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InVEST 17-0013

NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

First Annual Report, project year 2019

(Presentations from First Annual Review - 1/21/2020)

Steven P. Love,

L. A. Ott, M. E. Dale, C. L. Safi, J. Theiler, H. D. Mohr, M. Hehlen, B. R. Foy, C. G. Peterson, A. A. Guthrie, K. G. Boyd, J. A. Wren, R. Hemphill, and M. K. Dubey

Los Alamos National Laboratory

NACHOS Annual Review Agenda – 1/21/2020

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- **8am – Tour & Demo of Instrument**
  - Shock-Vibration Lab, Thermal Testing Room, Cubesat Assembly Lab, Systems Operations Center
- **9am – Overview & Status** – *p. 2*
  - Publications – *p. 22* ; Students – *p. 23*
- **9:20am – Algorithms** – *p. 24*
- **9:40am – Optical System** – *p. 53*
- **10:00am – Mechanical** – *p. 73*
- **10:20am – Software** – *p. 82*
- **10:40am – Attitude Determination & Control System** – *p. 90*
- **11:10am – Electrical** – *p. 96*
- **11:25am – Host Bus Status** – *p. 104*
- **11:45am – System, Schedule, & Budget** – *p. 111*

NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

(InVEST 17-0013)

First Annual Review

Introduction

Steven P. Love,

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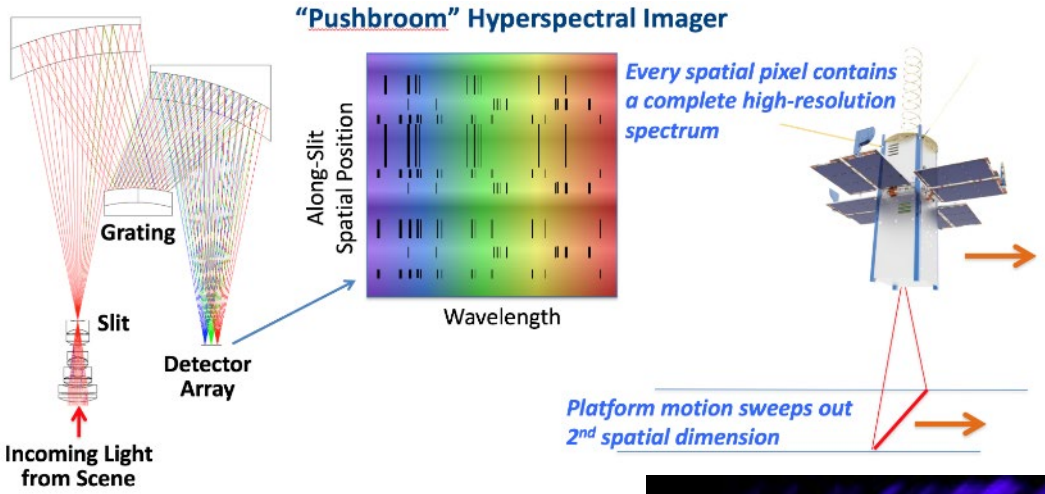
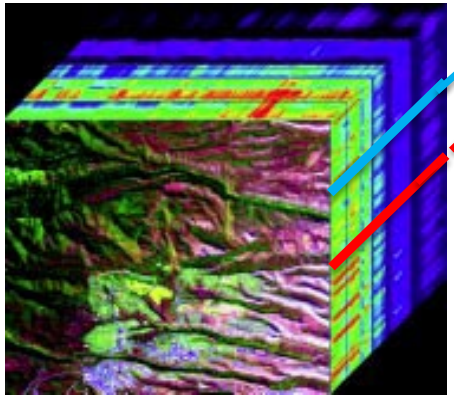
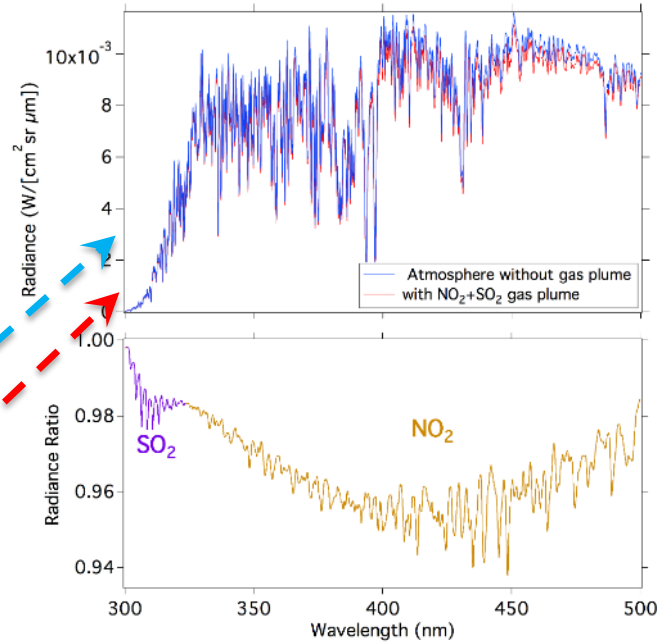
NACHOS is an ultra-compact, high-resolution hyperspectral imager



Hyperspectral Data Cube (~400 MB):

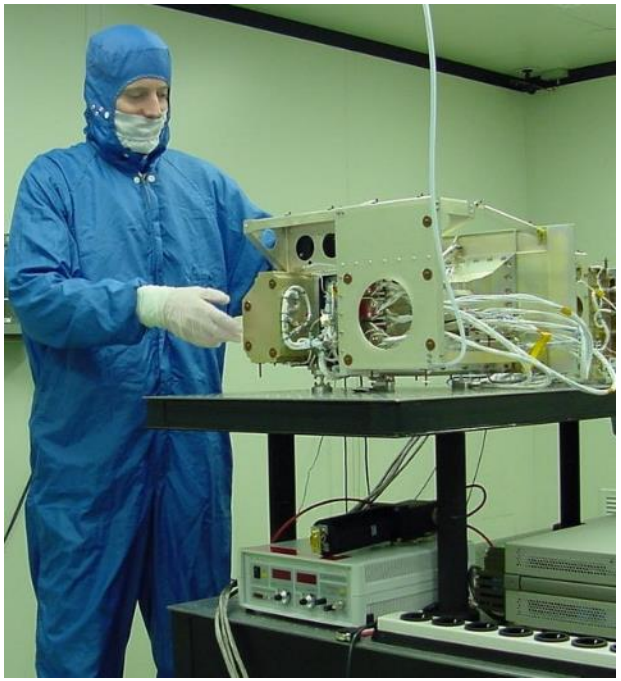


Individual Pixel Spectra

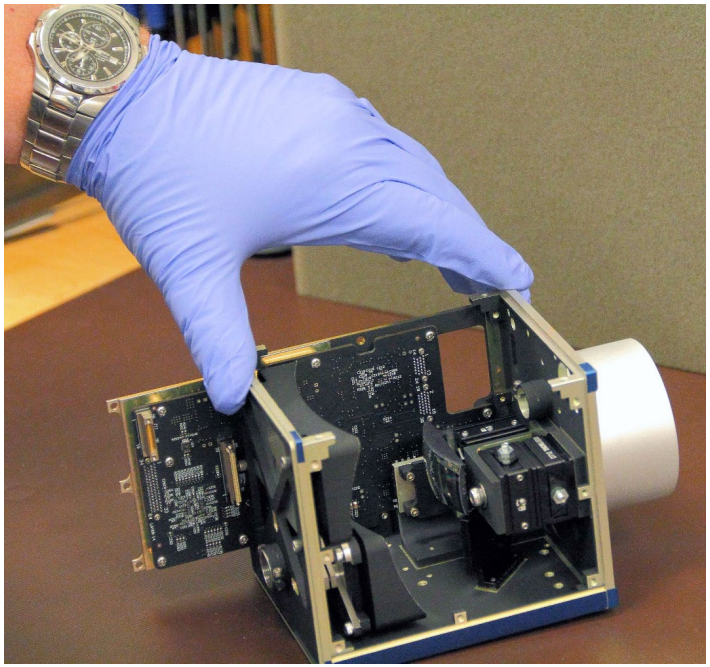


Primary Goal: On-orbit validation of a CubeSat-based hyperspectral imager capable of trace gas measurements. Advance technology from TRL-5 to TRL-7

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

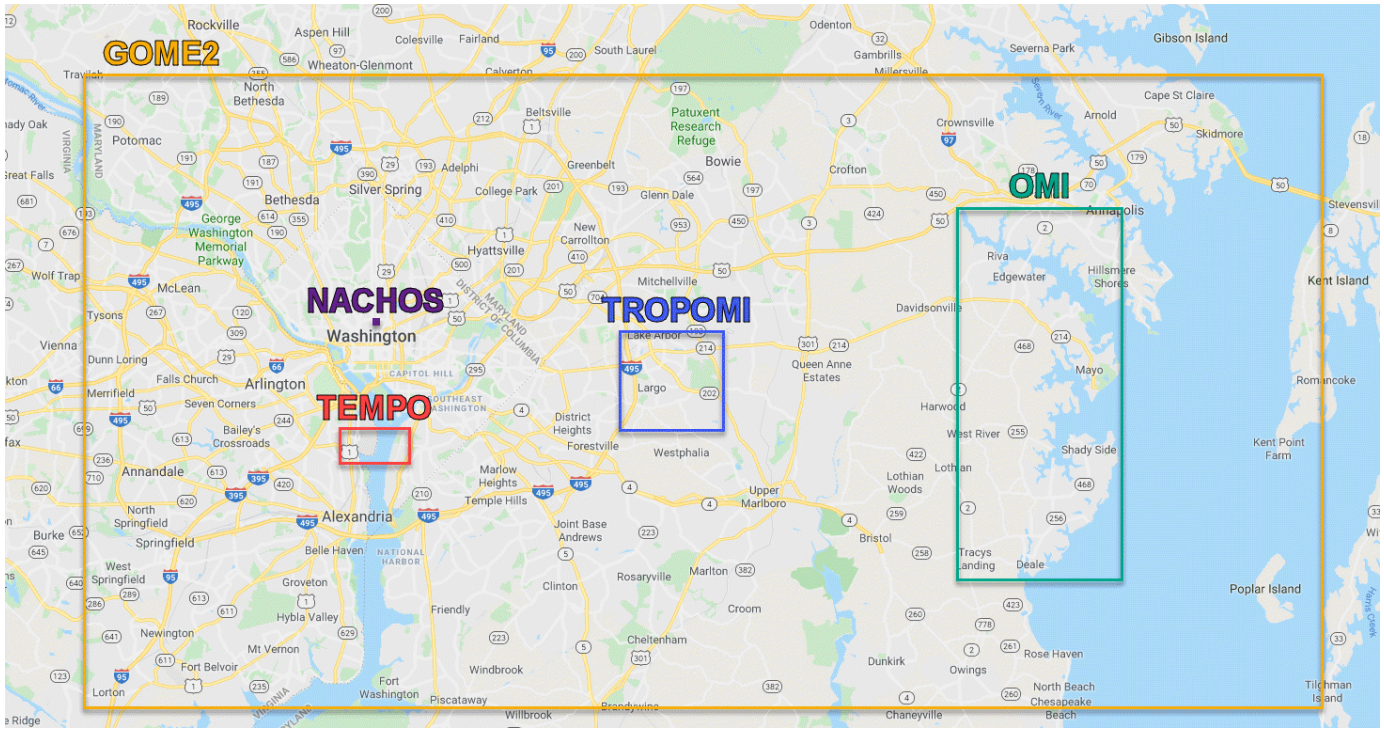


LANL Targeted Atmospheric Chemistry Observations Spectrometer (TACOS)
- 300-500 nm, 0.6 nm resolution
- ~4 kg (complete satellite)



NACHOS Niche: *Targeted*, high spatial resolution gas imaging

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

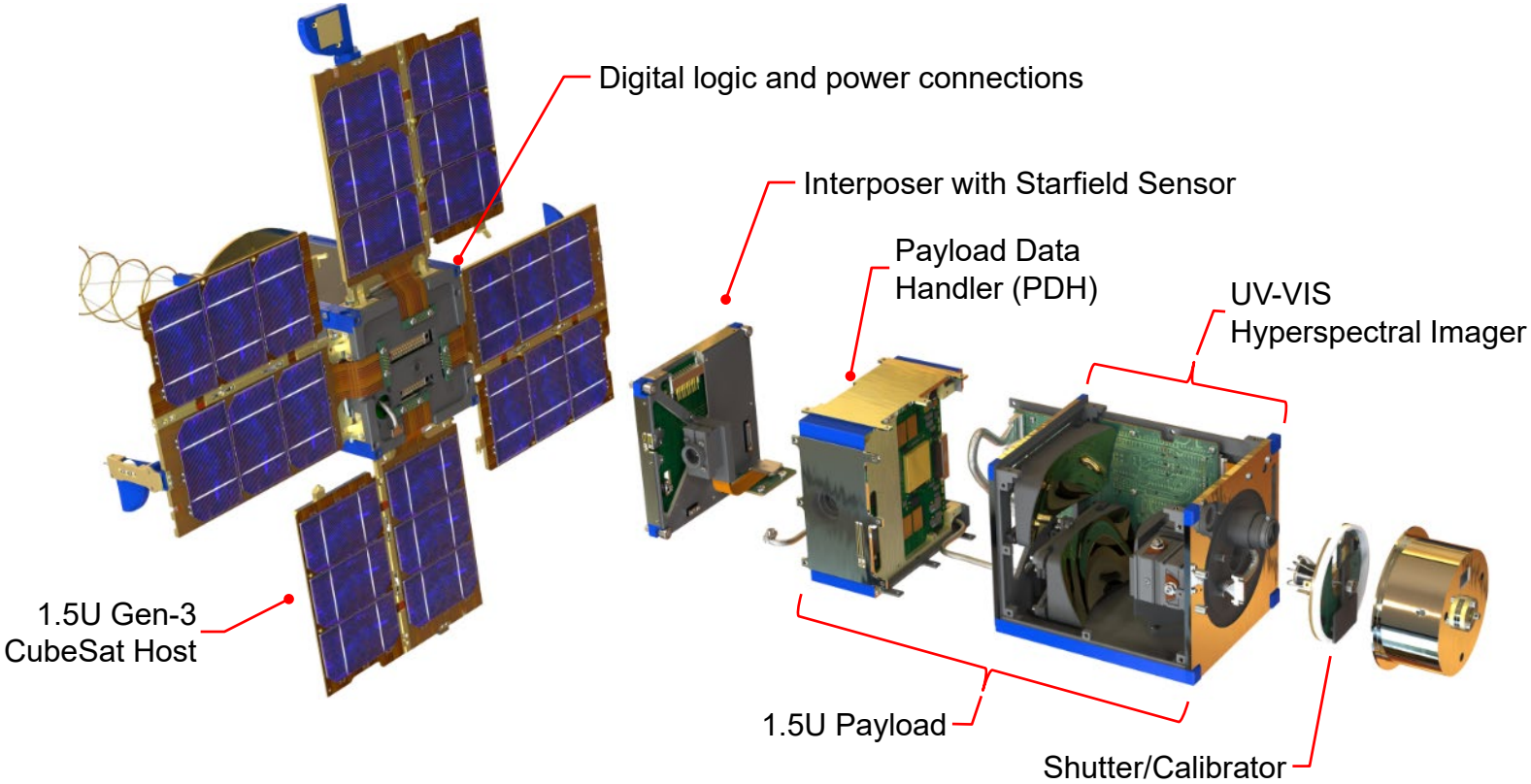


- **NACHOS pixel: ~0.5km at 500km altitude**
- **Envisioned NACHOS constellation would provide frequent target revisits**

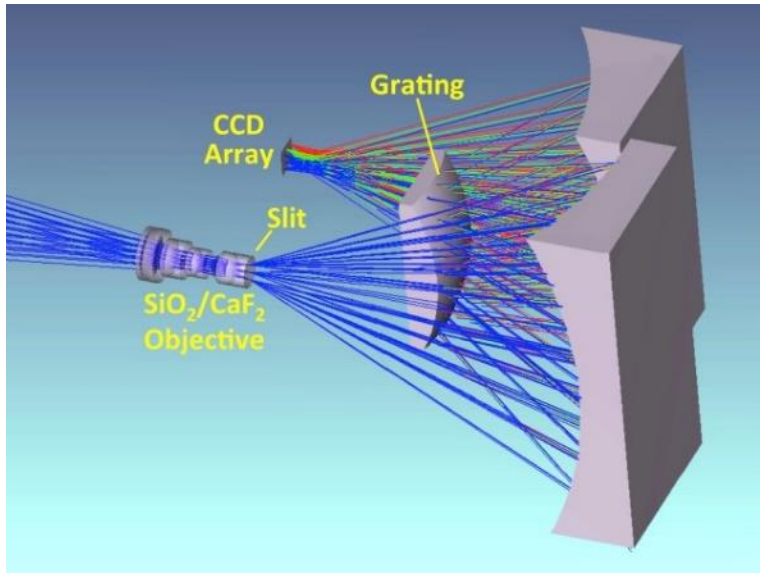
NACHOS Project History

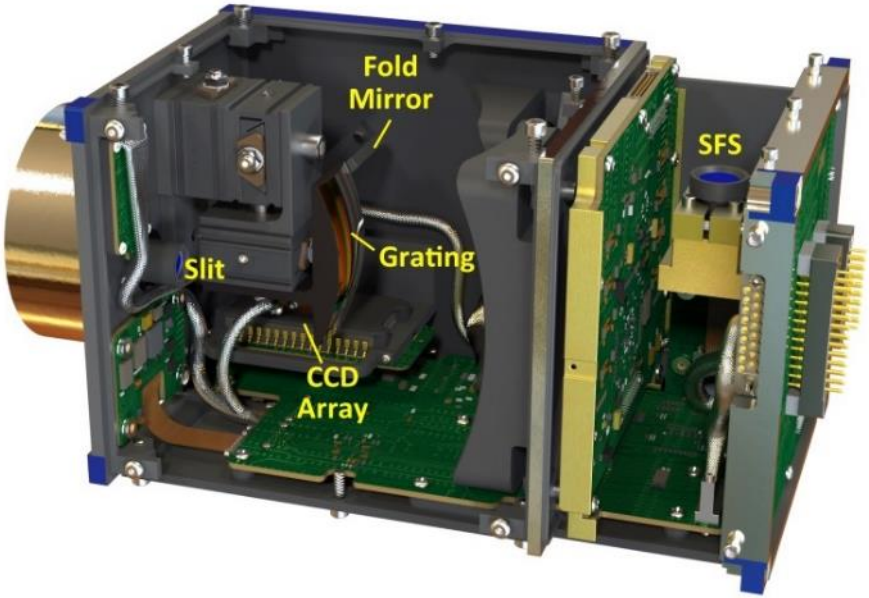
- 3-year internally-funded project, “TACOS,” brought instrument from concept to TRL-5 working instrument ready for integration with CubeSat bus
- Current NASA 3-year InVEST project, “NACHOS,” started January 2019, with launch and space mission to occur in 2021.
- Original TACOS instrument, and a twin, now serve as the Engineering Development Units (EDU-1 and EDU-2) for NACHOS.
- NACHOS project is building the Engineering Qualification Model (EQM) and final Flight Model of the instrument payload.
- Launch in early 2021 under NASA’s CubeSat Launch Initiative (CSLI)

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



NACHOS Hyperspectral Imager Payload





NACHOS Project Goals

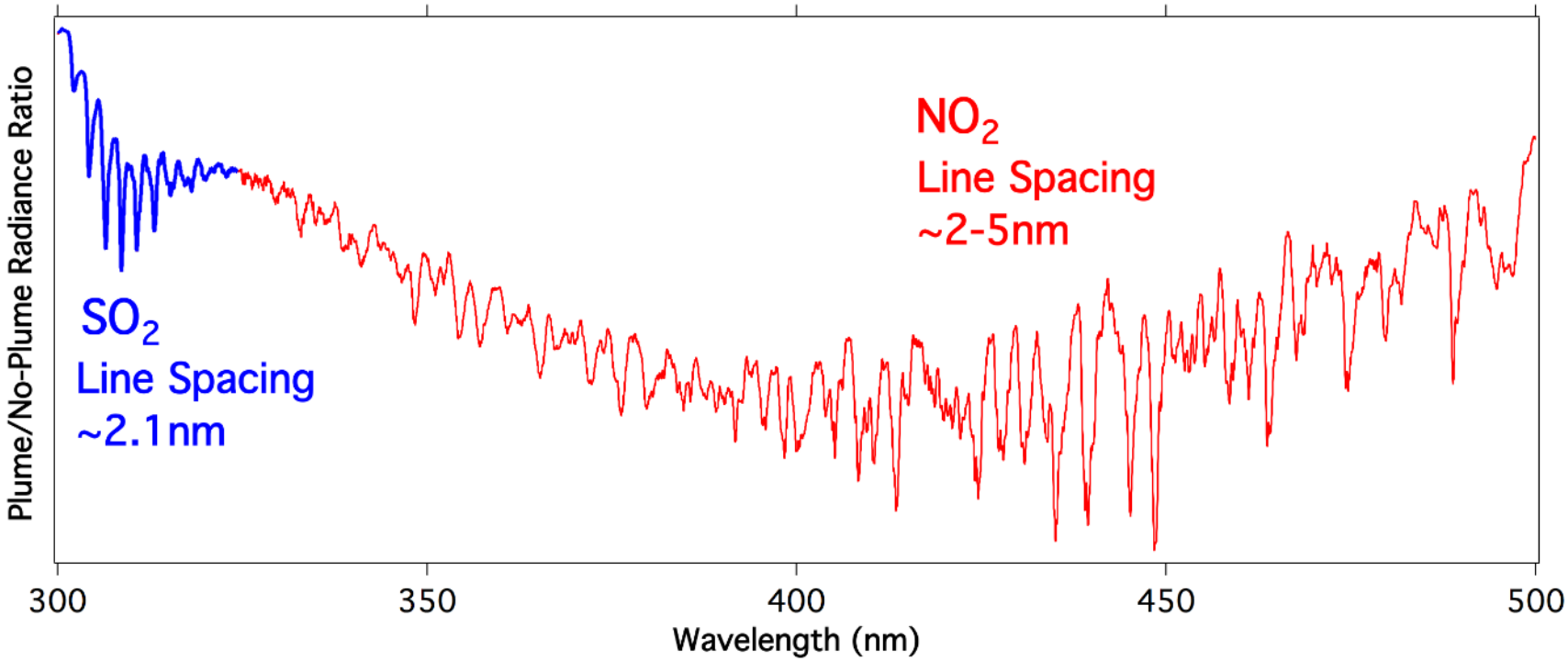
NASA InVEST missions are on-orbit technology validation missions, not science missions. The NACHOS project goals are:

- **On-orbit validation of our ultra-miniaturized high-resolution hyperspectral imager, demonstrating spectral resolution and sensitivity sufficient for dilute gas detection.**
- **On-orbit validation of on-board gas retrieval hyperspectral processing on a CubeSat.**

There are earth science objectives, however, that motivate this work:

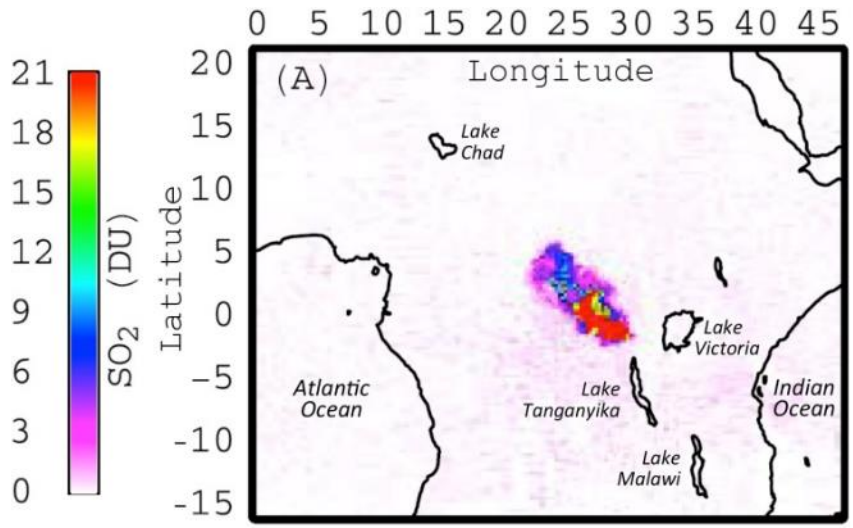
- Demonstrate space-based NO_2, SO_2 proxy-gas tracking and attribution of anthropogenic greenhouse gas emissions – our proposed strategy for a potential climate treaty verification system
- Demonstrate space-based monitoring volcanic SO_2 emissions at the low levels and small spatial scales relevant for early warning of new volcanic activity
- Also: Tropospheric O_3, Aerosol Absorbing Index (absorbing soot/smoke *vs* scattering aerosols), CH_2O (forests, cities), volcanic BrO (subduction zone volcanoes)

Technology Challenge: To achieve sensitivity goals, spectrometer must be able to resolve the line structure of SO_2 and NO_2

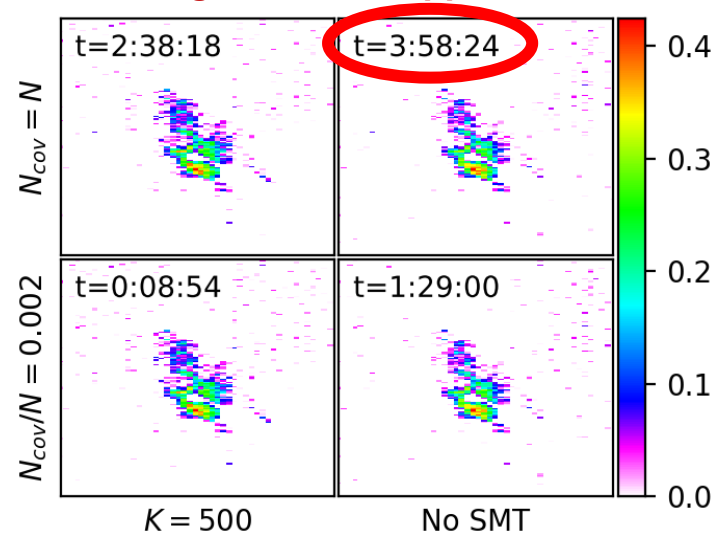


Major NACHOS Project Goal: On-Orbit Validation of streamlined hyperspectral processing algorithms developed under TACOS internal project

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



Standard Algorithm: No approximations



Comparison of published retrieval* of the SO_2 plume from Nyamulagira volcano (left) with on-board processing results and execution times of the TACOS ACE detector algorithm (right) for the same 320x320x1444 OMI dataset.

