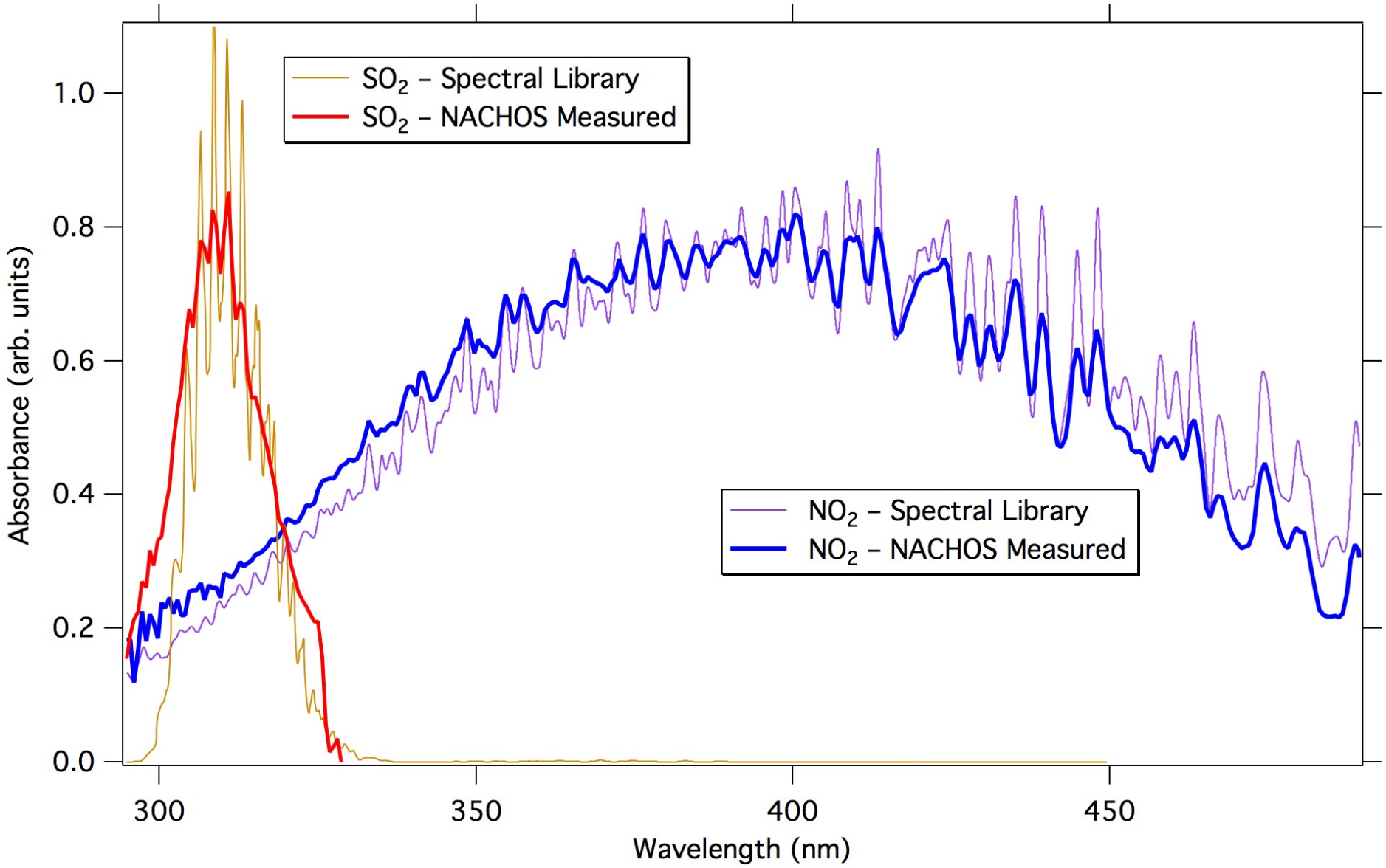


NACHOS Qualification Model: Fully integrated satellite



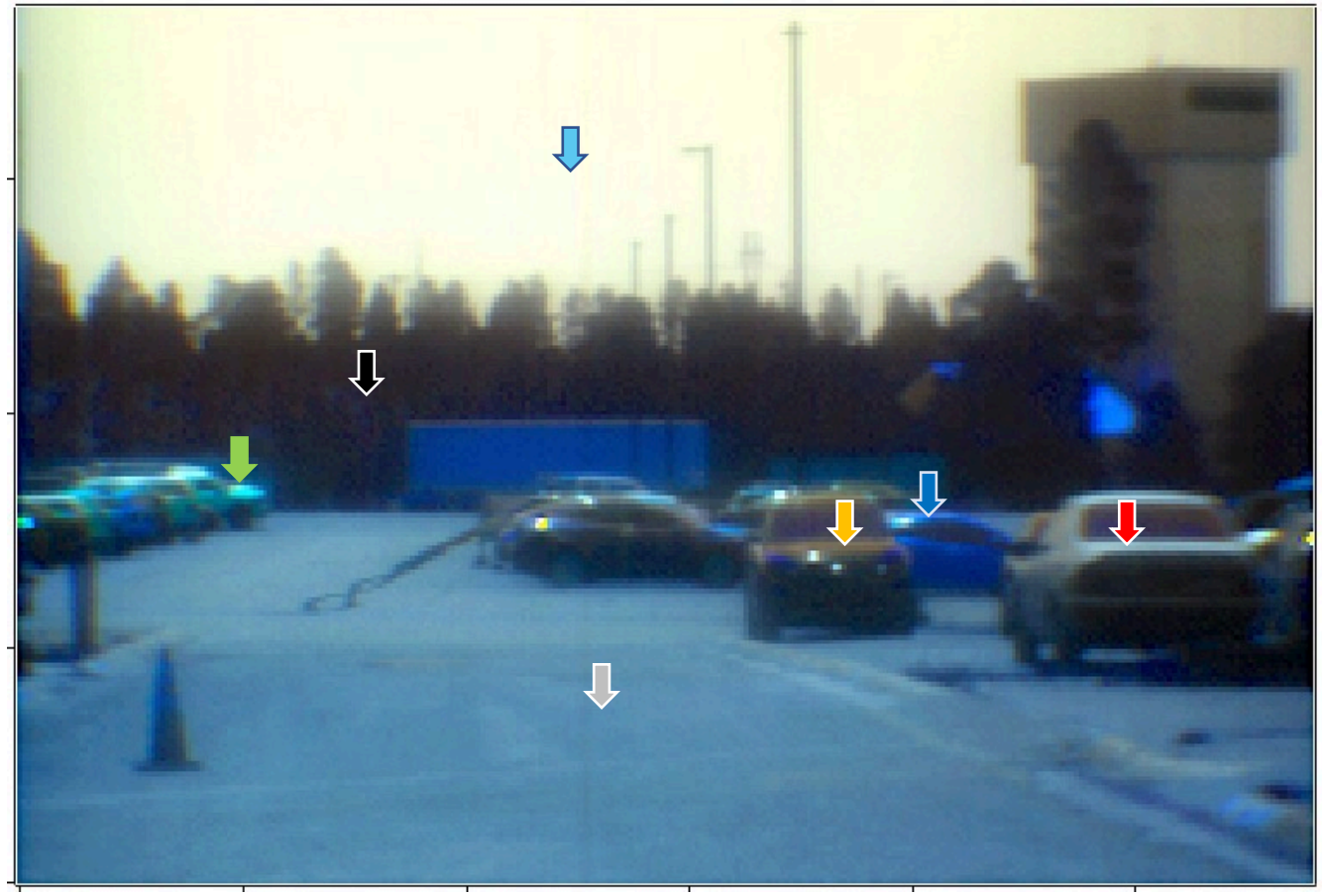
- Thermal vacuum testing begins June 17
- Vibration testing in early July
- If NACHOS-2 mission goes forward, delivery to launch integrator scheduled for end of December 2021 for a February 2022 launch

