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

Steven P. Love


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

Hyperspectral Imaging: Each pixel contains a high-resolution spectrum

- **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.

**Hyperspectral Data Cube (~400 MB):**

- **“Pushbroom” Hyperspectral Imager**
  - Every spatial pixel contains a complete high-resolution spectrum
  - Platform motion sweeps out 2nd spatial dimension

**Individual Pixel Spectra**

- Atmosphere without gas plume
- with NO$_2$+SO$_2$ gas plume
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:

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.


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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-Generation CubeSat Bus

Complete Host/Payload assembly comprises a 3U+ CubeSat

1.5U Gen-3 CubeSat Host

Interposer with Starfield Sensor

Payload Data Handler (PDH)

UV-VIS Hyperspectral Imager

1.5U Payload

Objective Lens Shroud
(sun shade, thermal stability, and atomic O protection)
Science applications: (1) NO$_2$ as marker of fossil fuel burning

OMI provides regional-scale imagery:

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:

Soufriere Hills, 2006

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

Typical passive degassing (White Island, NZ)

~200 ppm*m SO$_2$
... and many more

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

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:

4X external ballast fastens with #2-56 threads tapped into electronics housings. Extra mass extends over, but not attached to, optics housing.

Optics/electronics housing boundary

2x internal ballast with #4-40 self tapping inserts (triserts)
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:

- 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)

- RGB Context Camera
- Objective Lens: f/2.3
- 15° across-track f.o.v.
- Sun Vector Sensor
  (one on payload; two on host bus)
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

Most of the obvious spectral features seen here arise from the solar spectrum. Some prominent solar absorption lines are labeled.
Gas detection sensitivity modeling, SO₂ example (K. Post)

OMI datacube

- Reduce sampling/resolution to measured NACHOS performance
- Convert to Signal
- Add noise

OMI data downgraded to measured NACHOS performance

NACHOS measured outdoor spectrum

Simulated SO₂ retrievals based on OMI data, adjusted to match NACHOS resolution and SNR, and with rectangular SO₂ "plume" inserted artificially

Modelled NACHOS SO₂ Detection Maps

10 ppm⋅m
20 ppm⋅m
30 ppm⋅m
40 ppm⋅m
50 ppm⋅m
60 ppm⋅m
70 ppm⋅m
80 ppm⋅m
90 ppm⋅m
100 ppm⋅m
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