*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*, vol. 112, p. D24S43, 2007.

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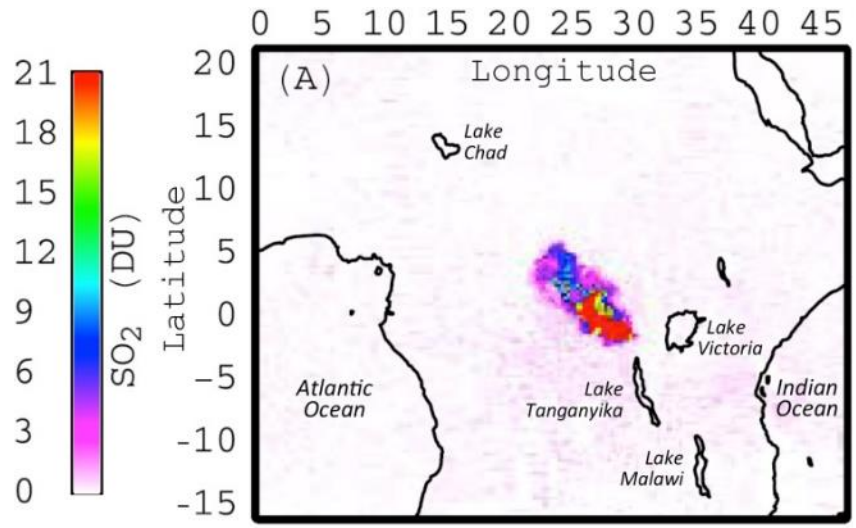

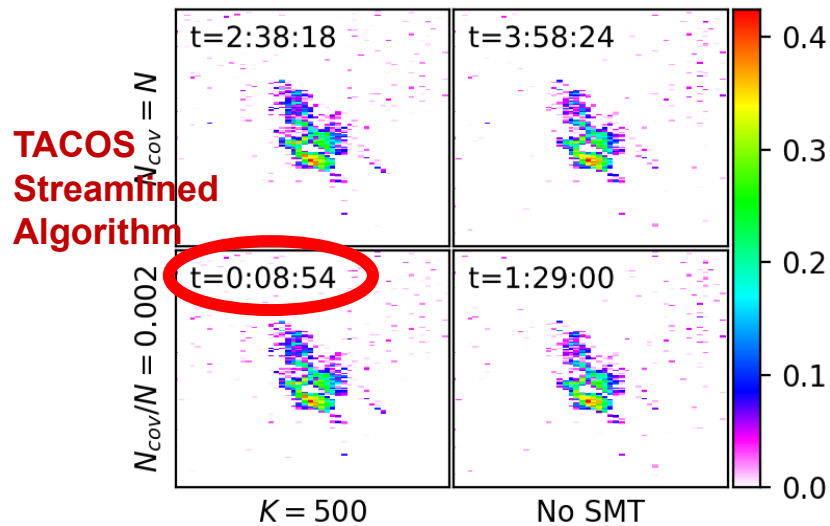

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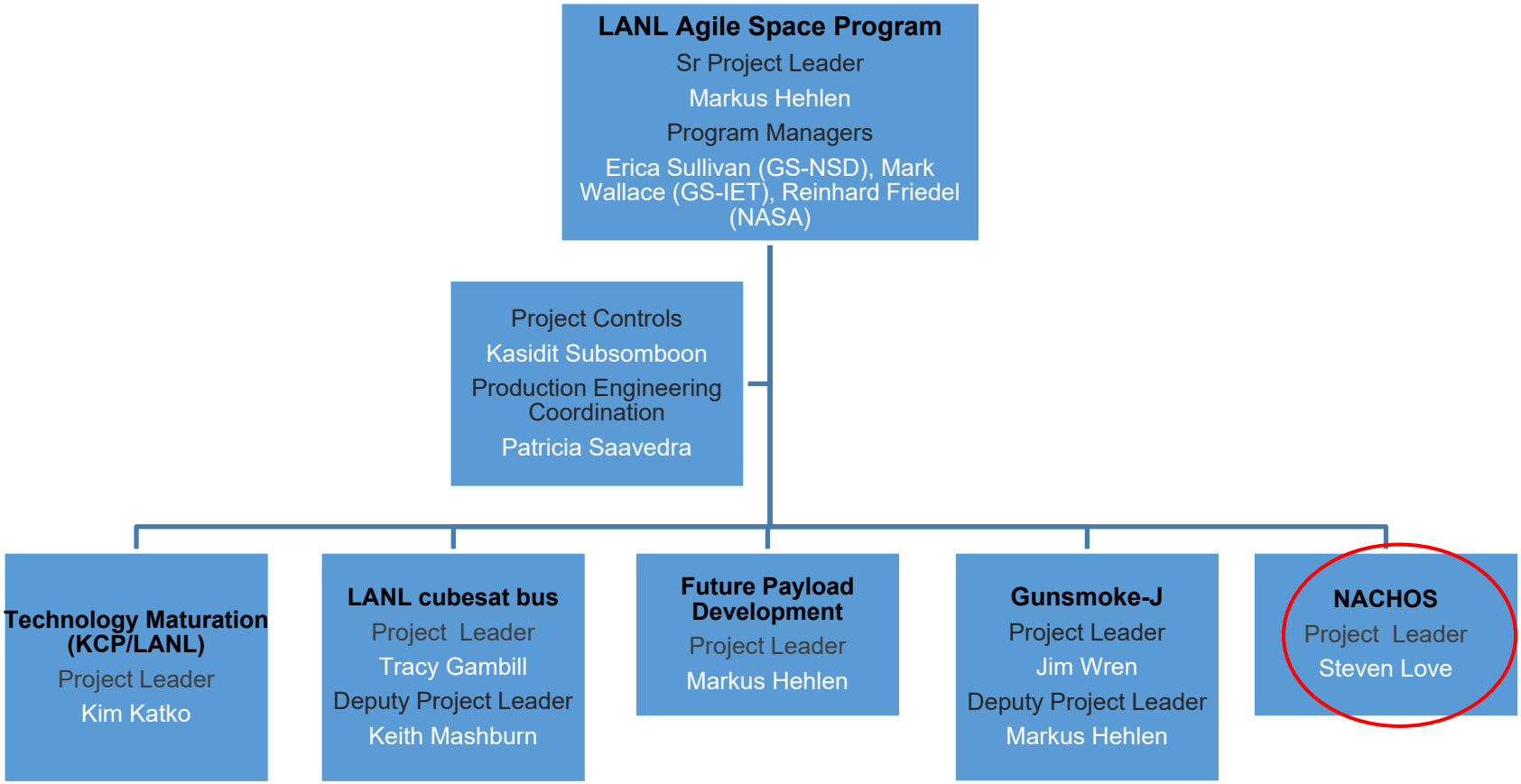
NACHOS On-Orbit Technology Validation Mission

- **This is not a CubeSat bus development project; it is an instrument payload technology validation project. We believe we have a highly capable CubeSat bus that can meet the needs of a hyperspectral imaging gas-monitoring mission. But a full hyperspectral imaging mission places demands on our host bus never exercised in previous missions.**
- **Depending on actual host bus performance (in terms of pointing accuracy and control), we envision three levels of possible on-orbit validation mission for the instrument payload:**
- **Threshold, Level 0: Lowest-level host pointing accuracy (worse than already achieved)**
  - Can still achieve a basic validation mission, validate payload functionality, launch survival, resolution intact. Exercise algorithms, demonstrate on-board gas retrievals
  - Atmosphere Spectrum, retrieve atmospheric species (water vapor, ozone, etc.)
  - Simple nadir pointing, targets of opportunity
- **Level 1: Rough target pointing as demonstrated by block 1 host bus (+/- 10 degrees)**
  - Large scale targeting, most targets will fall in f.o.v..
  - Can perform some science as part of validation mission.
- **Level 2 (stretch): High-accuracy (sub-degree) control and knowledge using star field sensor**
  - Geo-located gas mapping informed by SFS
  - Demonstrate on-board target-of-interest recognition and cueing downlink

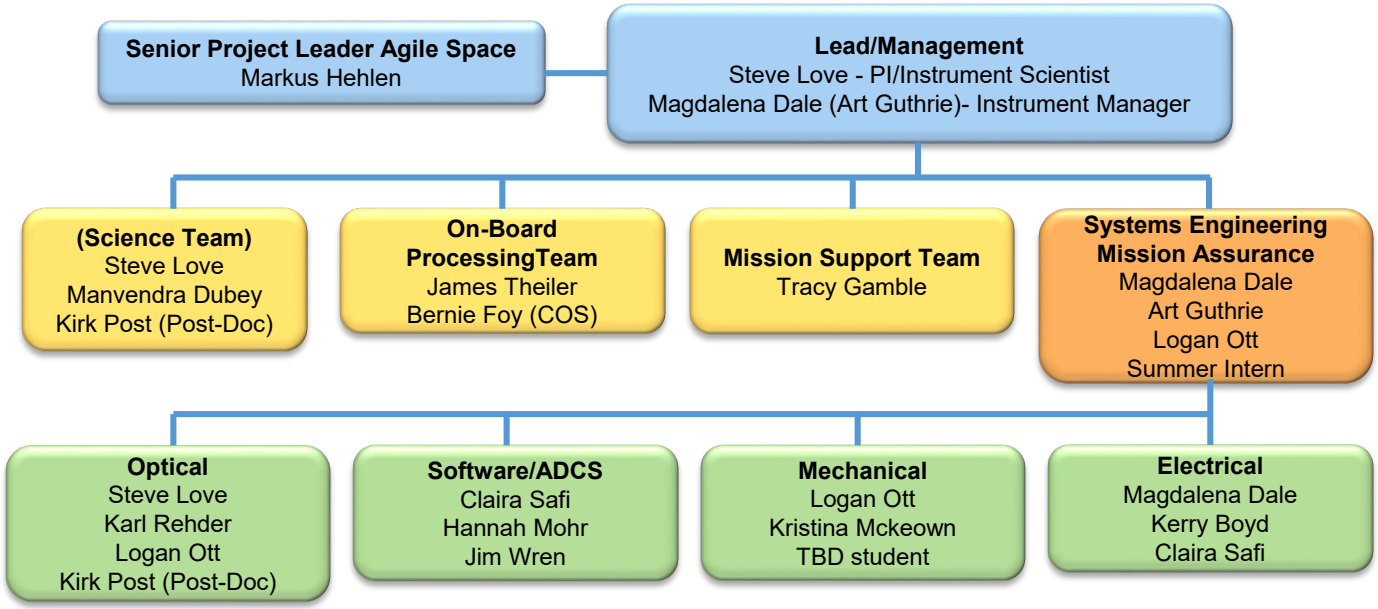
Instrument Requirements & Goals

Criterion	Minimum for Success (Req't)	Desired, Best-Case (Goal)	Implementation	Status
On-orbit optical spectral/spatial resolution (opto-mechanical robustness through launch and deployment)	4x design (spectral 2.5 nm or >15 % modulation at SO2 line spacing; spatial 3.3 mrad)	Design (spectral 0.6nm or >70% modulation at SO2 line spacing; spatial 0.8 mrad)	-Exhaustive pre-launch qual. testing w/ redesign if needed. -Untargeted Earth look; atmospheric lines.	-meeting best case spatial resolution -already better than minimal spectral resolution (~2.5x design res, ~35% modulation of SO2 structure) -very likely to improve with higher quality mechanical components
On-orbit CCD temperature	<35°C during data collect	<0°Cat data collect	-Passive radiative cooling -Thermal modeling and testing -assess its effects on dark noise and stability of pixel-to-pixel non-uniformity calibration in the on-orbit environment	-preliminary thermal testing complete -thermal modeling and analysis planned
On-board Calibration	Fine-scale pixel-to-pixel nonuniformities calibrated to 0.5% rms	Fine-scale pixel-to-pixel nonuniformities calibrated to 0.1% rms	LED-based OBCS	-Tested in lab and found to meet best-case requirements -Next step is to add this into the image capture operations
On-board Processing	Demonstrate on-board retrieval of atmospheric gases (water vapor, ozone, etc.)	On-board retrievals of dilute target gases (SO_2, NO_2, etc.)	-LANL streamlined retrieval algorithms implemented in hardware. -System autonomously calibrates, computes, stores and downlinks gas retrieval images in a manner robust to the space environment.	-Tested algorithms using OMI data on NACHOS processor -integration of processing into payload hardware complete
Basic demonstration of on-board gas retrievals, with or without spatial distortion	Ubiquitous atmospheric gases (H2O, O3, etc.)	-Gas plume images for NO2, SO2 targets of opportunity -NO2, SO2 gas plume images of localized targets; ground validation 4-corners and/or volcanoes	-Minimal (±25°) 1st-generation host pointing accuracy and attitude control -Best-case target (±0.2°) host pointing/attitude accuracy; SFS in ACDS control loop	-on-orbit ADCS pointing verified to (±10°) -ongoing work adding SFS to ADCS control loop -calibration of bus magnetometer & sun sensors

LANL Agile Space Management Structure



NACHOS Team Organization



Team Management Background

Name	Background
Steven Love	PI for NACHOS, TACOS, MAHI (micromirror-based programmable spectral imager), ORCAS (LWIR hyperspectral imager). Physics PhD (Cornell) with 30 years experience in optics, spectroscopy, spectral remote sensing instrumentation.
Markus Hehlen	Leader of the LANL cubesat bus and other project payload projects for the past 1½ years. 15+ years of experience in developing optical materials and devices for space & global security applications. 30 years of experience in material science.
Magdalena Dale	At LANL principal engineer for ZEP & ZPG sensors on SABRS and lead electrical engineer for various PCBs in JTA, SCAM, and OCAM. Prior to LANL 8 yrs of experience in kW-MW scale power conversion with 2 of those as lead engineer for R&D converter projects.
Art Guthrie	15 years experience building and managing space instruments at LANL. This includes ChemCam (Curiosity Rover), Cibola, IBEX-H, Van Allen Probe, Mars2020, SABRS2, and SABRS3
James Theiler	Mathematical physicist. Expert in machine learning, pattern recognition, spectral image processing. Laboratory Fellow with 30 years experience.

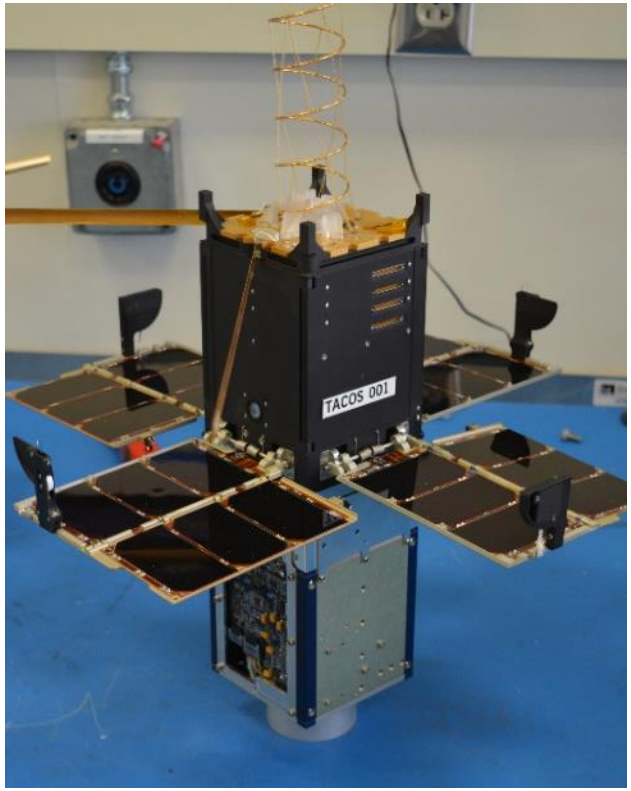
History of Reviews & Actions

Review	Date	Outcome/Feedback
TACOS Kickoff Meeting	January 2017	Identification of individuals and work required
TACOS Electrical Peer Review	May 2017	Pass, actions included in design
TACOS Mechanical Peer Review	May 2017	Pass, actions included in design
TACOS Preliminary Design Review	June 2017	Pass, actions addressed and noted in actions-status doc
TACOS Subsystem Review	January 2018	Pass, actions addressed and noted in actions-status doc
TACOS Critical Design Review	July 2018	Pass, actions addressed and noted in actions-status doc
NACHOS Kickoff Meeting	March 2019	Pass, actions addressed and noted in actions-status doc
TACOS Final Internal Review	July 2019	Excellent, actions being looked into and noted in actions-status doc
NACHOS 6mo Review	July 2019	Pass, actions being looked into and noted in actions-status doc
CSLI Launch Feasibility Review	October 2019	Pass, results/actions included in CSLI launch application
NACHOS 1 year Review	January 2020	Pass, actions being looked into and noted in actions-status doc

- **All issues and concerns from meetings are noted and addressed by team.**
- **Reviews have occurred at least every 6 months through the internal TACOS project and continue in the same manner for NACHOS.**
- **NASA requires a written status update every 2 months.**

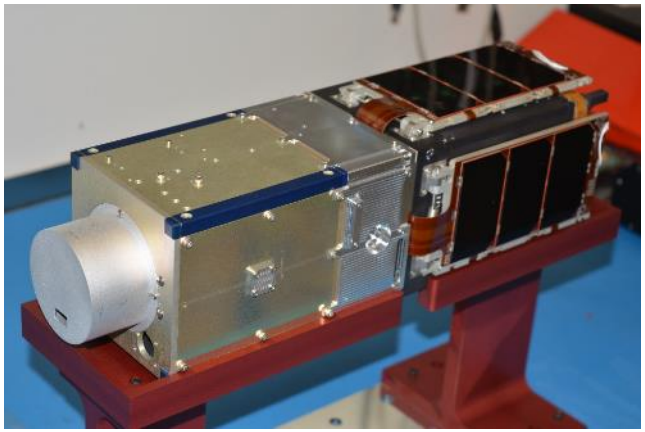
First-year Achievements, Big-Picture Summary

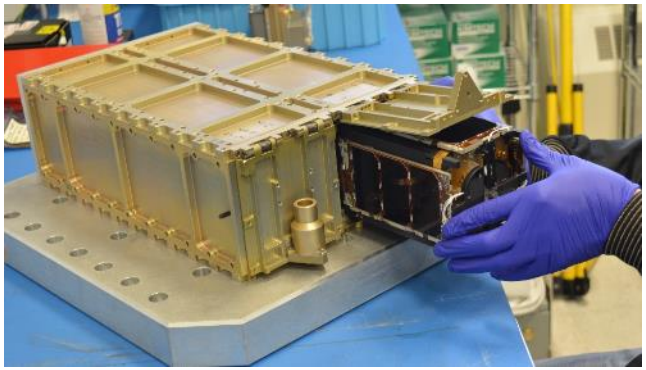
- **Two TRL-5+ instruments, EDU-1 & EDU-2, up and running**
- **Optical System**
  - Preliminary alignment of EDUs yields spectral resolution meeting minimum mission requirements.
  - Further improvement expected with rigorous alignment of EQM and flight instruments.
  - Objective lens performs at design level, achieving full pixel-Nyquist spatial resolution (0.4 km @ 500 km altitude).
  - Objective lens bi-material thermal compensation mount yields athermal focus.
- **On-board calibration system**
  - External Shutter/Diffuser vs. lower-risk LED-based system evaluation and down-select
  - LED-based system quantitatively evaluated and found to meet requirements
- **On-board processing**
  - Highly streamlined algorithms validated, exercised with real-world data on CubeSat processor.
  - New approaches developed for ground-based high-sensitivity gas detection post-processing using our small down-linked data sets



First-year Achievements, Big-Picture Summary, cont.

- **Electrical**
  - All electrical requirements met at end of TACOS to achieve overall science goals: e-/bit, fps, data storage, and diffuse light images for calibration (LED)
- **Software**
  - Individual Software pieces completed including all key spectrometer operation functions (CCD readout and buffering, etc.); integration for operations is ongoing. TacoView GUI for benchtop instrument operation and testing.
- **Mechanical**
  - LED Calibration system, baffle design and modifications
  - Tertiary mirror mount redesign, testing
  - Final grating substrates, tighter tolerance
  - Successful mechanical test fit of host and payload
  - Successful test fit of complete satellite in NLAS and Quad-M dispensers
  - Optical focus troubleshooting: CMM measurements, alignment fixture design/fab.





First-year Achievements, Big-Picture Summary, cont.

- **Environmental Testing of Payload**
  - Thermal: Multiple cycles from +30°C to -40°C, plus survival test to +60°C
    - Full system passes test, apart from a couple minor software issues that have been (or are being) addressed
    - Optical system remains in focus over entire operational range
  - Vibration: Three tests so far (GEVS qual. spectrum and duration).
    - 1st reveals slippage of tertiary mirror mount – redesign mount
    - 2nd test: new tertiary mount not locked down properly
    - 3rd test: near-pass – minor tertiary mount shift, probably due to damage sustained in 2nd test
    - Object lens/slit assembly performs excellently; no significant focus shift
- **CubeSat Host Buses**
  - Qualification Unit Host in hand
  - Flight Host scheduled to be delivered in early February
  - Sister projects have uncovered some issues with the bus electronics; analysis underway. Required modifications will be applied to NACHOS buses before full integration.