NACHOS NO_2 and SO_2 laboratory spectra

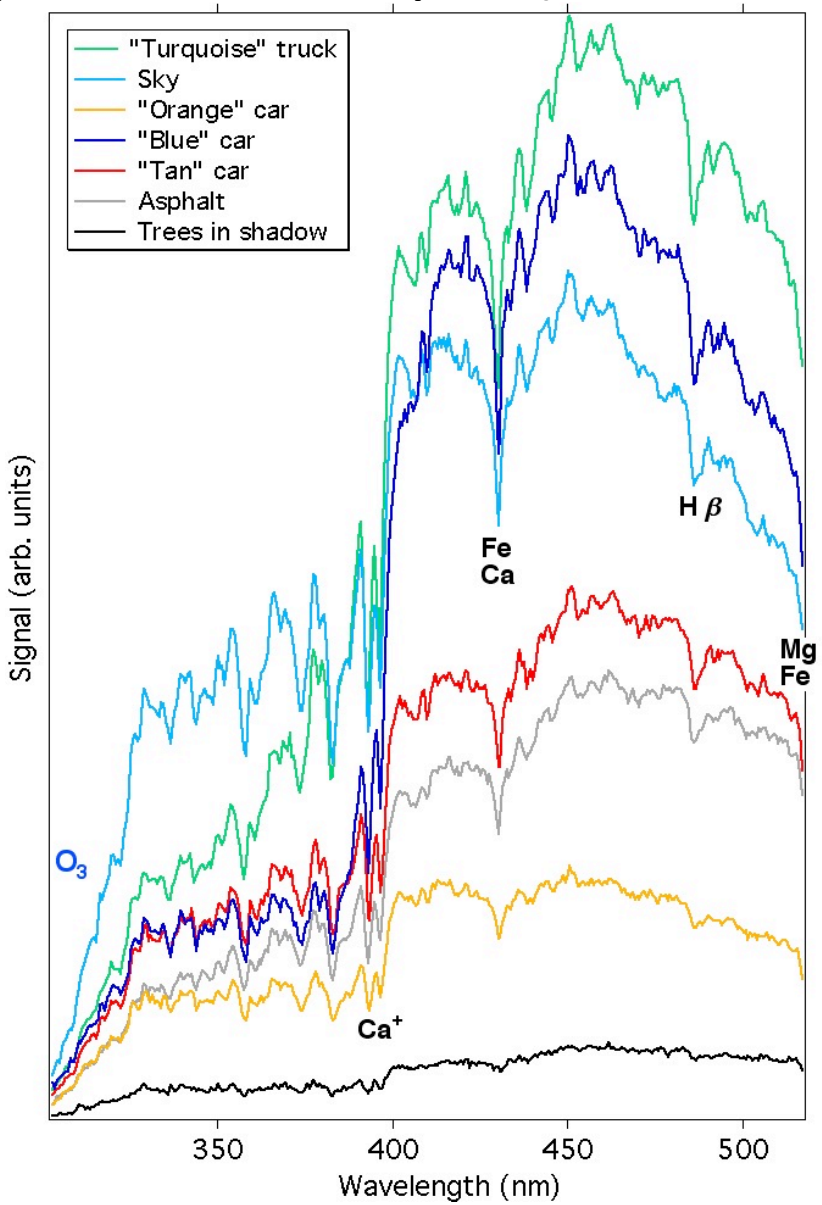


NACHOS Qualification Model: Hyperspectral image of outdoor scene

NACHOS Qualification Unit False-Color Image (May 26, 2021)
R=334nm, G=389nm, B=442nm