Publications and Conferences

- [“Onboard Cubesat Data Processing for Hyperspectral Detection of Chemical Plumes,” J. Theiler, B. R. Foy, C. Safi, and S. P. Love, *Proc. SPIE* **10644,** 1064405 (2018). – *paper on algorithm work performed under pre-NACHOS internal funding*]
- [“High-resolution hyperspectral imaging of dilute gases from CubeSat platforms,” S. P. Love, L. A. Ott, J. Theiler, B. R. Foy, C. Safi, M. E. Dale, C. G. Peterson, A. A. Guthrie, N. Dallmann, K. G. Boyd, P. S. Stein, J. A. Wren, M. C. Proicou, and M. K. Dubey, *2018 Fall Meeting of the American Geophysical Union* (2018). – *presentation on pre-NACHOS groundwork*]

- “CubeSat-Based High-Resolution Hyperspectral Imagers for Atmospheric Trace Gas Monitoring,” S. P. Love, L. A. Ott, J. Theiler, B. R. Foy, C. Safi, M. E. Dale, C. G. Peterson, A. A. Guthrie, N. Dallmann, K. G. Boyd, P. S. Stein, J. A. Wren, M. C. Proicou, and M. K. Dubey, *99th Annual Meeting of the American Meteorological Society* (2019).
- “Algorithm development with on-board and ground-based components for hyperspectral gas detection from small satellites,” J. Theiler and S. P. Love, *Proc. SPIE* **10986,** 109860O (2019).
- "Some closed-form expressions for absorptive plume detection," J. Theiler, *Submitted to IGARSS* (2020).

Educational Outreach

- **Summer Students:**
  - Kai Coblentz (summer 2019 & 2020, protoype parts & fixtures design, CCD module assembly, mirror mount analysis)
  - Angus Guider (summer 2019, thermal chamber window design, analysis)
  - John Pederson (summer 2019, radiative heat transfer analysis)
  - Dylan Kemelor (summer 2020, thermal modeling and software development)
- **Postdoc:**
  - Kirk Post (joined project Jan. 2020)

Algorithm design for on-board hyperspectral gas detection

James Theiler

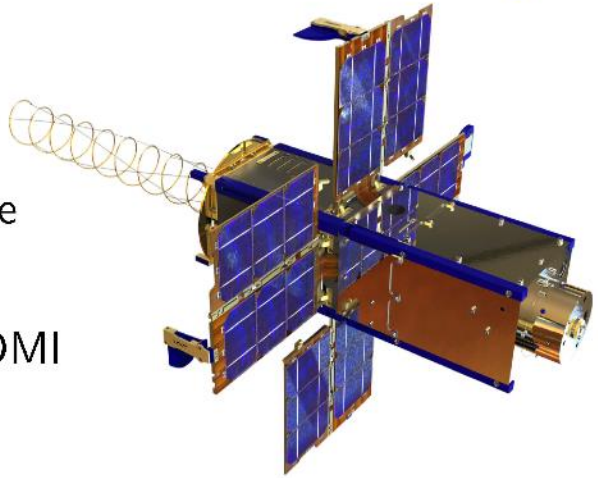
Intelligence and Space Research Division
Los Alamos National Laboratory

21 January 2020

Initial research supported by the United States Department of Energy (DOE)
Los Alamos Laboratory Directed Research and Development (LDRD).
Current work supported by the NASA InVEST program.
Acknowledge: Steven P. Love, Claira Safi, Bernard R. Foy, and the NACHOS team.

Nanosat Atmospheric Chemistry Hyperspectral Observation System

- Mission: detect and characterize anthropegenic and volcanic gas-phase emissions
- Targets include: NO_2, SO_2, ozone, formaldehyde
- 300–500nm wavelength range in 320 channels
- Smaller pixels – 0.4km vs 12km – than NASA OMI



- Limited downlink bandwidth
- Limited onboard computation
- What can we do with the downlinked data?
- Quadratic MF

Limited downlink bandwidth

Data and Data Processing

- Full hyperspectral image cube: 2000×320×320 16-bit values (∼400MB)
- Downlink capacity: ∼17MB per pass over ground station

- Strategy: use onboard computation, and downlink only chemical detection maps

- But what detection algorithm to use?
  - Adaptive Matched Filter (AMF)
  - Adaptive Coherence Estimator (ACE)
  - EC-GLRT (additive target on elliptically-contoured background)
  - MPML (machine learning) in MFR space
  - RX (diagnostic for anomalies)

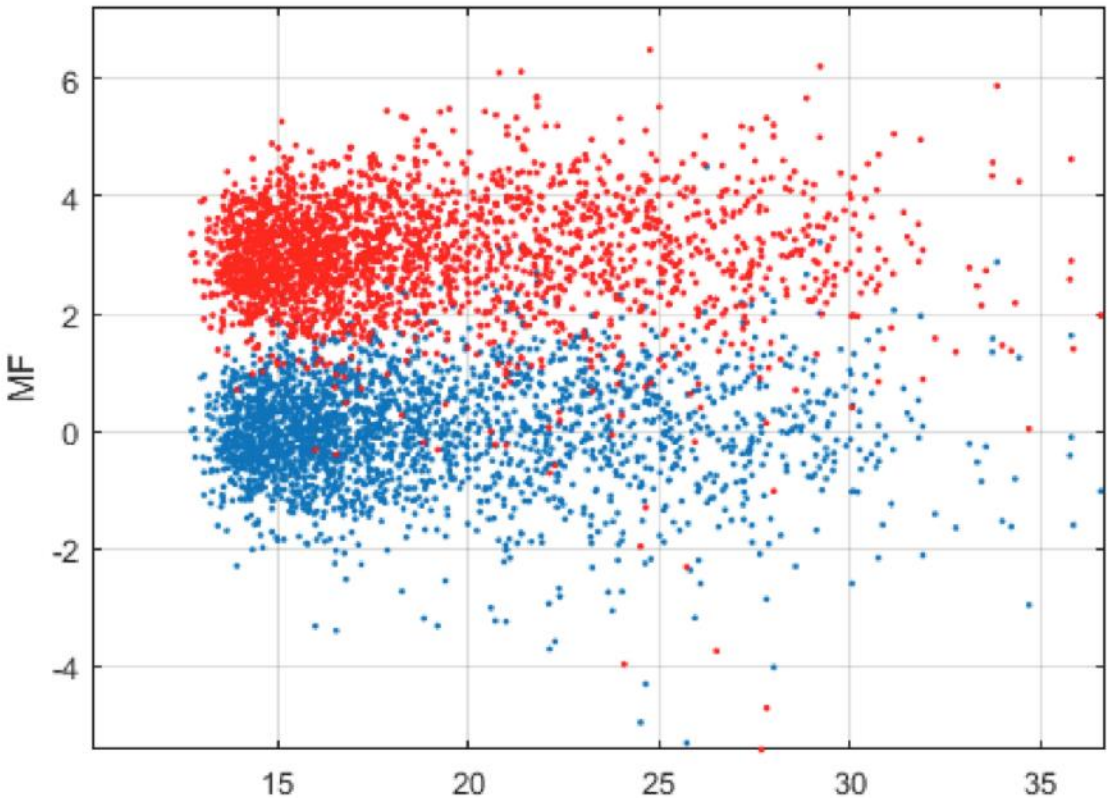
All of the above!

- But what detection algorithm to use?
  - Adaptive Matched Filter (AMF)
  - Adaptive Coherence Estimator (ACE)
  - EC-GLRT (additive target on elliptically-contoured background)
  - MPML (machine learning) in MFR space
  - RX (diagnostic for anomalies)

- Downlink, for each chemical of interest, $\mathrm{AMF} = \mathbf{s}^\top R^{-1}(\mathbf{x}-\boldsymbol{\mu})/\sqrt{\mathbf{s}^\top R^{-1}\mathbf{s}}$
- Downlink auxiliary image: $\mathrm{RX} = (\mathbf{x}-\boldsymbol{\mu})^\top R^{-1}(\mathbf{x}-\boldsymbol{\mu})$

- $\mathrm{ACE} = \mathrm{AMF}/\sqrt{\mathrm{RX}}$
- $\mathrm{EC\text{-}GLRT} = \sqrt{\dfrac{(\nu-1)}{(\nu-2)+\mathrm{RX}}} \times \mathrm{AMF}$
- MFR space defined by $\mathrm{MF} = \mathrm{AMF}$ and $\mathrm{R} = \sqrt{\mathrm{RX} - \mathrm{AMF}^2}$

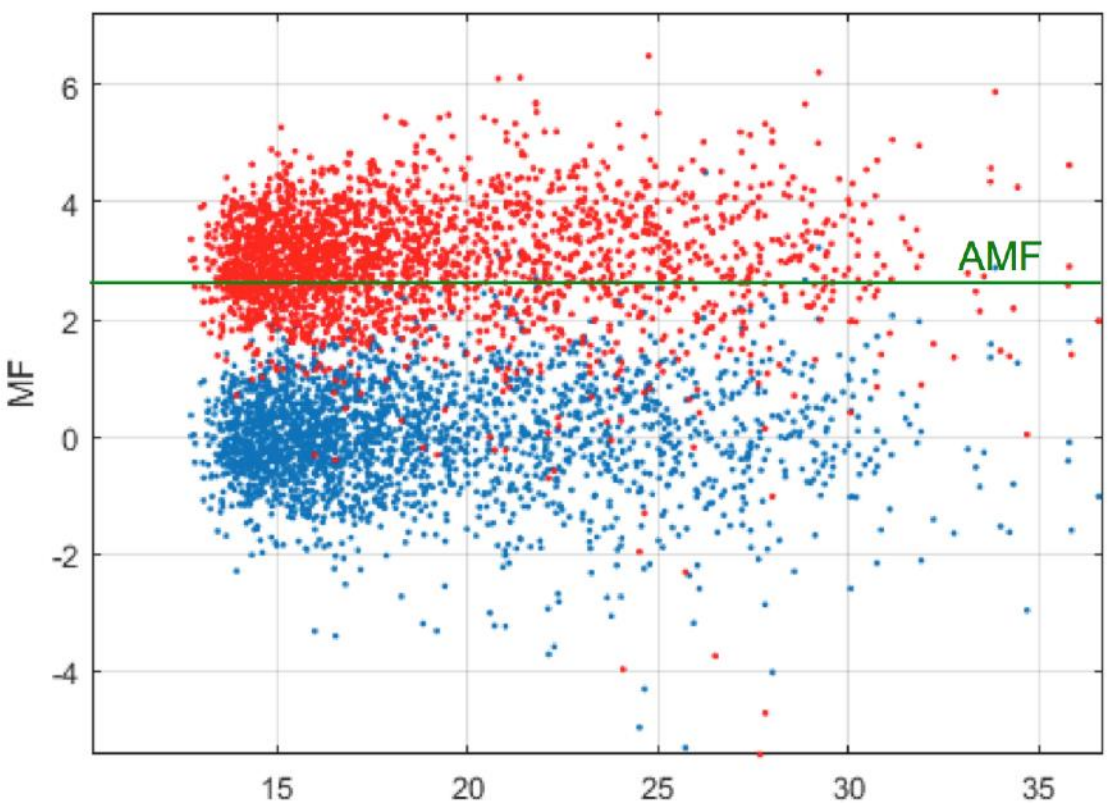
MatchedFilter-Residual (MFR) space



$$\mathrm{MF} = \mathrm{AMF}$$

$$\mathrm{R} = \sqrt{\mathrm{RX} - \mathrm{AMF}^2}$$

MatchedFilter-Residual (MFR) space



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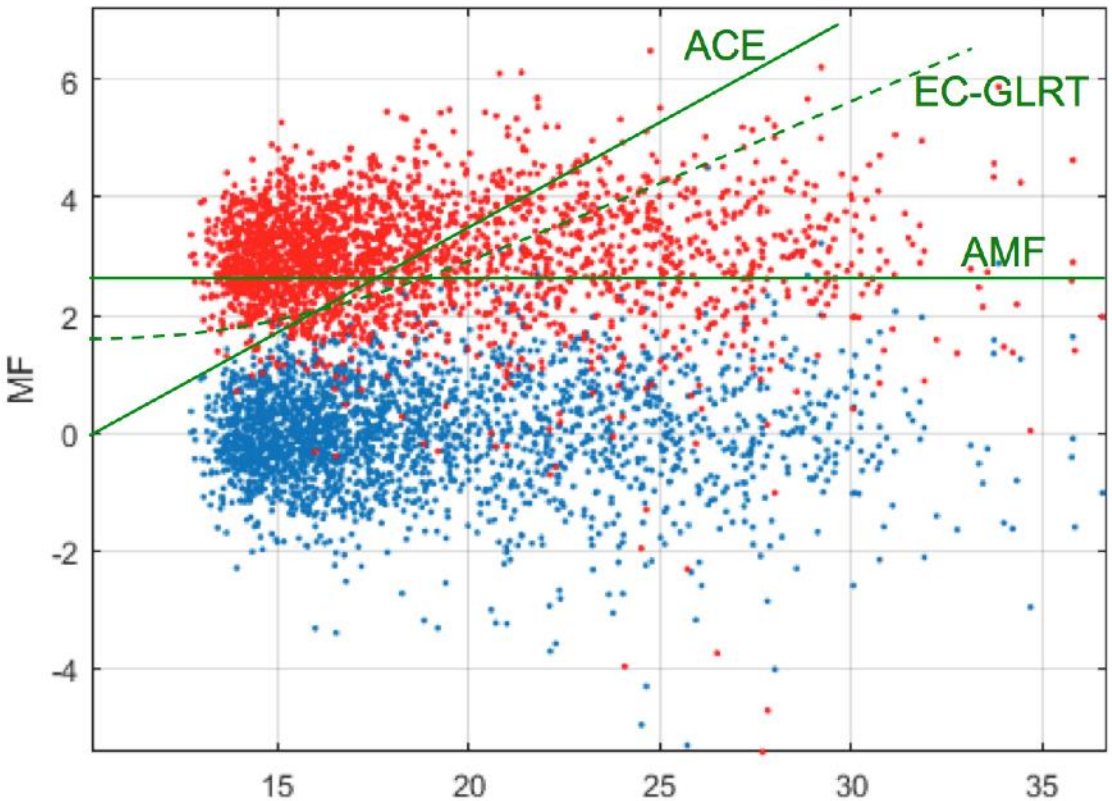
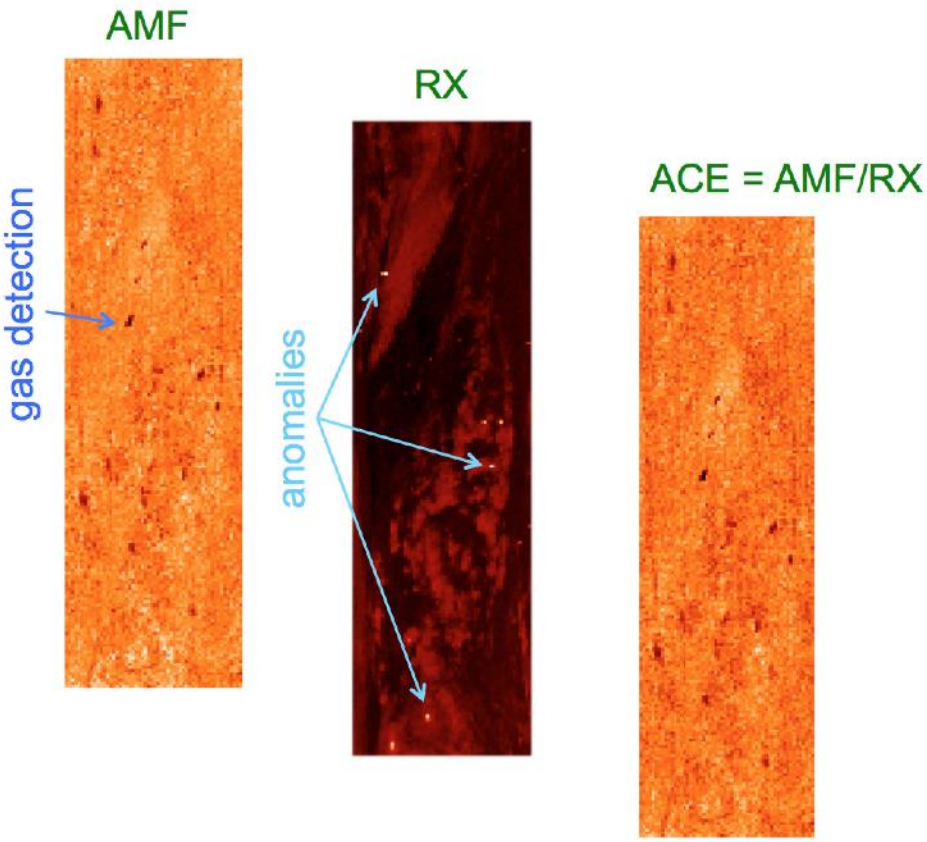
MatchedFilter-Residual (MFR) space



$$\mathrm{MF} = \mathrm{AMF}$$

$$\mathrm{R} = \sqrt{\mathrm{RX} - \mathrm{AMF}^2}$$

Application to an NO_2 plume identified in OMI datacube



- Associated with wildfires
- RX serves two purposes
  - Detection of anomalies
  - Creation of ACE image

Aside: solid targets

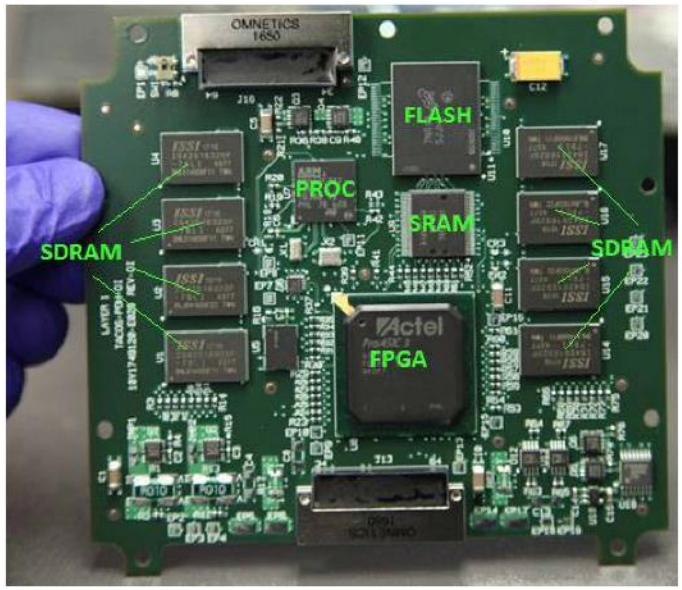
- TACOS mission only includes gas-phase chemical targets, but...
  what if we wanted to look for solid subpixel targets as well?

- Invoke replacement-model algorithms: $\mathbf{x} = (1-\alpha)\mathbf{z} + \alpha\mathbf{s}$
  - FTMF, MTMF, MF-FAM, EC-FTMF, adaptive residuals, *etc*
  - These include terms such as "mean subtracted matched filter:" $(\mathbf{s}-\boldsymbol{\mu})^\top R^{-1}(\mathbf{x}-\boldsymbol{\mu})$

- Suggests further downlinks:
  - AMF for each solid target signature $\mathbf{s}$
  - New auxiliary image: $\boldsymbol{\mu}^\top R^{-1}(\mathbf{x}-\boldsymbol{\mu})$
    - like AMF for $\mathbf{s} = \boldsymbol{\mu}$

Limited onboard computation

TACOS/NACHOS onboard processor



Microcontroller	ARM Cortex-M7
FPGA	A3P100L
Bus Width	32 bits
Clock Speed	216 MHz
Flash Program Memory	2 MB
Instruction/Data Cache	16 kB
Internal RAM	512 kB
External SRAM	8 MB
External SDRAM	512 MB
External Storage (Flash)	2-4 GB

- Includes Field Programmable Gate Array (FGPA) and associated microcontroller
- External SDRAM, accessed through the FPGA, stores hyperspectral image
- External SRAM, accessed directly by microcontroller, stores covariance matrix

Execution times using onboard computer

Operation	Execution time H:MM:SS $N = 320 \times 2000$	$N = 320 \times 320$	Big-O
Mean vector (μ) calculation	0:01:26	0:00:14	$O(Nd)$
Covariance matrix (R) calculation	3:27:20	0:33:10	$O(Nd^2)$
Cholesky decomposition of R	0:00:07	0:00:07	$O(d^3)$
Covariance matrix inversion	0:00:04	0:00:04	$O(d^3)$
Mahalanobis distance	1:54:40	0:18:21	$O(Nd^2)$
AMF calculation (per chemical)	0:06:30	0:01:02	$O(Nd)$
Total Time (one chemical)	5:30:07	0:52:59	

Execution times using onboard computer

Operation	Execution time H:MM:SS $N = 320 \times 2000$	$N = 320 \times 320$	Big-O
Mean vector (μ) calculation	0:01:26	0:00:14	$O(Nd)$
Covariance matrix (R) calculation	3:27:20	0:33:10	$O(Nd^2)$
Cholesky decomposition of R	0:00:07	0:00:07	$O(d^3)$
Covariance matrix inversion	0:00:04	0:00:04	$O(d^3)$
Mahalanobis distance	1:54:40	0:18:21	$O(Nd^2)$
AMF calculation (per chemical)	0:06:30	0:01:02	$O(Nd)$
Total Time (one chemical)	5:30:07	0:52:59	

- Bottleneck computations are $O(Nd^2)$
- We only have ~90 minutes between ground-station passes

Covariance matrix computation

- Each pixel is a vector in d-dimensional space (d=320 spectral channels)
- Let $\mathbf{x} \in \mathbb{R}^d$ be a pixel vector
- Compute mean of pixels: $\boldsymbol{\mu} = \langle \mathbf{x} \rangle = (1/N) \sum_{n=1}^{N} \mathbf{x}_n$
- Compute covariance matrix: $O(Nd^2)$

$$R = \langle (\mathbf{x} - \boldsymbol{\mu})(\mathbf{x} - \boldsymbol{\mu})^\mathsf{T} \rangle = (1/N) \sum_{n=1}^{N} (\mathbf{x}_n - \boldsymbol{\mu})(\mathbf{x}_n - \boldsymbol{\mu})^\mathsf{T}$$

- Approximate covariance with subsample of $N_* \ll N$ points: $O(N_* d^2)$
  - Good statistical approximation as long as $N_* \gg d$
  - Nominally, we use $N_* = N/100$

Mahalanobis distance (RX) computation

- Note that AMF is cheap: AMF $= \mathbf{q}^\top(\mathbf{x} - \boldsymbol{\mu})$ for $\mathbf{q} = R^{-1}\mathbf{s}/\sqrt{\mathbf{s}^\top R^{-1}\mathbf{s}}$
  - Because $\mathbf{q}$ can be pre-computed
  - Cannot do this for RX
- Cannot subsample because we need $(\mathbf{x} - \boldsymbol{\mu})^\top R^{-1}(\mathbf{x} - \boldsymbol{\mu})$ for *every* pixel $\mathbf{x}$
- Strategy: need to somehow "sparsify" R^{-1}
  - Graphical lasso
  - Low Rank Decomposition
  - Sparse Matrix Transform (SMT)

Sparse Matrix Transform (SMT) to approximate RX

- Express $\widehat{R} = EDE^{\mathsf{T}}$ with $E = G_1 G_2 \ldots G_K$
  - With D diagonal, and each G_k a sparse orthogonal matrix (Givens rotation)

$$G = \Theta(i,j,\theta) = \begin{array}{c} \\ \\ \\ \\ \\ \\ \end{array}\begin{array}{cc} \begin{array}{ccccccc} & & i & & j & & \end{array} & \\ \begin{bmatrix} 1 & \cdots & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & & \vdots & & \vdots \\ 0 & \cdots & \cos\theta & \cdots & \sin\theta & \cdots & 0 \\ \vdots & & \vdots & \ddots & \vdots & & \vdots \\ 0 & \cdots & -\sin\theta & \cdots & \cos\theta & \cdots & 0 \\ \vdots & & \vdots & & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 1 \end{bmatrix} & \begin{array}{c} \\ \\ i \\ \\ j \\ \\ \\ \end{array} \end{array}$$

Sparse Matrix Transform (SMT) to approximate RX

- Express $\widehat{R} = EDE^{\mathsf{T}}$ with $E = G_1 G_2 \ldots G_K$
  - With D diagonal, and each G_k a sparse orthogonal matrix (Givens rotation)
  - Note approximation is of full rank (so readily invertible)
- Thus: $\widehat{R^{-1}} = \widehat{R}^{-1} \approx ED^{-1}E^{\mathsf{T}}$, and

$$\mathrm{RX} = (\mathbf{x}-\boldsymbol{\mu})^T R^{-1}(\mathbf{x}-\boldsymbol{\mu}) \approx \|D^{-1/2}E^{\mathsf{T}}(\mathbf{x}-\boldsymbol{\mu})\|^2 = \|D^{-1/2}G_K^{\mathsf{T}} \ldots G_2^{\mathsf{T}} G_1^{\mathsf{T}}(\mathbf{x}-\boldsymbol{\mu})\|^2$$

- G_k is sparse, so matrix-vector multiplication is cheap (only 4 ops!)[†]
- Thus RX estimate requires $2K + 2d$ operations[‡]
  - K sparse matrix-vector multiplications
  - One diagonal matrix-vector multiplication
  - One norm of a d-dimensional vector

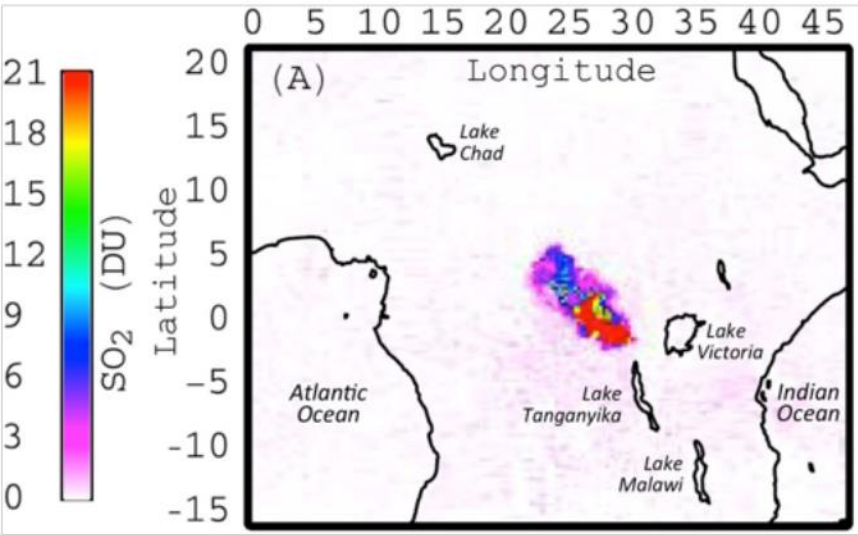
[†] There is a "trick" to reduce that to only 2 ops

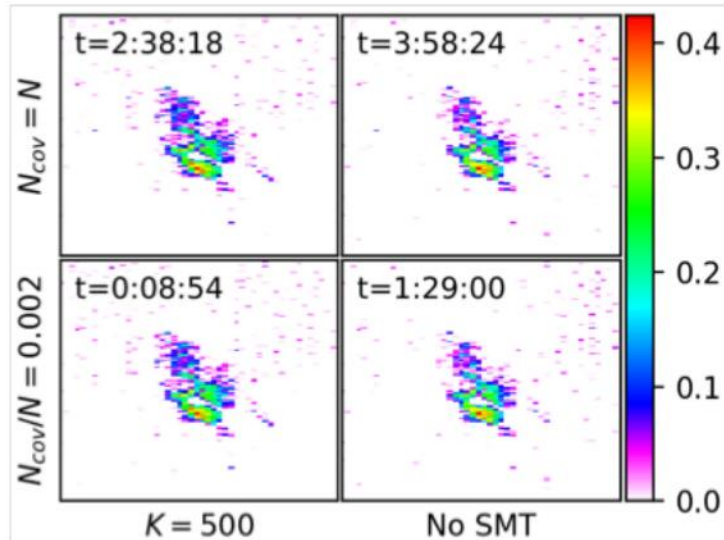
[‡] With $K \ll d^2$, this is much faster than nominal $O(d^2)$ ops per pixel

Execution times using onboard computer (faster processing)

Operation	Execution time H:MM:SS $N = 320 \times 2000$	$N = 320 \times 320$	Big-O
Mean vector (μ) calculation	0:01:26	0:00:14	$O(Nd)$
Covariance matrix (R) full	3:27:20	0:33:10	$O(Nd^2)$
Covariance matrix (R) sampled	0:02:04	0:00:20	$O(N_* d^2)$
Cholesky decomposition of R	0:00:07	0:00:07	$O(d^3)$
Covariance matrix inversion	0:00:04	0:00:04	$O(d^3)$
Mahalanobis distance	1:54:40	0:18:21	$O(Nd^2)$
SMT Decomposition of R	0:00:41	0:00:41	$O(Kd^2)$
Mahalanobis distance (SMT)	0:13:57	0:02:14	$O(NK) + O(Nd)$
AMF calculation (per chemical)	0:06:30	0:01:02	$O(Nd)$
Total Time (one chemical)	5:30:07	0:52:59	
Total Time (one chemical)	0:24:50	0:04:42	

$K = 2000,\ N_* = N/100$


(A)
Longitude
Latitude
0 5 10 15 20 25 30 35 40 45
20 15 10 5 0 -5 -10 -15
21 18 15 12 9 6 3 0
SO_2 (DU)
Lake Chad
Lake Victoria
Lake Tanganyika
Lake Malawi
Atlantic Ocean
Indian Ocean


t=2:38:18
t=3:58:24
t=0:08:54
t=1:29:00
$N_{cov} = N$
$N_{cov}/N = 0.002$
$K = 500$
No SMT
0.4
0.3
0.2
0.1
0.0

$$K = 500,\ N_* = N/500$$

What can we do with the downlinked data?

Reconstruction

For what shall it profit a man if
he shall gain the whole spectrum?

- Let $\mathbf{x} \in \mathbb{R}^d$ be the full d-component spectrum at a pixel
- Let $\mathbf{t}_1, \ldots, \mathbf{t}_k$ be the k target spectra whose matched filters are downlinked
  - Could include $\mathbf{t} = \boldsymbol{\mu}$ (useful for solid targets)
  - Could include $\mathbf{t}$ associated with first few principal components
  - Write $d \times k$ matrix of target spectra: $T = [\mathbf{t}_1, \ldots, \mathbf{t}_k]$
- Then $\mathbf{u} = T^\top R^{-1}(\mathbf{x} - \boldsymbol{\mu}) \in \mathbb{R}^k$ is vector that is downlinked for each pixel
- Mahalanobis magnitude: $v^2 = (\mathbf{x} - \boldsymbol{\mu})^\top R^{-1}(\mathbf{x} - \boldsymbol{\mu})$ is also downlinked

- Given $\mathbf{u}$, v^2, try to reconstruct the full spectrum $\mathbf{x}$

Reconstruction: solution

- Problem is underconstrained: many solutions
- All solutions can be expressed as: $\mathbf{x} = A^{\mathsf{T}}\mathbf{u} + B^{\mathsf{T}}\mathbf{z}$
  - Matrices A and B can be expressed in terms of target matrix T
  - $\mathbf{u}$ is vector of matched filter outputs
  - $\mathbf{z}$ is arbitrary, up to magnitude (which depends on v^2)
- If $\mathbf{u}$ includes high-amplitude components (eg, mean $\boldsymbol{\mu}$ or top principal components) then amplitude of $\mathbf{z}$ will be relatively small
- Gory details in the Proceedings paper...

Stripe Correction

- Subtle stripe artifact often visible in OMI data
  and more generally, in data produced by push-broom imagers
- Presumably due to small differences in gain and offset
  of the individual pixels on the focal plane
- One fix: compute separate mean $\boldsymbol{\mu}_k$ for each stripe k
  and adjust matched filter appropriately

$$\mathbf{q}^\mathsf{T}(\mathbf{x} - \boldsymbol{\mu}_k) = \mathbf{q}^\mathsf{T}(\mathbf{x} - \boldsymbol{\mu}) - \mathbf{q}^\mathsf{T}(\boldsymbol{\mu}_k - \boldsymbol{\mu})$$

- Need not be performed onboard; can be done *after* data acquisition

New: quadratic matched filter

Linear matched filter

- Consider purely absorptive plume (ignore scattering)
- Write diagonal matrix $T_{\lambda\lambda} = [1 - \exp(-\epsilon t_\lambda)]/\epsilon$
  - t_λ is absorption coefficient for gas at wavelength channel λ
  - $T_{\lambda\lambda} \approx t_\lambda$ for weak (small ϵ) plume
- On-plume pixel: $\mathbf{x} = \mathbf{z} \cdot exp(-\epsilon \mathbf{t}) = \mathbf{z} - \epsilon T \mathbf{z}$
- Off-plume pixel: $\mathbf{x} = \mathbf{z}$
- For linear matched filter, we <u>*treat*</u> $\epsilon T \mathbf{z}$ as an "additive constant"
  - Argue backgound spectrum $\mathbf{z}$ is "relatively flat", take $\mathbf{z} \to \mathbf{1}$, then $\mathbf{s} = \mathbf{t}$
  - Argue constant that best estimates background $\mathbf{z}$ is mean $\boldsymbol{\mu}$, take $\mathbf{z} \to \boldsymbol{\mu}$, then $\mathbf{s} = T\boldsymbol{\mu}$
- Detector: $\mathcal{D}(\mathbf{x}) = \mathbf{q}^\top(\mathbf{x} - \boldsymbol{\mu})$ with $q = -R^{-1}\mathbf{s}$

Quadratic matched filter

On-plume pixel: $\mathbf{x} = \mathbf{z} - \epsilon T \mathbf{z}$

Off-plume pixel: $\mathbf{x} = \mathbf{z}$

- Find optimal detector using likelihood ratio (assuming Gaussian background)

$$\mathcal{L}(\mathbf{x}) = \frac{P_{\text{plume}}(\mathbf{x})}{P_{\text{bkg}}(\mathbf{x})} = \frac{P_{\text{bkg}}(\mathbf{x} + \epsilon T \mathbf{x})}{P_{\text{bkg}}(\mathbf{x})} = \frac{\exp\left[-\frac{1}{2}(\mathbf{x} + \epsilon T \mathbf{x} - \boldsymbol{\mu})^T R^{-1} (\mathbf{x} + \epsilon T \mathbf{x} - \boldsymbol{\mu})\right]}{\exp\left[-\frac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^T R^{-1} (\mathbf{x} - \boldsymbol{\mu})\right]}$$

- To leading order in ϵ, detector $\mathcal{D}(\mathbf{x}) = 2 \log \mathcal{L}(\mathbf{x})$ is given by

$$\mathcal{D}(\mathbf{x}) = \mathbf{q}^{\mathsf{T}}(\mathbf{x} - \boldsymbol{\mu}) - \tfrac{1}{2}(\mathbf{x} - \boldsymbol{\mu})^{\mathsf{T}} Q (\mathbf{x} - \boldsymbol{\mu})$$

- with

$$\mathbf{q} = -R^{-1} T \boldsymbol{\mu}, \quad \text{and}$$
$$Q = R^{-1} T + T R^{-1}$$

Taxonomy of expressions for absorptive plume detectors

	Gaussian ($\nu \to \infty$)	EC	Fat ($\nu \to 2$)
Additive	$\mathcal{D}_{\text{AMF}}(\mathbf{x}) = -(T\boldsymbol{\mu})' R^{-1}(\mathbf{x}-\boldsymbol{\mu})$	$\mathcal{F}_\nu(\mathbf{x})\mathcal{D}_{\text{AMF}}(\mathbf{x})$	$\dfrac{\mathcal{D}_{\text{AMF}}(\mathbf{x})}{\sqrt{(\mathbf{x}-\boldsymbol{\mu})' R^{-1}(\mathbf{x}-\boldsymbol{\mu})}}$
LMP	$\mathcal{D}_{\text{QAMF}}(\mathbf{x}) = -(T\mathbf{x})' R^{-1}(\mathbf{x}-\boldsymbol{\mu})$	$\mathcal{F}_\nu^2(\mathbf{x})\mathcal{D}_{\text{QAMF}}(\mathbf{x})$	$\dfrac{\mathcal{D}_{\text{QAMF}}(\mathbf{x})}{(\mathbf{x}-\boldsymbol{\mu})' R^{-1}(\mathbf{x}-\boldsymbol{\mu})}$
GLRT	$\mathcal{D}_{\text{GLRT}}(\mathbf{x}) \approx \dfrac{\mathcal{D}_{\text{QAMF}}(\mathbf{x})}{\sqrt{(T\mathbf{x})' R^{-1} T\mathbf{x} + (T\mathbf{x})' T R^{-1}(\mathbf{x}-\boldsymbol{\mu})}}$	$\mathcal{F}_\nu(\mathbf{x})\mathcal{D}_{\text{GLRT}}(\mathbf{x})$	$\dfrac{\mathcal{D}_{\text{GLRT}}(\mathbf{x})}{\sqrt{(\mathbf{x}-\boldsymbol{\mu})' R^{-1}(\mathbf{x}-\boldsymbol{\mu})}}$

with: $\mathcal{F}_\nu(\mathbf{x}) = \sqrt{\dfrac{(\nu-1)}{(\nu-2) + (\mathbf{x}-\boldsymbol{\mu})' R^{-1}(\mathbf{x}-\boldsymbol{\mu})}}$

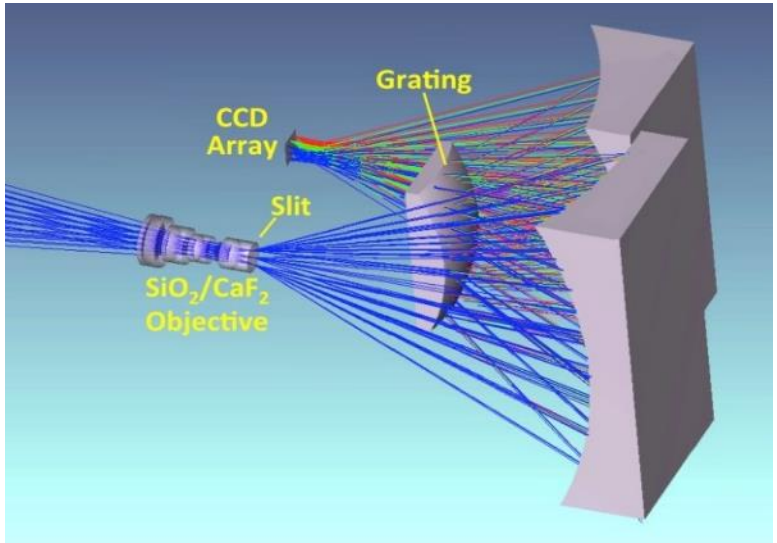
Recap

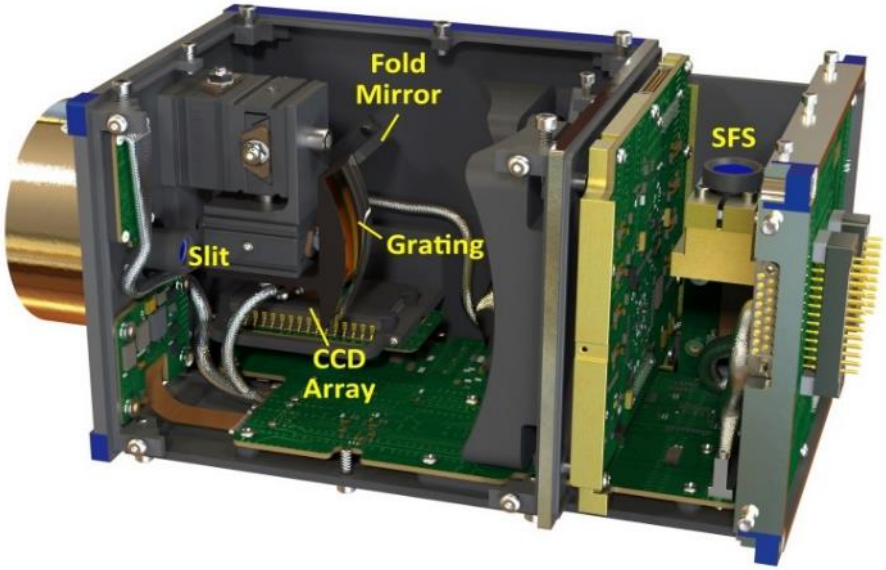
- Limited downlink capacity
  - Downlink AMF images, one for each chemical (NO_2, SO_2, ozone, formaldehyde, ...)
  - Downlink RX image
  - Can compute ACE, EC-GLRT, MFR-based ML detectors on the ground
  - Also: downlink a sample of full-spectrum pixels
- Limited computational power
  - Bottlenecks are covariance matrix and RX image
  - Estimate convariance matrix R with subsample of points: $O(Nd^2) \to O(N_* d^2)$
  - Estimate R^{-1} using SMT, compute RX efficiently: $O(Nd^2) \to O(NK) + O(Nd)$
- Post-downlink processing
  - Reconstruct full datacube
    - helps to downlink $\mathbf{t} = \boldsymbol{\mu}$ and/or $\mathbf{t} =$ top principal components
  - Stripe correction
- Quadratic matched filter
  - in progress...

Optical System

Steven Love

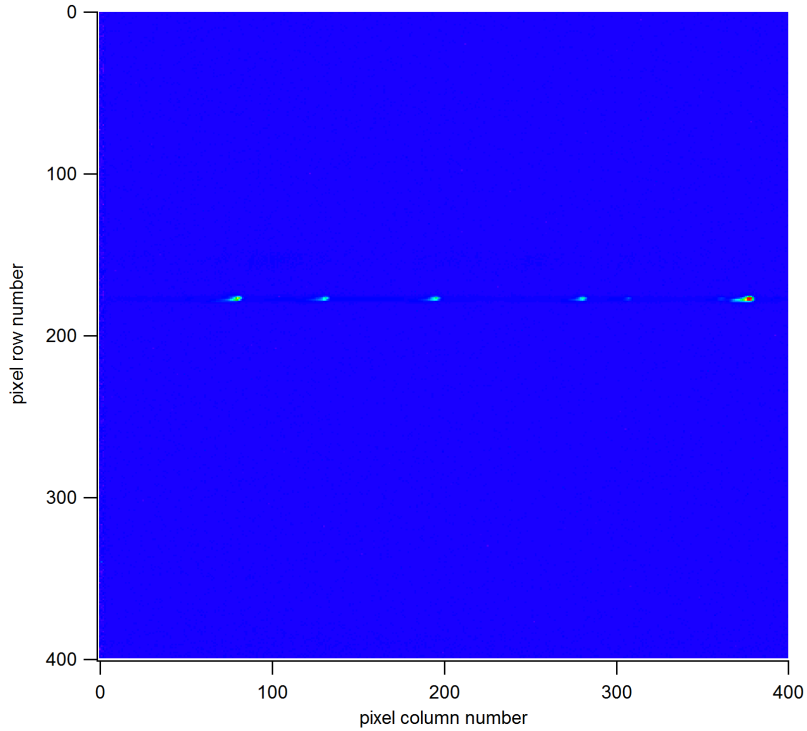
Optical Layout





Optical system status as of 6-month review

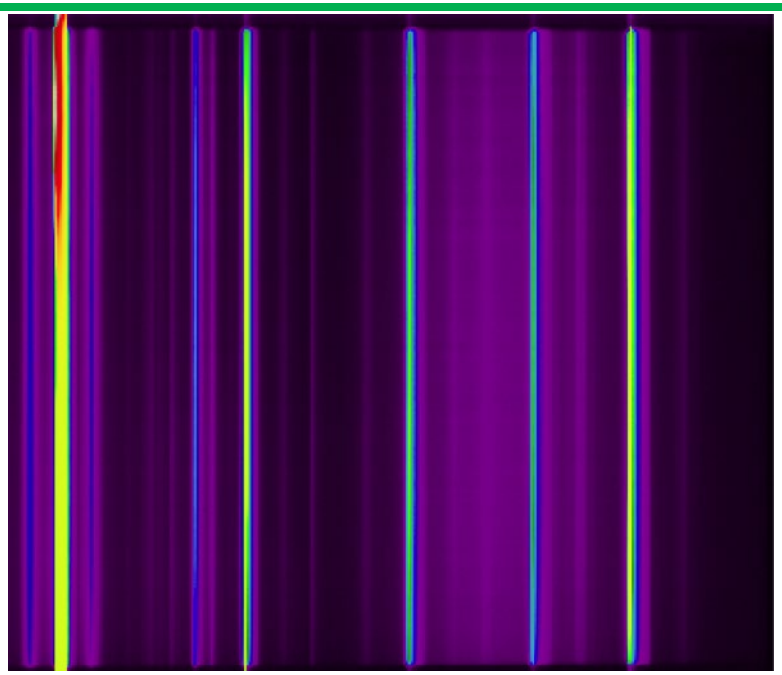
- **First light, first spectra with pinhole alignment aperture, 4/28/19**

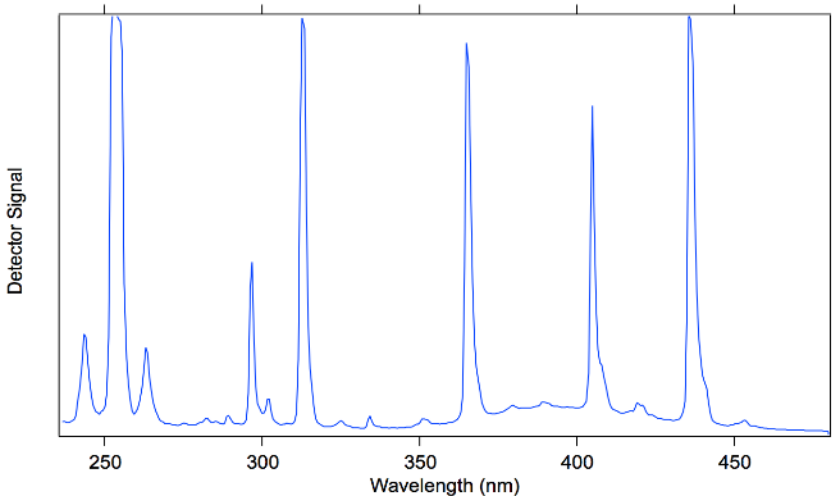


- **As of 6-month review, had only demonstrated obtaining spectra with pinhole alignment aperture in place of slit. Objective lens, slit, and full 2D geometric distortion performance had not been tested yet.**

Full system, with slit: Current Performance

Hg emission spectrum obtained with NACHOS EDU-2





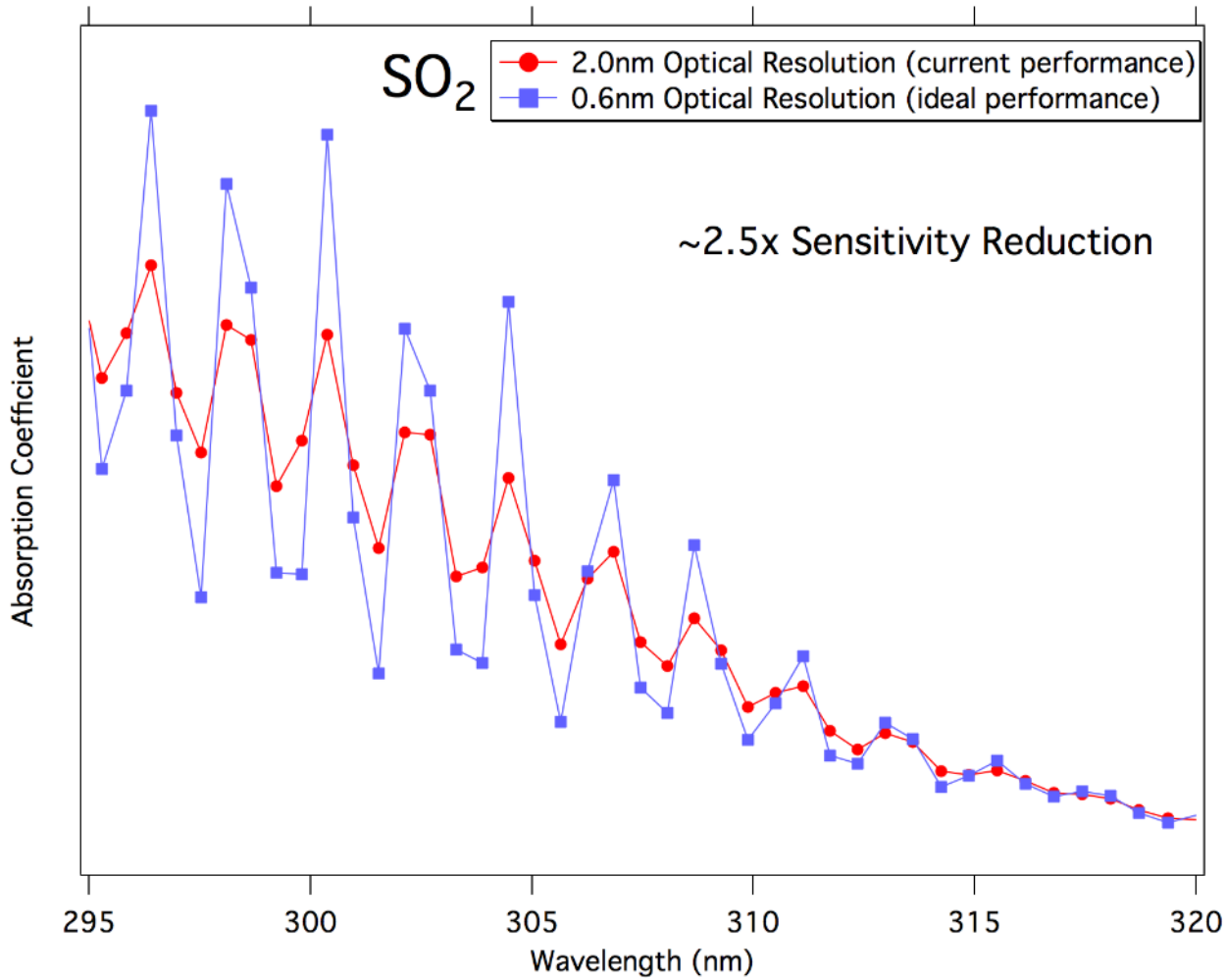
- Negligible geometric distortions (smile/keystone) – Meets mission criteria
- Spectral resolution good, but not yet achieving full design performance
- …but already meets minimum requirements for on-orbit validation mission

Not yet achieving design spectral resolution. How much does it matter?