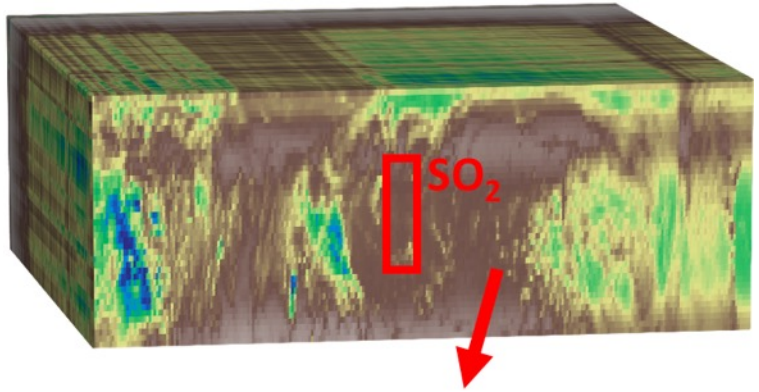
Spectra from selected pixels (arrows in image)

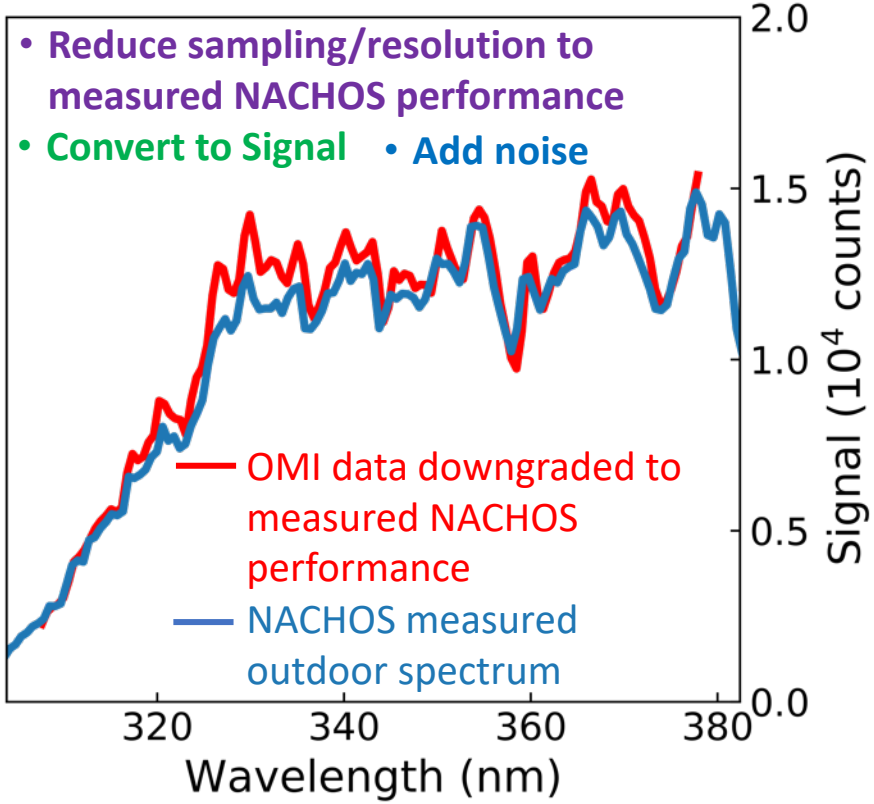


Most of the obvious spectral features seen here arise from the solar spectrum. Some prominent solar absorption lines are labeled.