Most challenging gas: SO_2

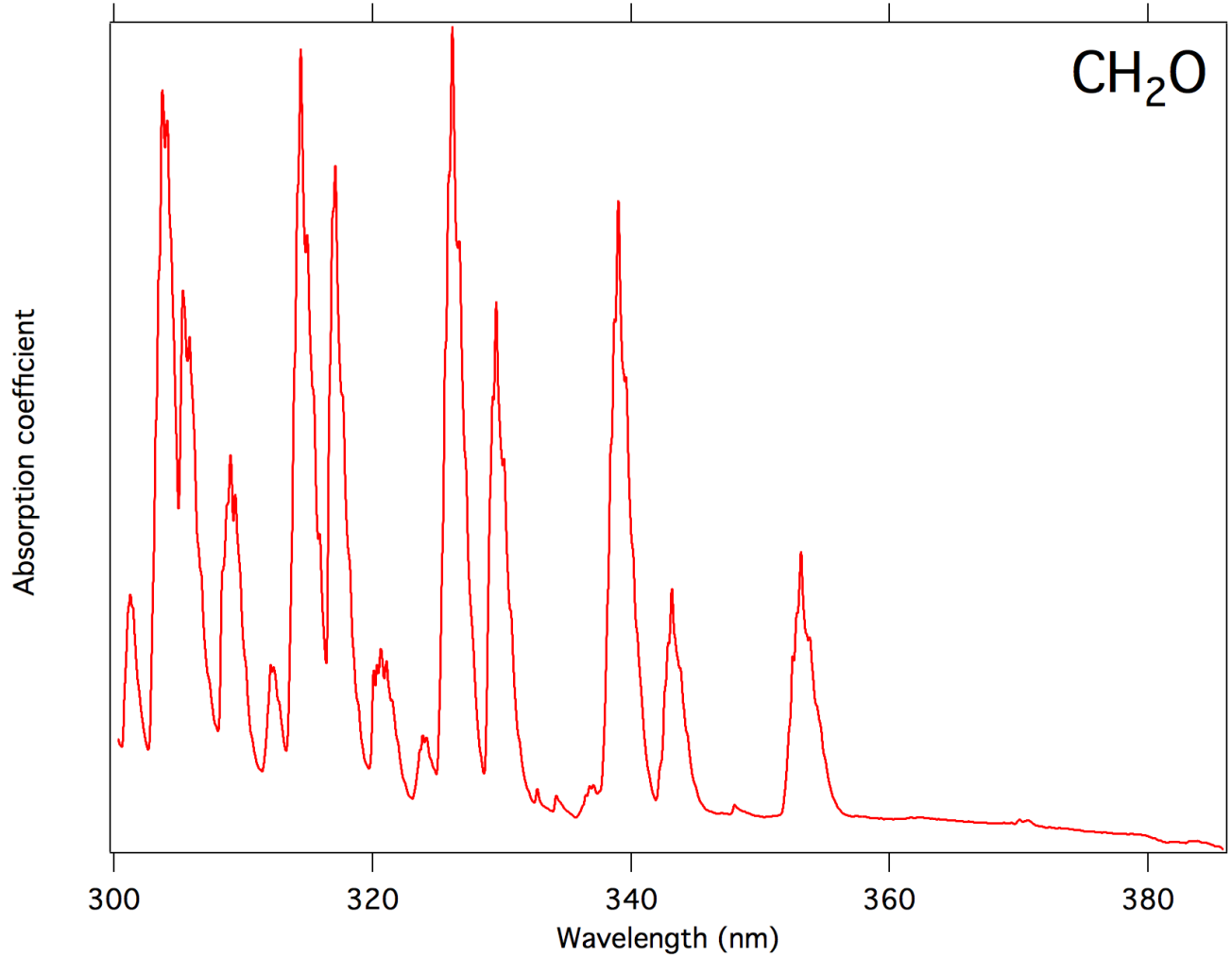
Simulated SO_2 spectra at current and ideal optical resolution

Experimental verification using SO_2 and NO_2 gas cells planned for near future.



Not yet achieving design spectral resolution. How much does it matter?

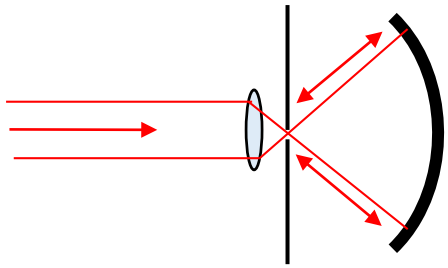
Other gases, like Formaldehyde or NO_2 , won't be much affected



Alignment/Spectral Resolution Mitigation Strategy

More rigorous alignment procedure using laser:

- **Align primary and tertiary mirrors to each other, and to spectrometer housing, using laser and alignment jig with pinhole fiducials for centers of curvature**
  - Alignment jig currently in-hand



- **Once these degrees of freedom are pinned down, remaining adjustments (grating x,y,z and slit z) are relatively straightforward.**
- **May not be necessary: Much of the difficulty experienced earlier was due to inability to adjust tertiary mirror with sufficient finesse. New tertiary mount provides excellent fine adjustment capability.**

Current Performance: Imaging

NACHOS image of laboratory targets (pushbroom image using rotating scan mirror)

Illumination: Overhead fluorescent room lights, plus Hg(Ar) spectral calibration lamp (bright area below center)

Single-band image:
NACHOS band #81: 435.83nm

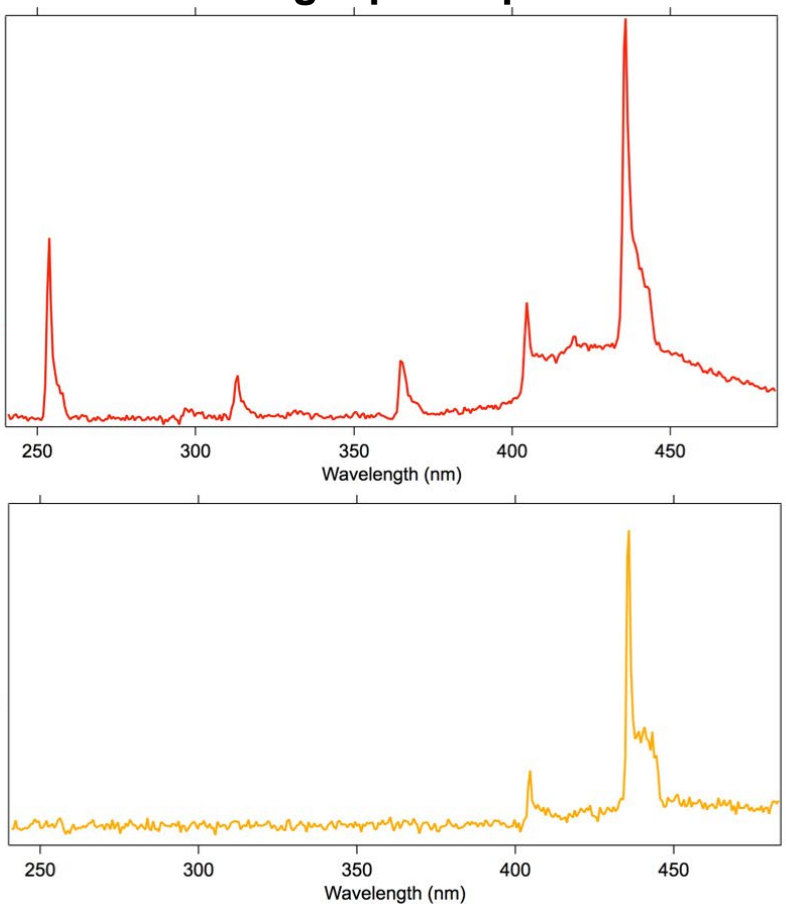
This is one slice of a 400 x 350 x 275 (spectral x spatial x spatial) hyperspectral image cube

- The finest scale bar targets, designed to be at the pixel Nyquist limit (i.e.,1 stripe/pixel, or 2 pixels for each black/white cycle), are resolved.
- Meets spatial resolution requirements, achieves design spatial resolution of 0.4 km at 500 km altitude.

Current Performance: Hyperspectral Imaging

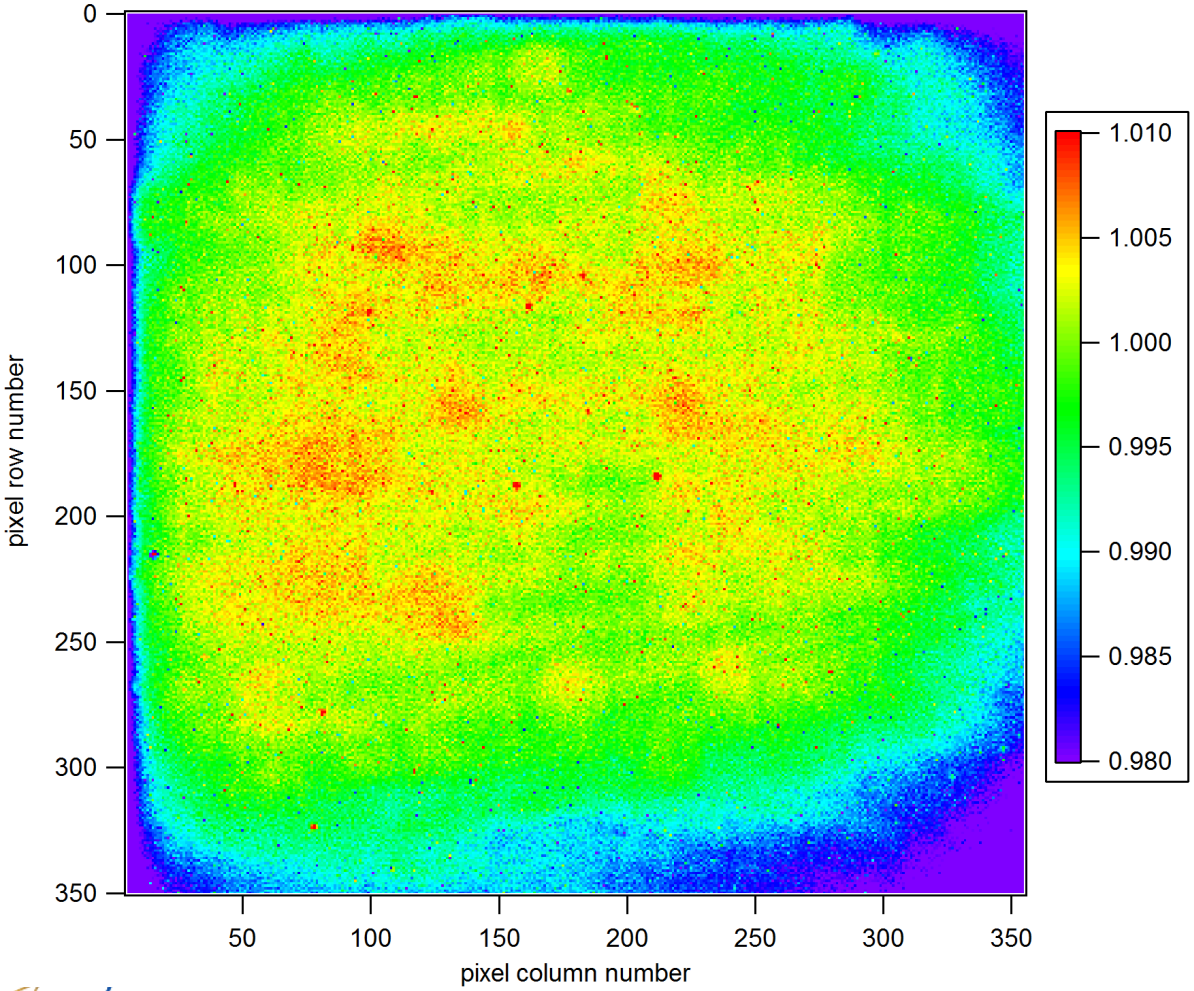
False-color image using three Hg wavelengths:
Red=435.83nm (band #81), Green=404.66nm (band #132), Blue=313.15nm (band #281)

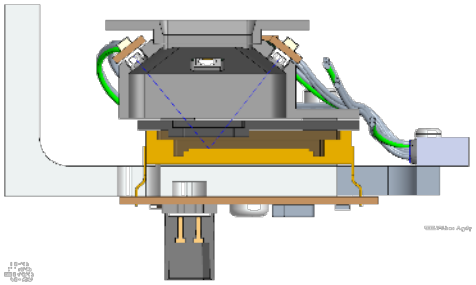
Single-pixel spectra:



Performance of LED-based on-board calibration system

Normalized LED illumination pattern, calibrated against external integrating-sphere uniform light source



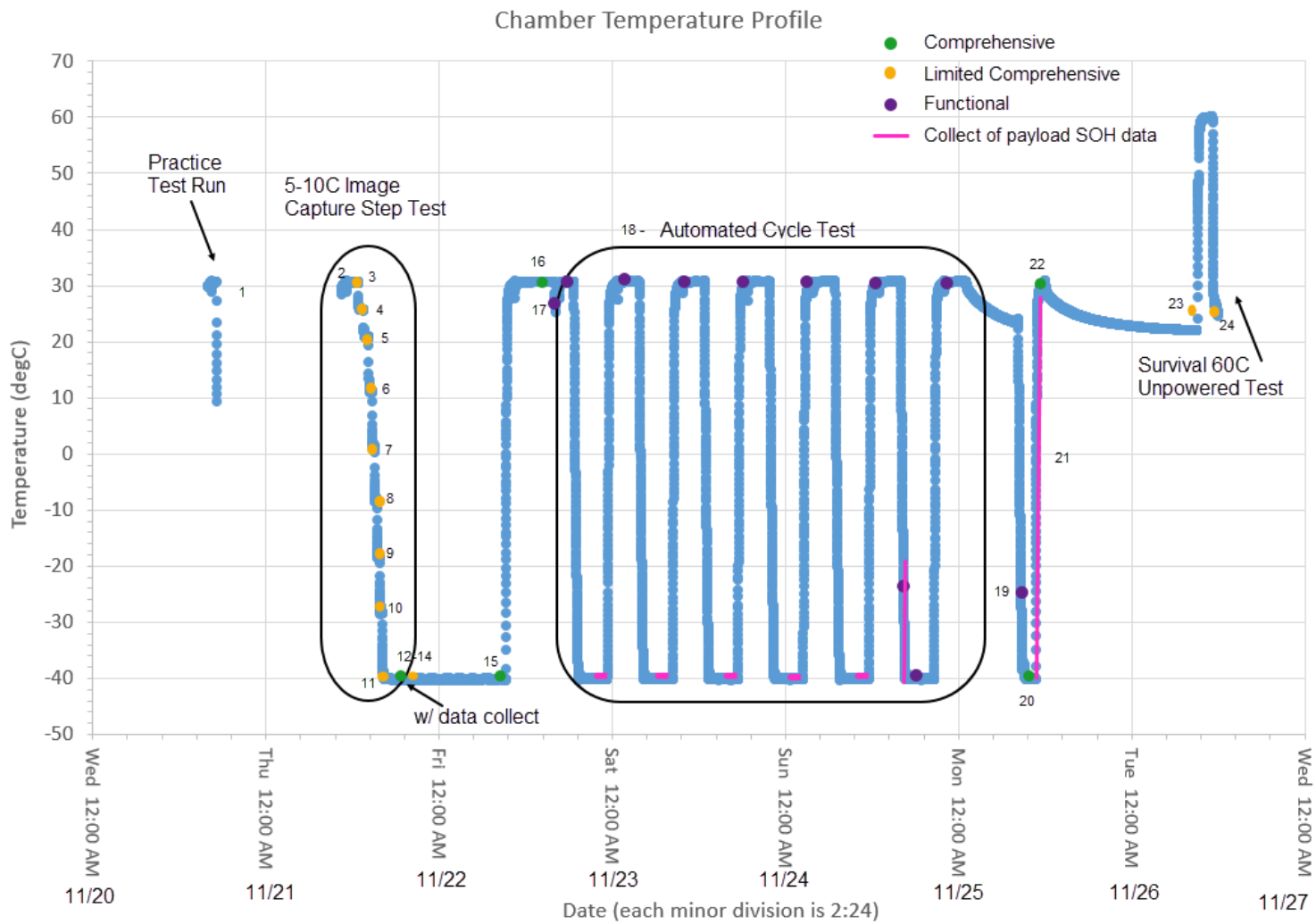


- Uniform to within ±1% over most of ROI
- ~2% drop-off at corners
- ==> *Acceptable uniformity*
- Stable, reproducible pattern
- Non-uniformity pattern does not resemble any chemical signature. Will drop out and be ignored by retrieval algorithms.
- Fine-scale pixel-to-pixel non-uniformities <0.1% rms
- **Meets mission requirements**

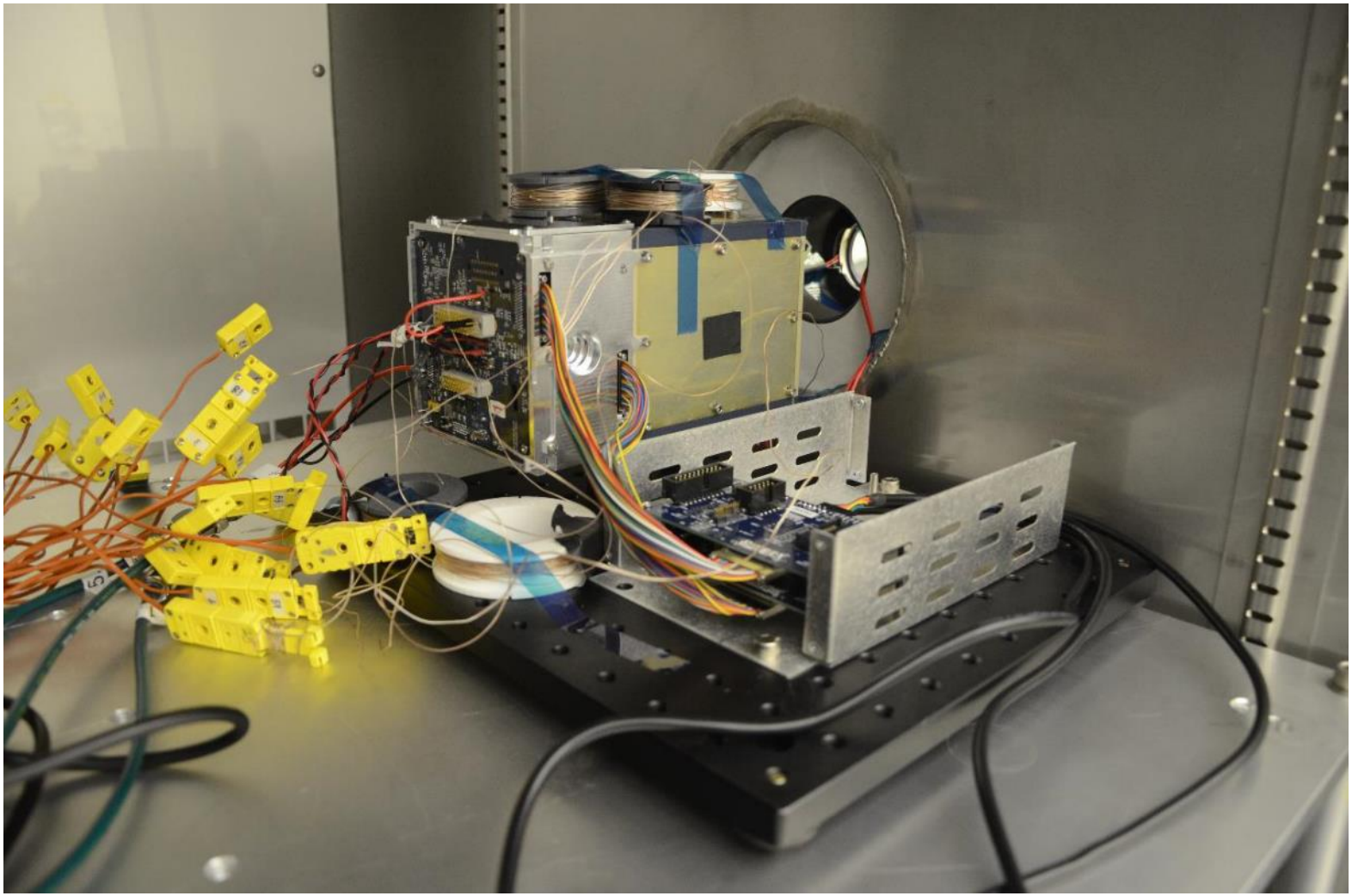
Thermal Testing

- **Optical system areas of concern in thermal test:**
  - Reflective spectrometer focus
    - All-reflective. Mirrors, housing, all same material (aluminum), except for small-thickness steel mirror mounts. Expect whole spectrometer to expand/shrink in proportion.
  - Objective/Slit focus
    - Significant change in refractive index of lens materials over temperature range.
    - Bi-material mounting scheme of lens assembly and slit designed to compensate for focus shift. Will this scheme work?
  - LED calibration system performance
    - Some LEDs are known to have significant output variation with temperature.

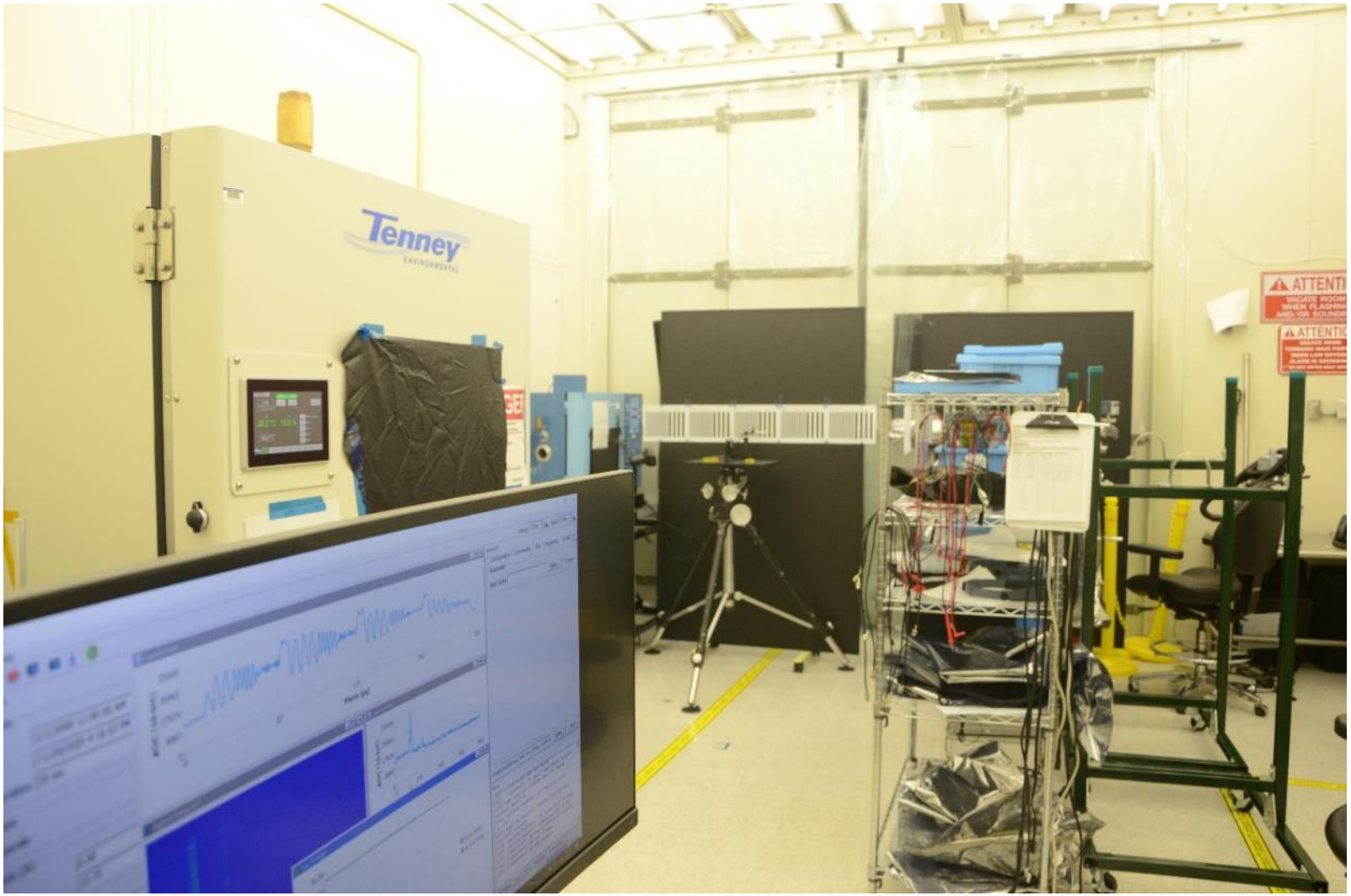
Thermal cycle sequence



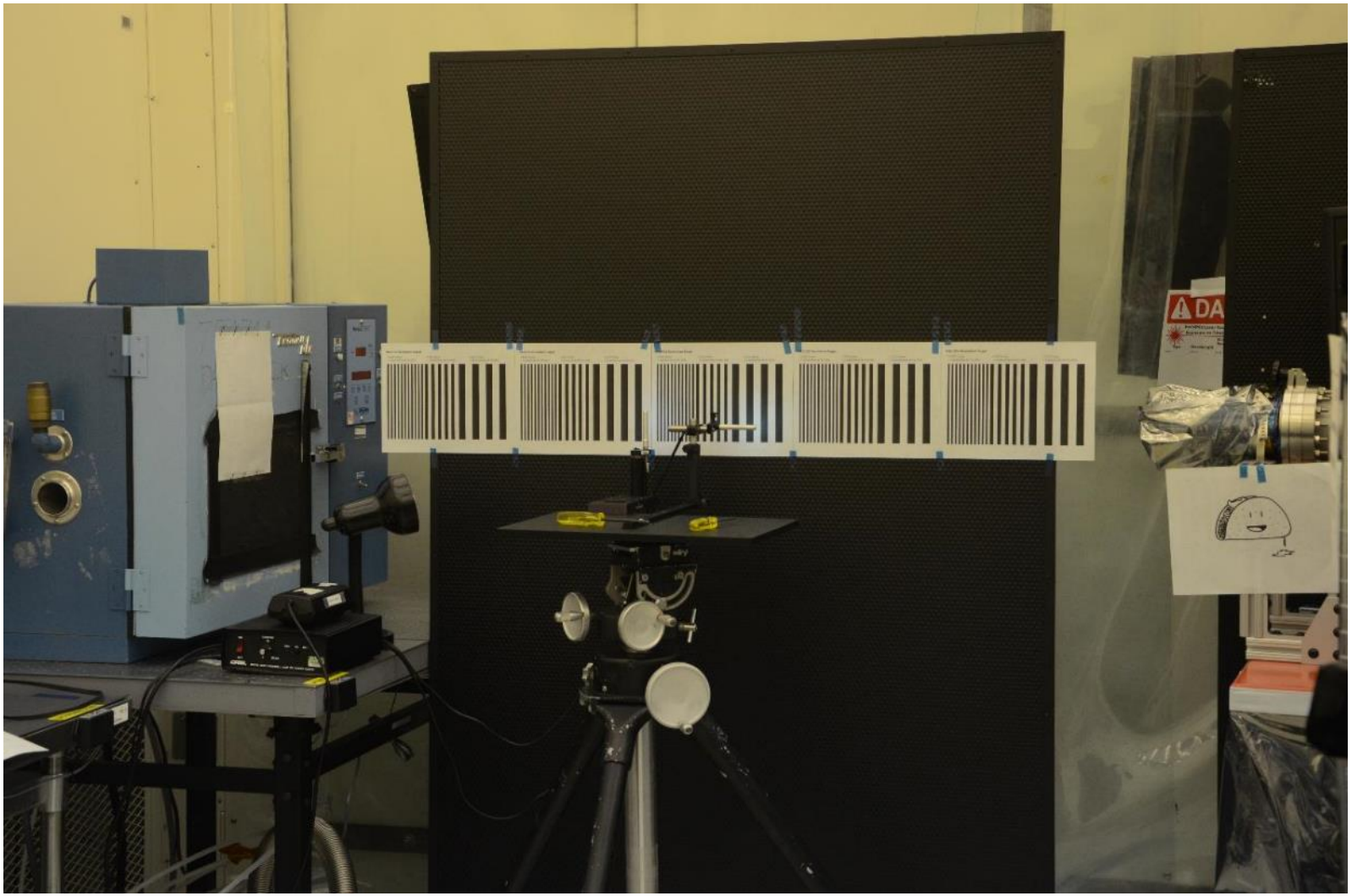
NACHOS payload inside thermal chamber



Thermal test setup in clean room



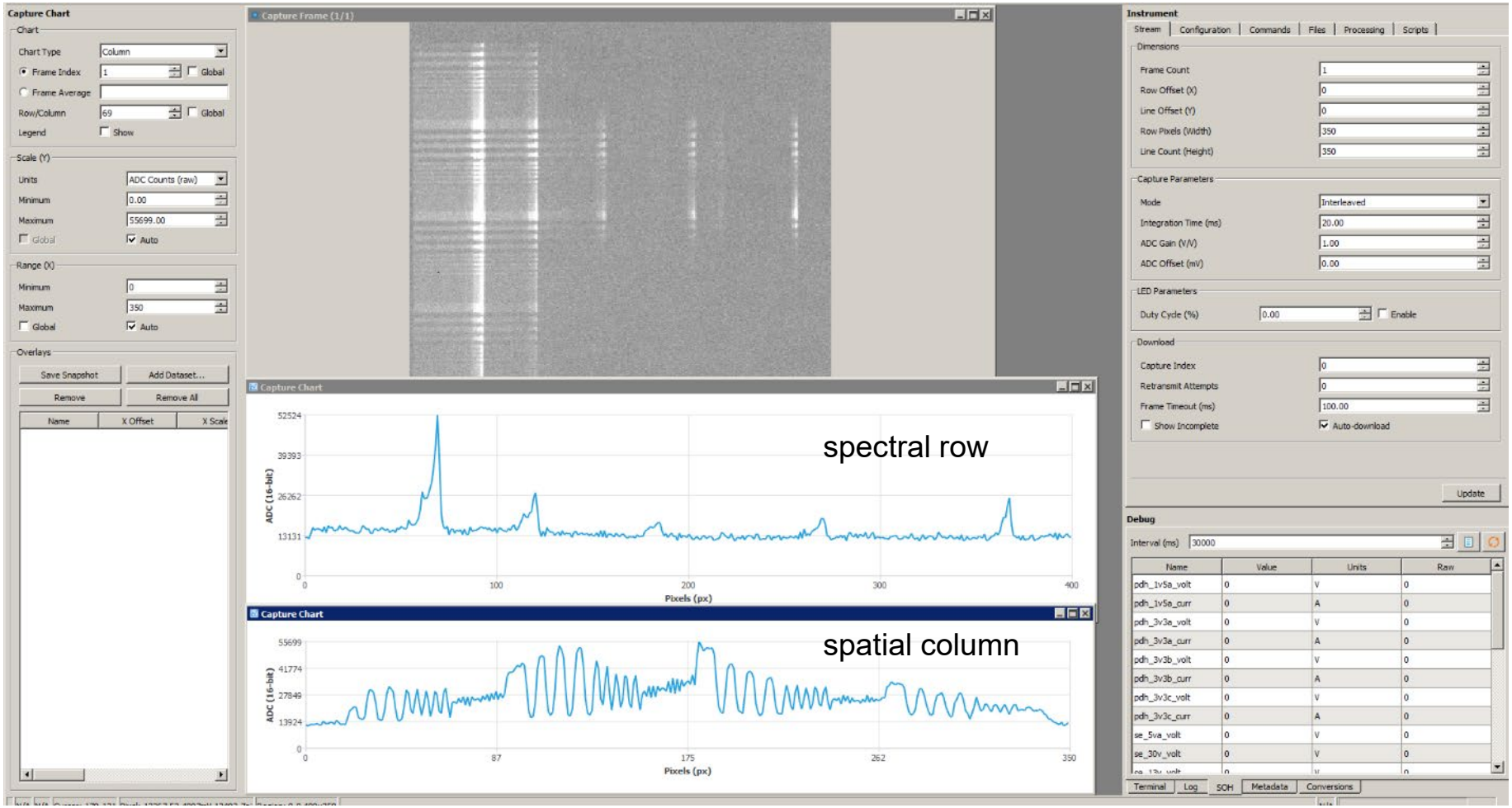
Optical resolution target w/ Hg lamp illumination



Optical performance as a function temperature

- **+30°C**

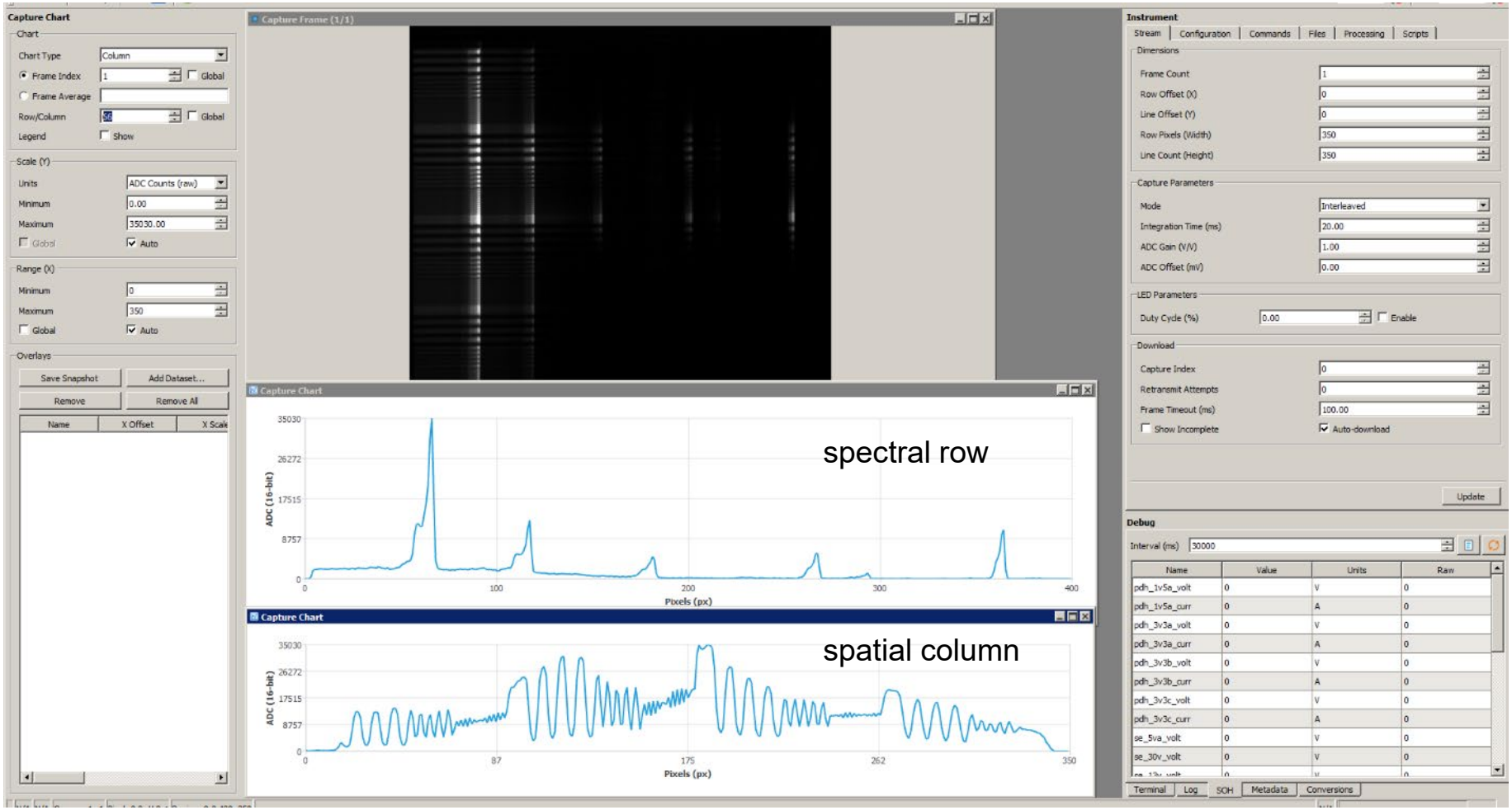
Screen shot: raw, uncalibrated data



Optical performance as a function temperature

- **-40°C**

Screen shot: raw, uncalibrated data



Thermal test optical results summary

- Both spectral (reflective spectrometer) and spatial (refractive objective lens) exhibit negligible focus change over -40°C to +30°C range.
- There is a shift (without loss of focus) of a few pixels over this T range (expected, due to expansion/shrinkage of entire spectrometer), but this is not a concern.
- LED calibration system performs well, with insignificant change in brightness, over entire temperature range.

Optical system status

- Optical performance meeting minimum on-orbit validation mission requirements has already been achieved with EDU-1 and EDU-2.
- LED-based calibration system demonstrated to achieve mission needs. Performs well over entire temperature range.
- Entire instrument, reflective and refractive components, are athermal over the operational range (and beyond).
- Objective lens focus is extremely sensitive, was a concern. But tests show focus is robust to both temperature and vibration.
- Still room for improvement in optical alignment and consequent spectral resolution. Affect on validation mission minimal, but would *like* to achieve high SO_2 sensitivity for potential bonus science results. Desired improvements expected as qualification and flight instruments are optimized.
- Tertiary mirror vibration robustness much improved with mirror mount re-design, but further tests needed to verify all issues have been resolved

Optical Instrument, Path to Meet Schedule

Milestone	Date	Effort Level	Can Meet?
Project Start	Jan 2019	High	Yes
Environmentally Tested EDU TACOS Completed	Jan 2020	Medium	Yes
EQM NACHOS Instrument Complete (Redesign of EDU)	April 2020	Medium	Yes
EQM NACHOS Instrument and TACOS CubeSat Host Integration Complete	May 2020	Medium	Yes
Qualification Level Environmental Testing of Integrated EQM Instrument and Host Complete	July 2020	High	Yes
Resolution of any Anomalies from EQM Testing Complete	Sept 2020	Medium/High	Yes
FM Instrument and NACHOS Host Build Complete	Nov 2020	Medium/High	Yes
Acceptance Testing of FM Instrument and Host Complete	Dec 2020	Medium	Yes
Pre-Shipment Review	Dec 2020	Medium/High	Yes
Delivery to Launch Site for Integration	Jan 2021	Medium	Yes
Launch	April 2021	Medium	Yes
Minimum Criterion for Success Completed	August 2021	Medium/High	Yes
Desired, Best-Case Criterion for Success Completed	Dec 2021	Medium/High	Yes

EDU = Engineering Design Unit
EQM = Engineering Qualification Model
FM = Flight Model

Mechanical Status

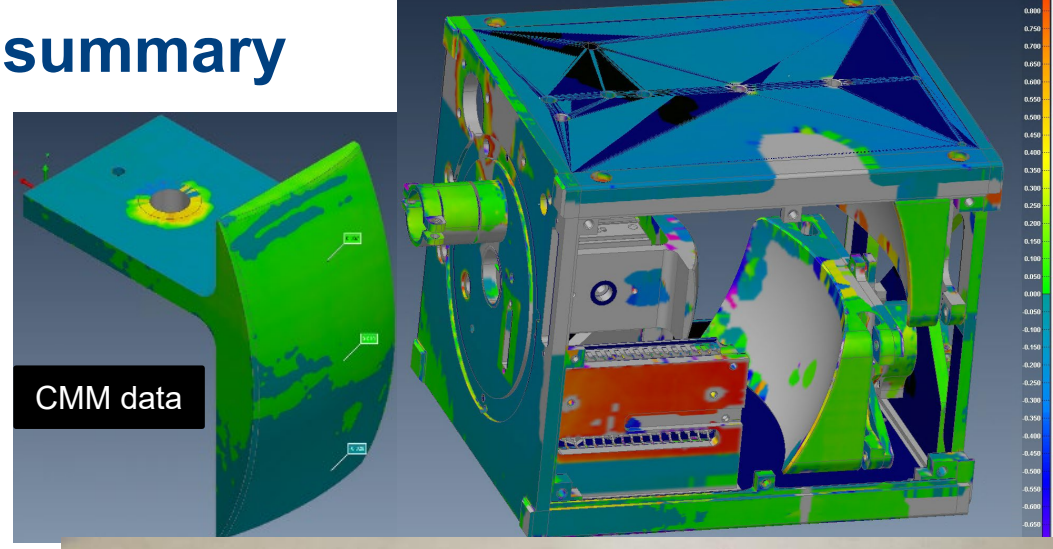
Logan Ott

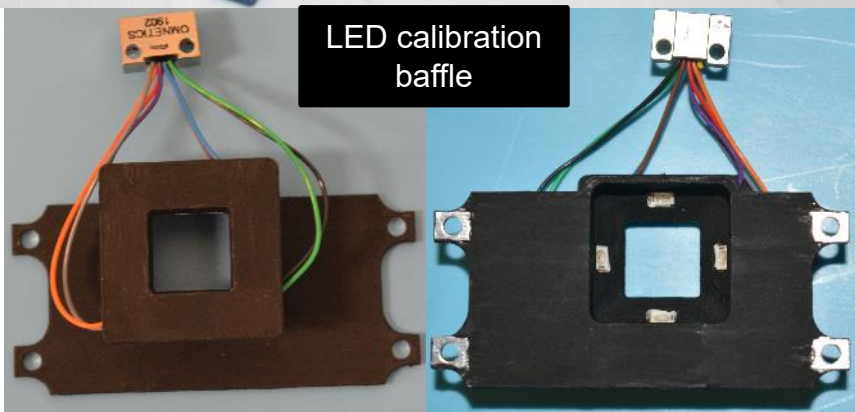
Outline

- Summary of progress in 2019
- Shake test lessons & results
- Thermal analysis management strategy
- Plans moving forward

2019 mechanical activities summary

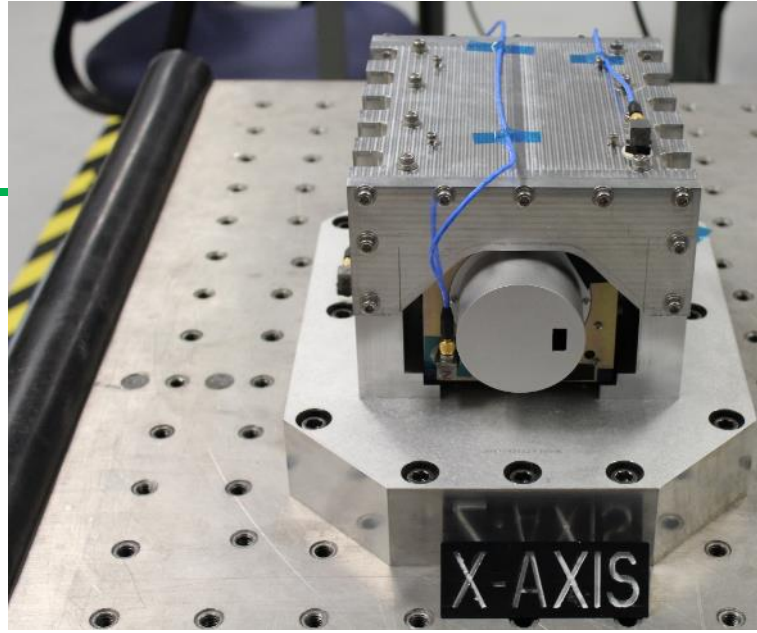
- **Assembled**
  - 2 engineering design units (EDUs)
- **Developed Focus process**
  - Coordinate measuring machine (CMM) aided early focusing efforts and identified grating substrate issues.
  - Worked out kinks in grating & tertiary adjustments & locking
  - Focus fixtures
- **Environmental Testing**
  - 3 rounds of vibration testing
    - Resulting in refinements to tertiary mirror mount
  - 2 thermal chamber tests
    - Lens mounts
    - Whole spectrometer
- **Structural & Thermal analysis**
  - To inform mirror mount re-design & surface tape selection
- **Design Refinements**
  - LED calibration
  - Improved Tertiary mirror mount
  - Pending changes on grating mount & main mir panel.