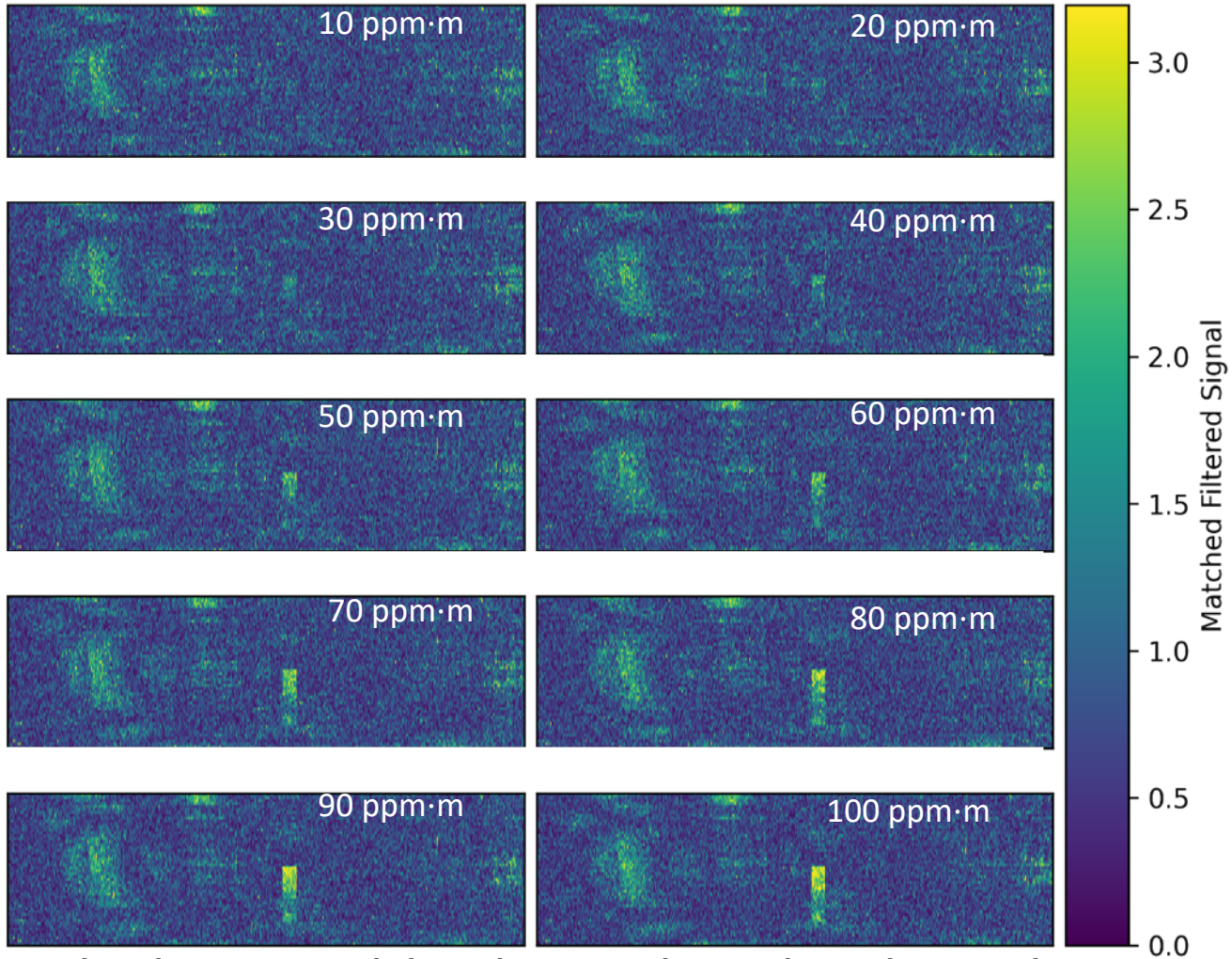
Gas detection sensitivity modeling, SO_2 example (K. Post)

OMI datacube





Modeled NACHOS SO_2 Detection Maps



Simulated SO_2 retrievals based on OMI data, adjusted to match NACHOS resolution and SNR, and with rectangular SO_2 "plume" inserted artificially

Next Steps

- Flight Unit host/payload integration: July 2021
- Flight Unit TVAC testing: Aug. 2021
- Flight Unit Vibration testing: Sept. 2021
- Pre-shipment Review: Nov. 2021
- Deliver to NanoRacks for integration: Dec. 1, 2021
- Launch to ISS aboard Cygnus vehicle (NG-17): Feb. 2022
- Deployment by Cygnus to final orbit: April-May, 2022