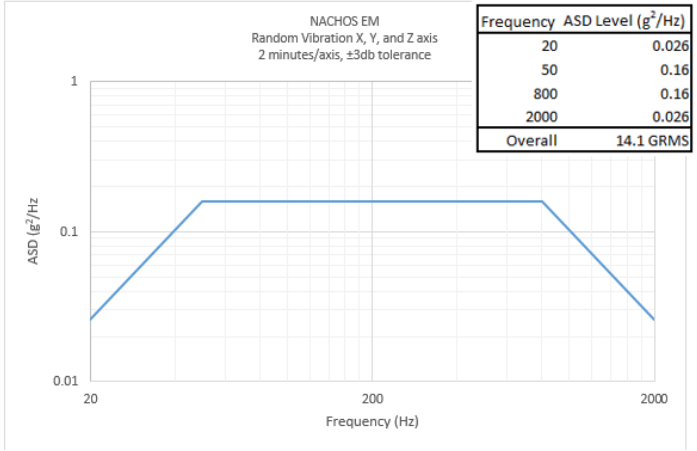




Shake testing approach

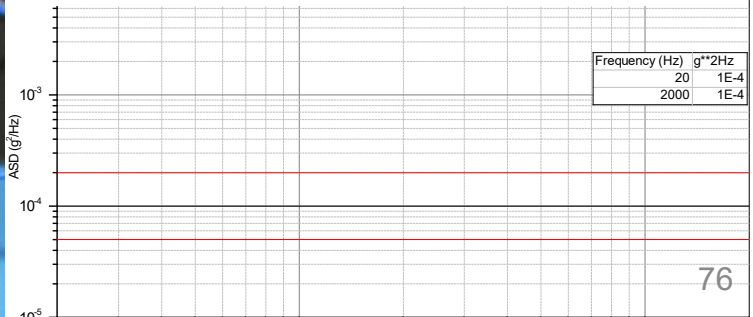
- Spectrometer clamped to shake table with fixture.
- One settling shake at -3db prior to first axis.
- GEVS qual spectrum & duration
- Mode signature surveys conducted before & after full level shake on each axis.
- Next round of testing planned in NLAS dispenser



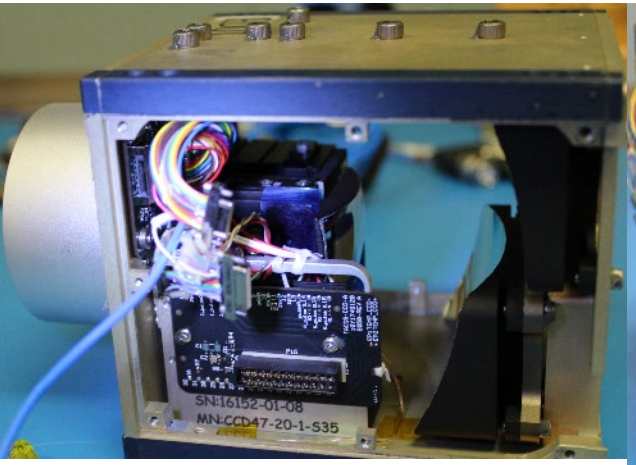


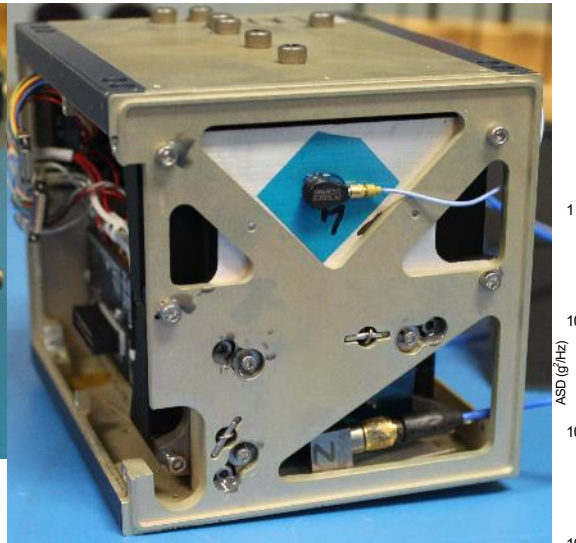
Frequency	ASD Level (g^2/Hz)
20	0.026
50	0.16
800	0.16
2000	0.026
Overall	14.1 GRMS

Figure 4.1-2 – EM Random Vibration Specification



Frequency (Hz)	g**2Hz
20	1E-4
2000	1E-4

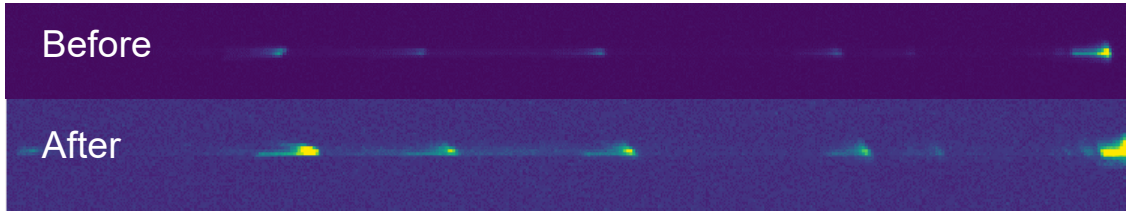




Shake test results

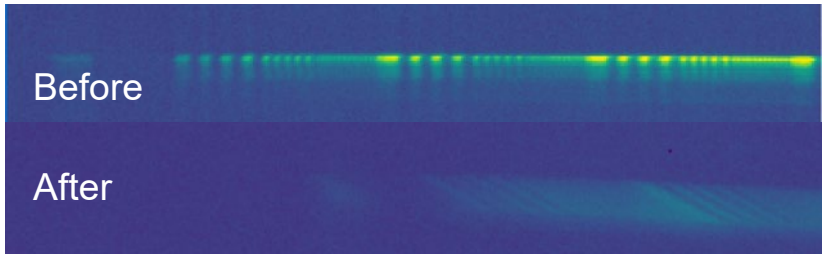
- **June shake testing resulted in major mirror mount revisions**
  - Greatly improved focusing process

June shake test (pinhole only, old mirror mount)



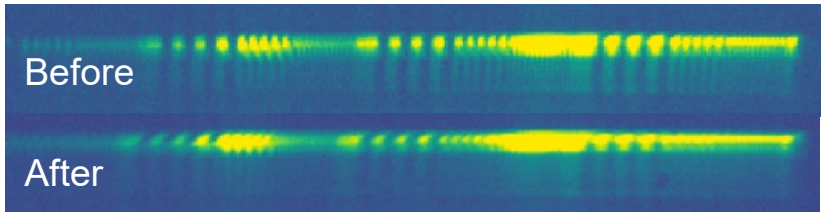
- **Locking strategy did not work**
  - Fortunately it was a trivial fix
  - Re-tested the next week

Early December shake test (bad locking screws)



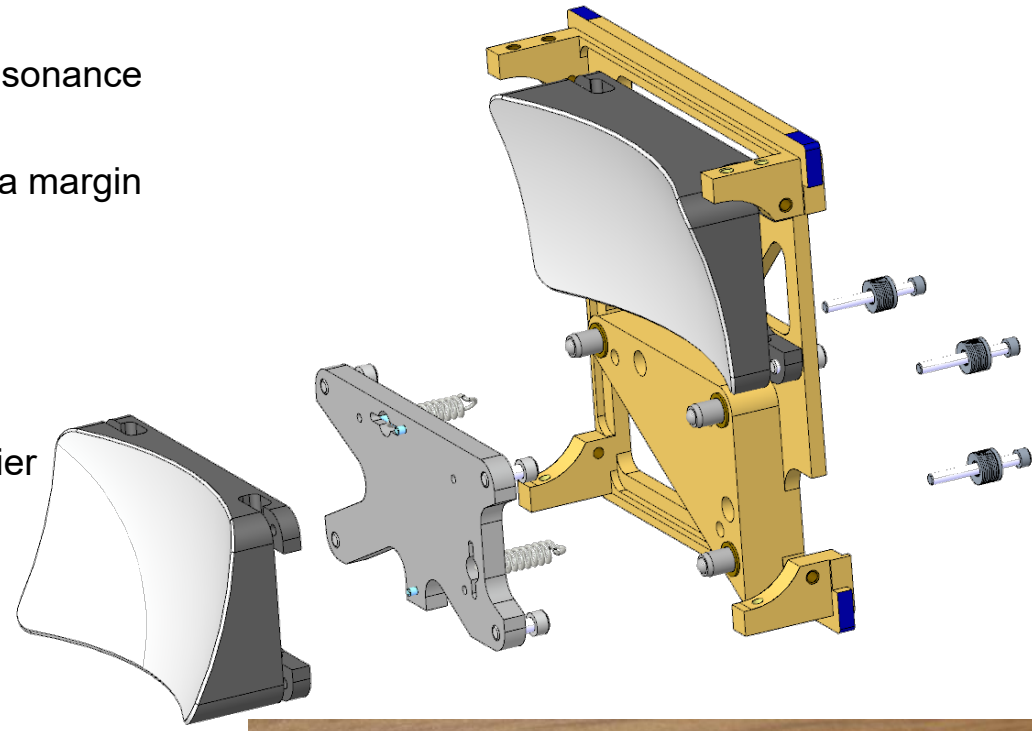
- **Small performance loss observed in most recent test**
  - Returned to nominal after accelerometers were removed!?
  - Attributed to damaged mirror mount from previous testing

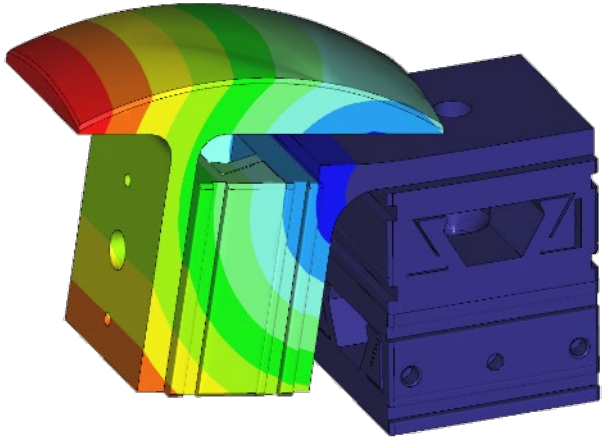
Mid December shake test

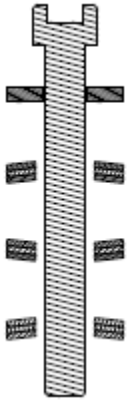


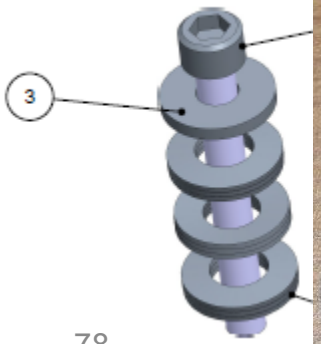
Shake test lessons

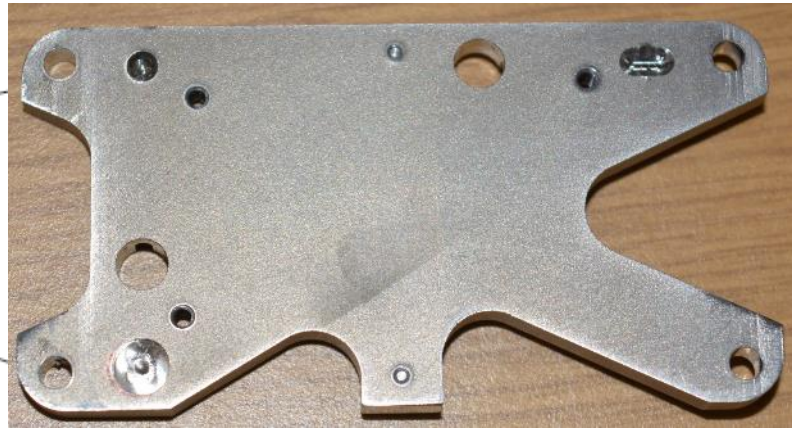
- **Grating mount passed despite suspicions**
  - 850Hz resonance was aligned with fixture resonance
  - It's panel has the lowest mode ~450Hz
  - Advisable to increase locking friction for extra margin
- **Mirror lock screws**
  - Preload limiting spring stack did not work
- **Mirror mount needs further testing**
  - Adjuster screw dimples enlarged during earlier testing
  - Increase hardness
  - Panel stiffening





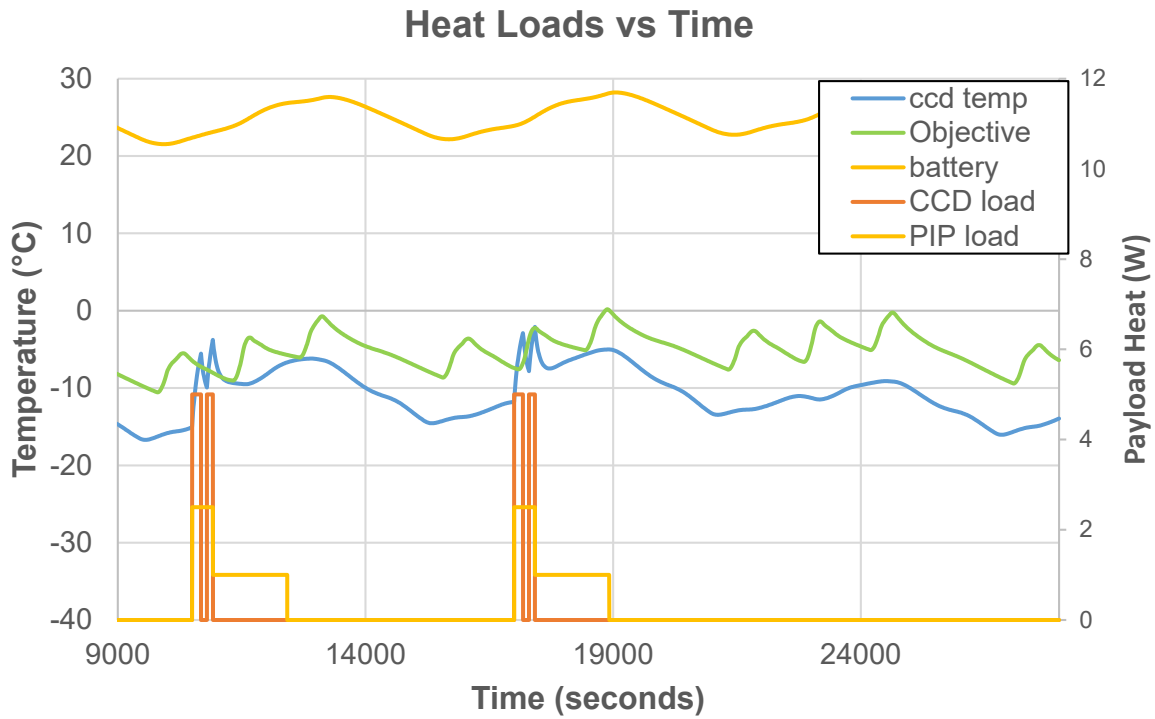


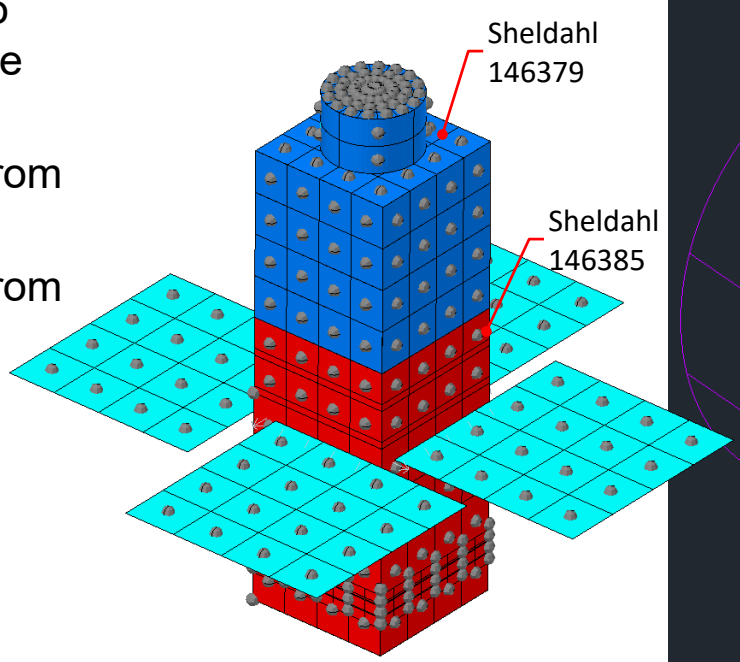


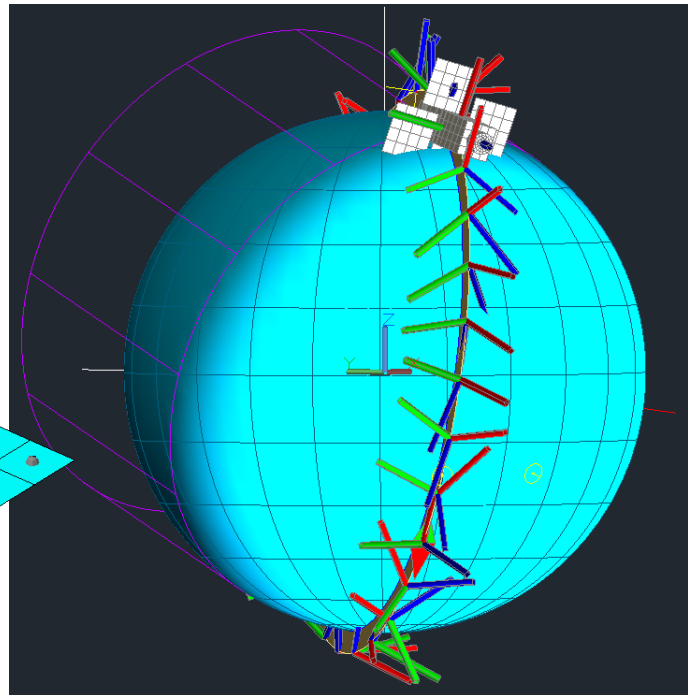


Thermal Models In Progress

- **Final thermal model pending final orbit parameters**
- **For now:**
  - Looks like we can easily select payload temperatures based on surface tape
- **Plan**
  - Perform thermal test to measure most sensitive model parameters:
  - Thermal conductivity from host to payload
  - Thermal conductivity from solar panels to host
  - Power consumption of payload







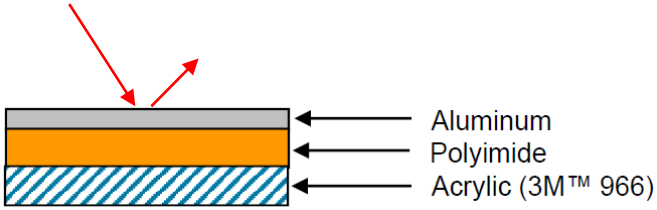
Thermal Risk & Mitigation

- **Risk**
  - Failure to regulate temperature within hardware and science requirements
- **Risk Sources**
  - Uncertainty in thermal model
    - ±10-15C with on hand orbit data
    - SV Attitude uncertainty
  - Host has not yet flown with payload.
    - Current temperature data from orbit will not represent our situation
    - Nachos payload expected to act as a heat sink, cooling host substantially if un-mitigated

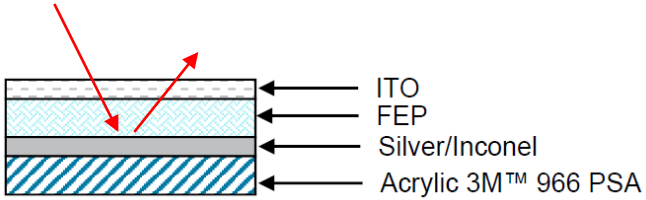
Subsystem	Survival temp (C)	Operating temp (C)
Payload Image Sensor	-120 to 100	-120 to 0
Payload Electronics	-40 to 80	-35 to 65
Host Electronics	-40 to 80	-35 to 65
Host Batteries	-5 to 65	-5 to 65

- **Mitigations**
  - Increase thermal model certainty
    - Thermal testing & electrical load measurement
    - Account for more host orbit temperature and attitude data as it becomes available
  - Reduce sensitivity to thermal variation
    - Reflective surface tapes that minimize temperature swing
    - Select α/ε ratios expected to maximize thermal margin
    - Insulate payload from host to reduce temperature compromise

****FSM = first surface mirror tape**



***SSM = second surface mirror tape**



Overall Path Forward

- **Proceed with shake testing in NLAS dispenser in February**
- **Order flight parts (March)**
- **Subsystem thermal tests (June)**
  - Measure host-payload heat transfer
  - Measure solar panel-host heat transfer
- **Refine thermal modeling (February-ongoing)**
  - Component hotspot modeling (now)
  - Orbital model revision as attitude linked temperature data becomes available
  - Final outer taping selection contingent upon orbit spect
- **Final qual and flight builds (July-Aug)**
- **Qualifacation & acceptance tests after receiving launch spec (Dec 2020)**
  - Testing performed on separate qual and flight models

NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

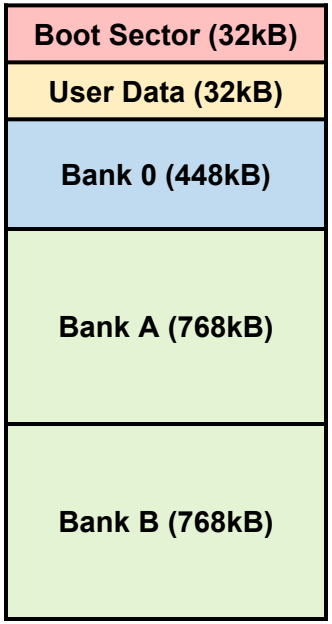
First Annual Review - 1/21/2020

Software & Firmware

Software Overview

- **Most boards in system have:**
  - ARM Cortex-M7 Microcontroller*
  - ProASIC 3 Actel FPGA

- **Board software comes in two flavors:**
  - **Bank 0** (Flight recovery code)
    - Runs after board power-up or long watchdog reset
    - Provides basic control, telemetry, file transfer, re-flashing of banks A/B with new code
    - Fixed at launch
  - **Bank A/B** (Flight mission code)
    - Must be manually booted into from bank 0 by mission manager or ground station command
    - Provides all of bank 0 features plus automation for executing and managing missions
    - Reprogrammed on-orbit for bug fixes or feature releases



- **Additionally, we have a desktop GUI (TACOView)**
  - Provides automated testing and instrument calibration

* Not present on SE board

Software Components

System	Board	Type	Required Development (Major)	Risk	Effort
Payload	SE	VHDL	Board-board spacewire	Low	Low
	PIP	VHDL	Board-board spacewire	Low	Low
	PDH	VHDL	Board-board spacewire, SDRAM refresh bug	Low	Low
	PIP	SW (Bank 0)	Telemetry/command finalization, integration test	Med	Med
	PIP	SW (Bank A/B)	SFS host integration	Med	Low
	PDH	SW (Bank 0)	Telemetry/command finalization, integration test	Med	Med
	PDH	SW (Bank A/B)	Integration with host target pass automation	Med	High
Host	CDH*	VHDL		N/A	N/A
	ADCS*	VHDL		N/A	N/A
	LBR/HBR*	VHDL		N/A	N/A
	CDH	SW (Bank 0)	Minor networking modifications	Low	Low
	CDH	SW (Bank A/B)	Mission automation	Med	High
	LBR/HBR*	SW (Bank 0)		N/A	N/A
	LBR/HBR*	SW (Bank A/B)		N/A	N/A
	ADCS*	SW (Bank 0)		N/A	N/A
	ADCS	SW (Bank A/B)	SFS integration, NACHOS pushbroom scanning, pointing accuracy	Med	High

SE = Spectrum Electronics Board
PDH = Payload Data Handler
PIP = Payload Interposer
ADCS = Attitude & Determination Control System

HBR = High Band Radio
LBR = Low Band Radio
CDH = Command & Data Handler

* Stable release available

Software Components (Cont.)

System	Board	Type	Major Milestones	Risk	Effort
Ground Station	LBR/HBR*	VHDL		N/A	N/A
	LBR/HBR	SW	NACHOS telemetry/command integration	Low	Low
	TACOView	SW (GUI)	Add. features for testing support	N/A	Low
	Ground Station	SW (GUI)	NACHOS telemetry/command integration	N/A	Low
Algorithms	PDH, Desktop	SW		Low	Low

SE = Spectrum Electronics Board
PDH = Payload Data Handler
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ADCS = Attitude & Determination Control System

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* Stable release available

Issues/Risks

Risk	Board	Cause	Fix/Mitigations	Resolve Date	Risk Level
Bootloader unable to communicate over UART at -40C	PDH	Oscillator supplying the bootloader clock is off-frequency by enough to change UART baudrate	Not a flight risk (affected UART is not used on-orbit). Modification of testing scripts as workaround.	Feb 2020	Low
PIP power-up sequence can occasionally hold payload systems in reset	PIP	Possible error in startup sequence of PIP SW and FPGA, or hardware issue with reset line. Issue identified in thermal chamber setup.	Issue needs to be recreated and the exact cause identified.	Feb 2020	Med
Randomly missing pixels on CCD data	PDH	FPGA control of SDRAM fails to stall processor requests over memory bus for data during SDRAM refresh cycles	VHDL fix may be possible. Other mitigations include patching data with redundant reads, reduced refreshes	Feb 2020	Low
Instability in integrated algorithm code under certain settings	PDH	Coupling of algorithm and flight code on processor have some memory usage bugs	Currently being investigated & fixed	Jan 2020	Low
Software development resources	-	Primary software developer currently overtasked	Time/effort to shift to 50% or higher on NACHOS within 1 month	Jan 2020	Low

SE = Spectrum Electronics Board
PDH = Payload Data Handler
PIP = Payload Interposer
ADCS = Attitude & Determination Control System

HBR = High Band Radio
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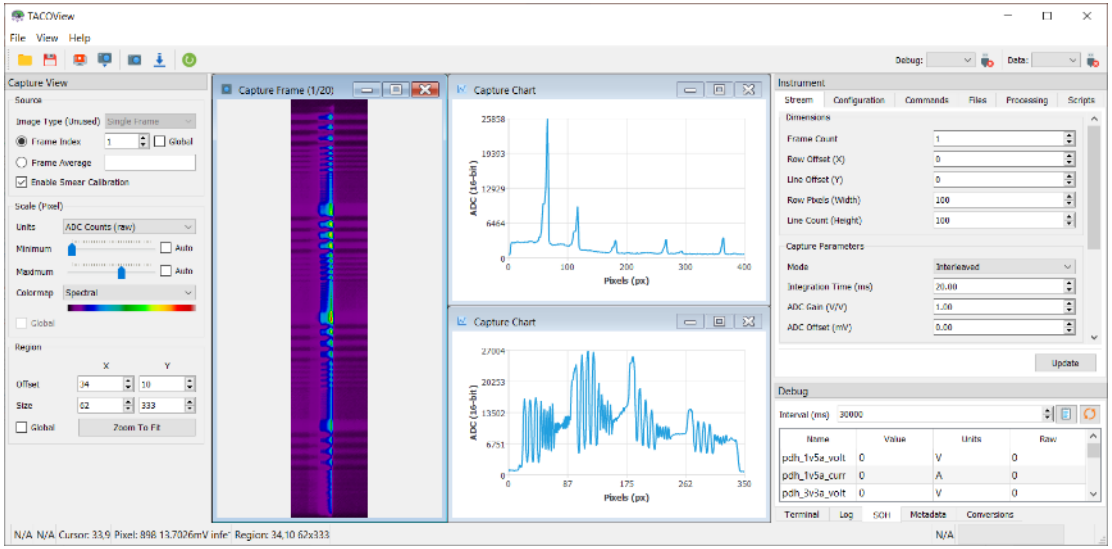
CDH = Command & Data Handler

* Stable release available

Software Progress

- **LED calibration systems developed and tested**
- **High framerate CCD readout modifications to VHDL to reach 28.6FPS complete**
- **Flash storage issues on PDH identified and fixed**
- **On-board processing queuing/command system developed, undergoing testing**
- **On-board processing algorithms incorporated into flight code**
- **Primary flight code command and telemetry developed**
  - Will be finalized during integration testing with host
- **Primary instrument command/control/processing/telemetry exercised in thermal chamber testing**
- **TACOView GUI improvements:**
  - Automated test scripts
  - Full command and telemetry testing
  - High speed file download/upload
  - On-board processing testing



Software Schedule

- **High effort level until start of EQM testing phase (Now - June 2020)**
  - **Starting EM payload/host integration work ◂ CURRENT FOCUS**
  - **Primary focus on completion/test of all Bank 0 releases (flight recovery code)**
    - Finalizing telemetry data (ping data and state-of-health logging contents)
    - Finalizing command/control capability through radios and ground station
    - Ground station radio support for NACHOS specific command/control/telemetry
    - Stability testing and tuning of operating system
  - **Secondary focus on completion/test of all Bank A/B releases (mission execution code)**
    - Integration of instrument command/control with host target pass automation
    - CDH mission management for payload systems
    - ADCS improvements
- **Medium effort level during EQM testing (July 2020 – Sept 2020)**
  - Iterative software testing/release schedule to identify & fix any flight-risk issues
  - Ground station GUI development for NACHOS specific command/control/telemetry
  - *Bank A/B will most likely continue development through this phase prior to FM acceptance testing*
- **Low effort level during FM acceptance and post-launch (Dec 2020 – Dec 2021)**
  - Operational support (SV control and data processing)
  - Bank A/B improvements, releases and on-orbit upload of new code

Schedule Milestones

Milestone	Date	Effort Level	Can Meet?
Project Start	Jan 2019	Med	Yes
Environmentally Tested EDU TACOS Completed	Jan 2020	Med	Yes
EQM NACHOS Instrument Complete (Redesign of EDU) ◄ **CURRENT FOCUS**	April 2020	High	Yes
EQM NACHOS Instrument and TACOS CubeSat Host Integration Complete	May 2020	High	Yes
Qualification Level Environmental Testing of Integrated EQM Instrument and Host Complete	July 2020	High	Maybe
Resolution of any Anomalies from EQM Testing Complete	Sept 2020	High	Maybe
FM Instrument and NACHOS Host Build Complete	Nov 2020	Med	Yes
Acceptance Testing of FM Instrument and Host Complete	Dec 2020	Low	Yes
Flight Readiness Review	Dec 2020	Low	Yes
Delivery to Launch Site for Integration	Jan 2021	N/A	Yes
Launch	April 2021	N/A	Yes
Minimum Criterion for Success Completed	August 2021	Med	Yes
Desired, Best-Case Criterion for Success Completed	Dec 2021	Med	Maybe

- **Highest schedule risk is unexpected effort during the EQM testing phase**
  - NACHOS will enter testing with a far more mature host/baseline SW compared to other payloads
  - Bugs found during this phase are historically fairly esoteric (time-consuming to identify and resolve) and iterative releases require extensive testing

EDU = Engineering Design Unit
EQM = Engineering Qualification Model
FM = Flight Model

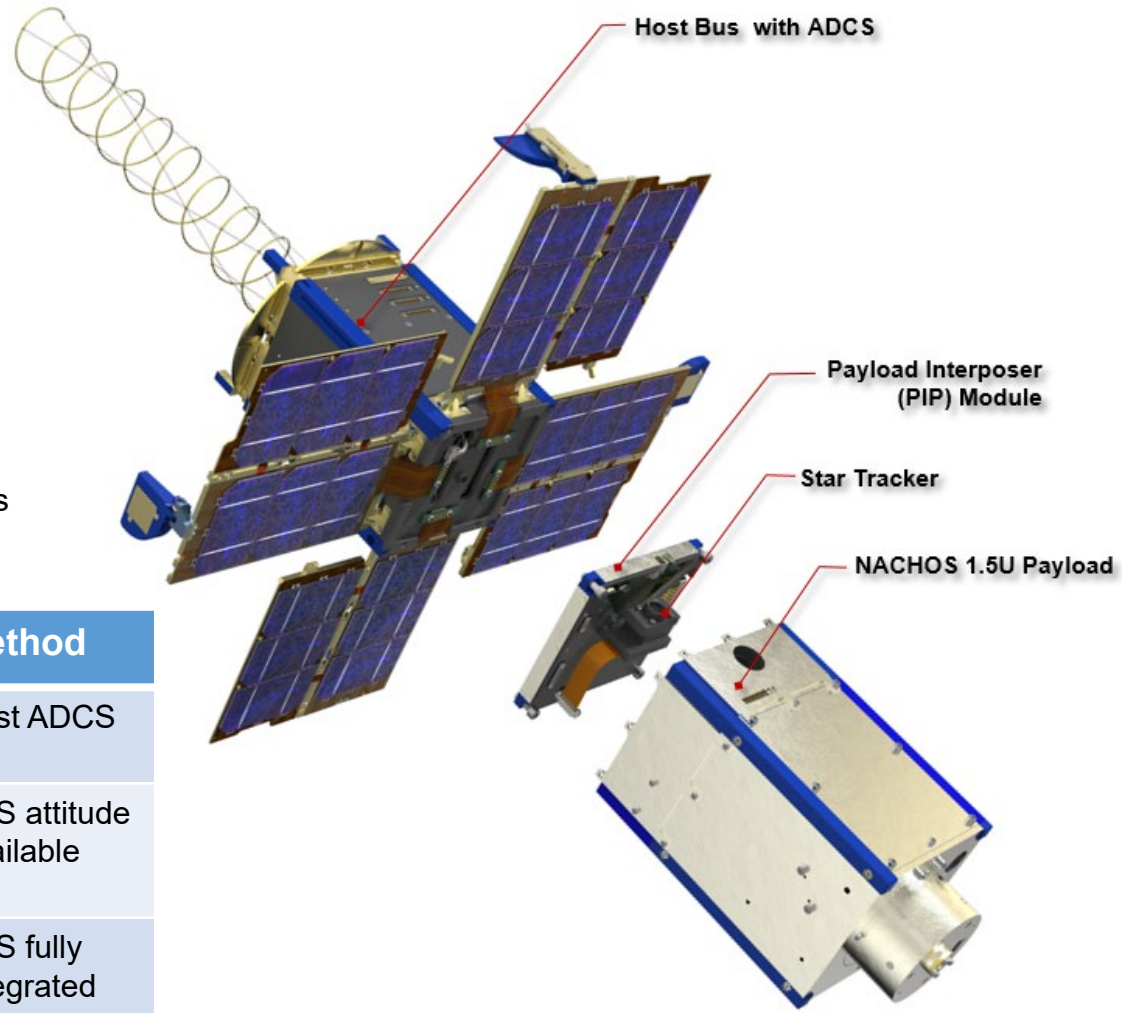
Attitude Determination and Control System (ADCS)

Hannah D. Mohr

ADCS Overview

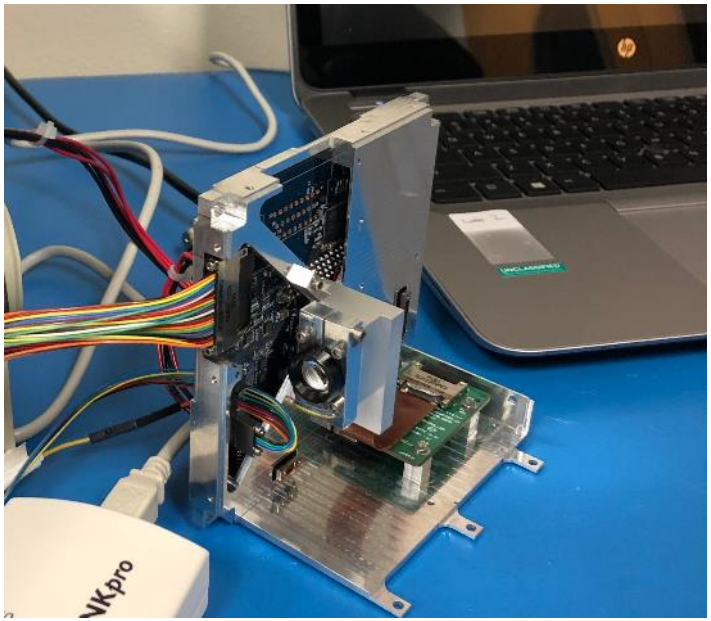
- **Host ADCS**
  - LANL CubeSat bus heritage
  - Momentum wheel control
  - Sun sensors, magnetometers, gyros for attitude knowledge
- **SFS**
  - Augments the Host ADCS attitude knowledge
  - High precision sensor
- **Mission Manager**
  - Autonomously executes mission activities
  - Partial heritage, requires some custom elements (e.g., bush-broom pointing)

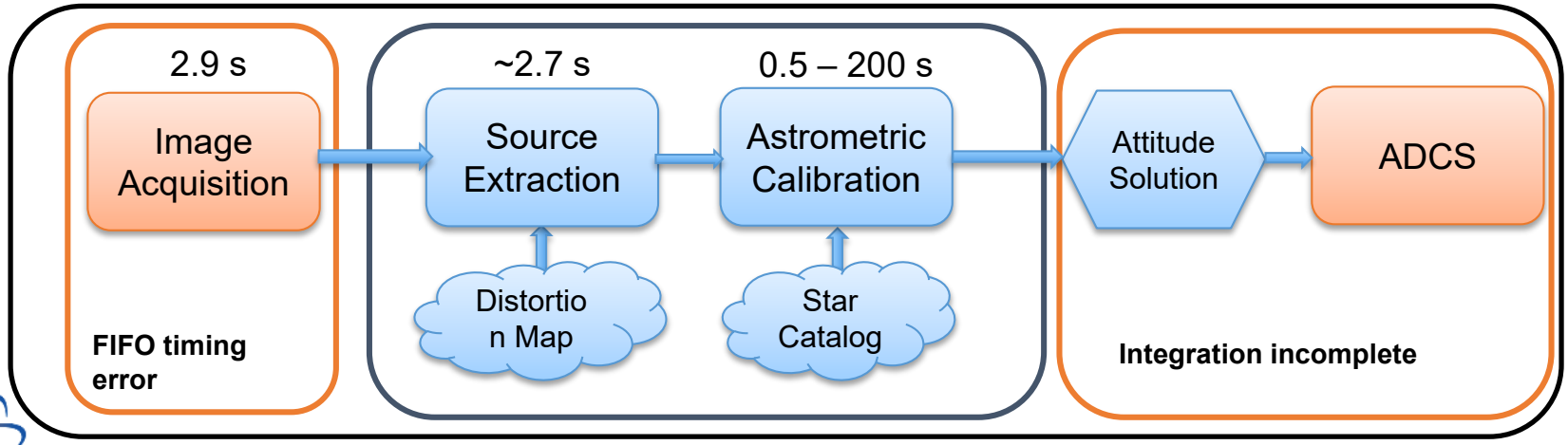
Objective	Pointing	Method
Basic demonstration of on-board gas retrieval	± 25°	Host ADCS
On-board gas retrieval of **specified targets** with minor spatial distortion	± 5°	SFS attitude available
High quality on-board gas retrievals with **geolocation of plumes**	± 0.2°	SFS fully integrated



SFS Status

- **Software**
  - SFS software implemented on PIP board
  - SFS attitude determination software operational on new F7 processor
  - Image readout experiencing clock synchronization issue
- **Risks**
  - Integration with ADCS
  - Not tested on-orbit
- **Watch Item**
  - Integration with payload
    - Initial grounding issue resolved





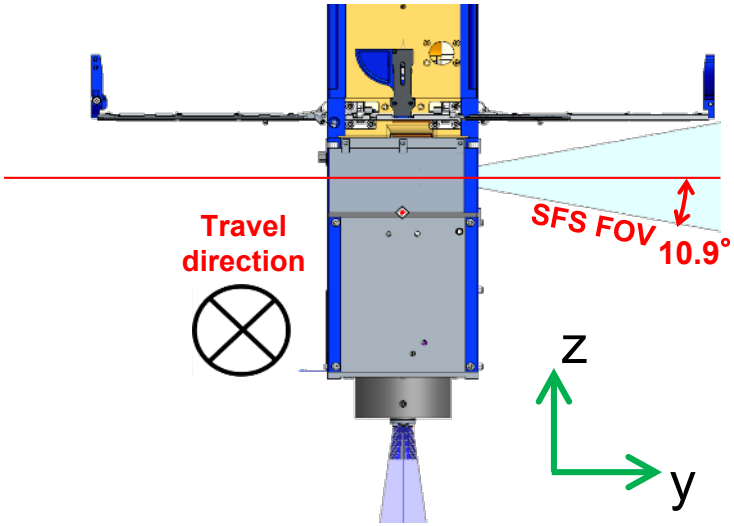
Host ADCS Status

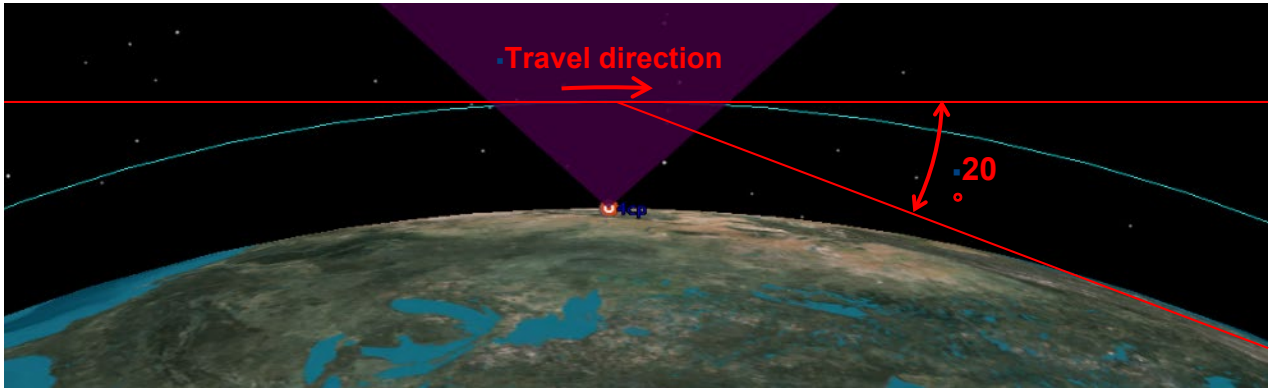
- **Heritage: On-orbit testing**
  - Sensor calibration concerns identified
    - Testing demonstrates improvements to pointing that NACHOS will receive
  - On-orbit checkout schedule slip
  - Lifetime
- **Ground testing**
  - Developed more detailed testing procedures
    - Reduces risk by characterizing nominal performance
  - Adding sensor calibration to improve pointing and reduce risk
    - Sun vector sensors
    - Gyros
    - Magnetometers

On orbit testing shows performance of bus meets basic NACHOS mission objectives

Mission Manager Status

- **On-orbit testing**
  - Ground station pass activities completed successfully
  - ADCS integration successful
- **NACHOS Custom features**
  - Accommodate SFS
  - Payload manager activities





ADCS Path Forward

- **SFS**
  - Integration with ADCS
  - Software improvements
    - Correct image readout
  - Outdoor testing
  - Environment Testing
    - SFS alignment and focus
- **ADCS**
  - Software conversion to F7 processor
  - Target pointing mode: push-broom
  - Integration with payload
- **Mission Manager**
  - Software conversion to F7 processor
  - NACHOS payload interaction

NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

First Annual Review - 1/21/2020

Electrical

M. Dale, K. Boyd, G. Peterson, C. Safi

Electrical Progress & Risk Items

- **Yearly Progress**
  - CCD control, data handling, and performance validated
  - LED calibration design completed
  - Payload interposer design updated
  - Final payload interposer power supply tested with host power
  - Electronics survived vibration test
  - Clocking of CCD updated to get >20fps across all possible integration rates
- **Recent Progress**
  - No issues with electronics operation found in thermal testing.
  - Basic EMI/EMC test showed no effects on CCD image quality.
  - PCB updates being completed on main boards.
  - Long lead parts (connectors) on order.
  - All major ICs on boards in stock.
  - 5 Flight Grade CCDs ordered, 1 recently arrived and the rest are due within 2 months
- **Risks**

Full payload interposer redesign and star field sensor were not validated in initial thermal cycle

Addition of hole to middle of spectrum electronics board to mitigate mirror vibration issue

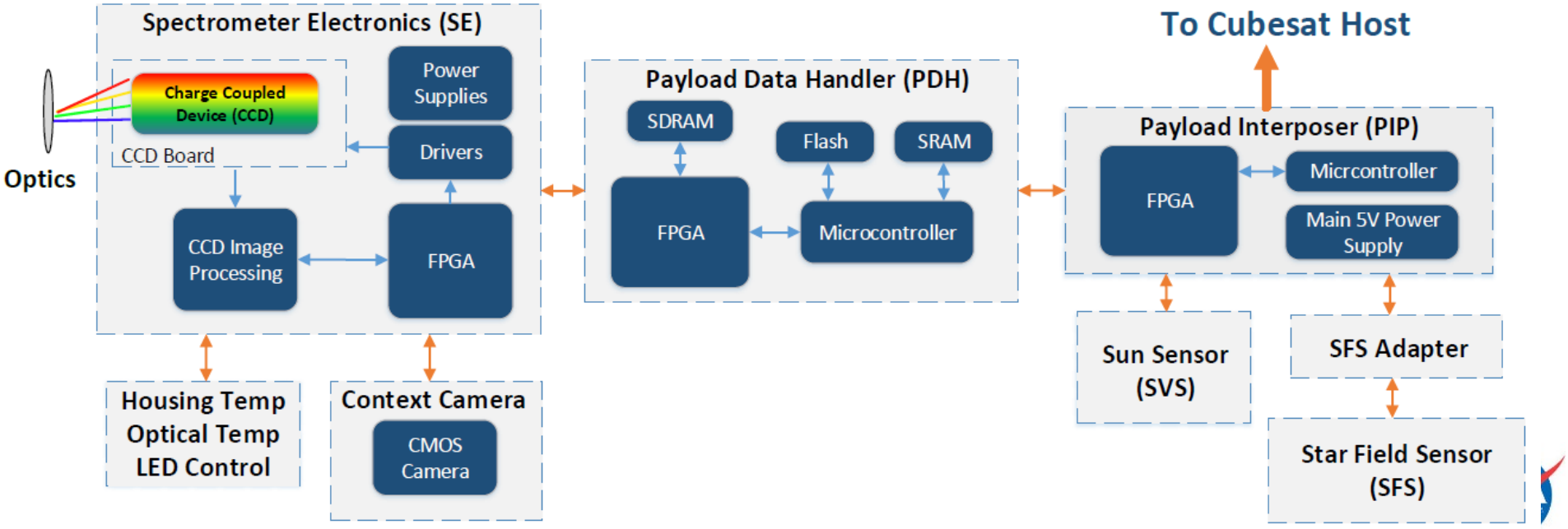
Interfacing to bus electronics (EMI/EMC, Power, and any on-orbit anomalies from hosted payload launches in Fall)

Electrical - Plans for this Year

- **PCB Updates**
  - Not many updates, confirm layout and new changes won't effect performance
  - If hole in SE PCB needed to mitigate vibe issue could cause longer lead for PCB, but likely OK.
- **Payload Power Characterization**
  - Confirm overall payload power during each operational state
  - Incorporate into power budget for understanding of how to operate system on orbit
- **PIP & SFS**
  - Confirm operation with thermal cycle
- **Host Integration**
  - Careful integration with host power source. Monitor voltage levels and power use
  - Monitor CCD performance throughout integration for EMI/EMC issues

PCB Status

- **SE -** Schematic updates completed, layout is in process. Awaiting decision on mirror mechanical that goes through PCB before ordering.
- **PDH -** Schematic updates in progress
- **PIP** - newest revision currently undergoing testing. This testing is highest priority, if any issues will need to address with white wires and not a board re-spin.
- **Context Camera** – no change, getting quotes and will order completed board at end of January
- **SFS** – currently undergoing software testing
- **CCD** – no changes**, LED** – no changes, **SVS** – received with host, design already validated on-orbit



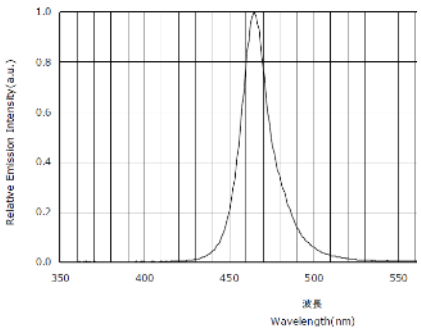
Payload Interposer (PIP) & Star Field Sensor (SFS)

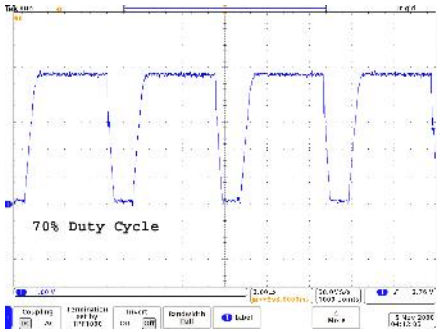
- **Payload Interposer**
  - Initial Design
    - Due to limited internal ECAD resources had to outsource layout which resulted in low quality design.
    - Digital electronics did work; on board power supply never had a chance
  - Second revision
    - Internal ECAD layout delayed many months due to other higher priority projects
    - This resulted in thermal cycle testing using initial design so operation of digital electronics verified but new power supply not validated at temperature
- **Start Field Sensor**
  - Thermal Cycle Revealed
    - Shorting issue
      - Mechanical mount shorted vias to ground, resolve by modifying mounting hardware
    - Software configuration issue
      - Meant no data collected during cycle
- **Planning for near term thermal cycle of PIP+SFS to reduce risk**

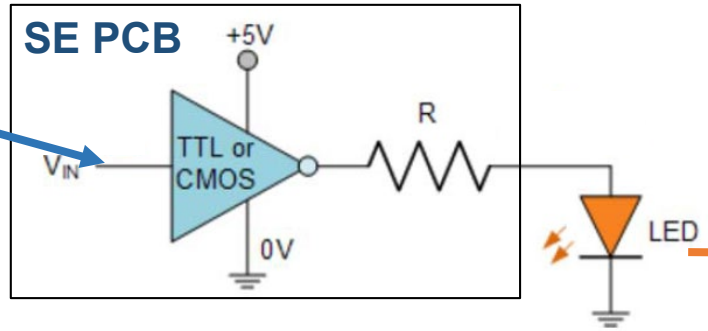
LED Electrical Operation

- **Design is based on heritage space instrument where it is used for optical verification of gamma ray detector**
- **Each LED has a matching resistor**
- **Each OpAmp drives two LEDs**

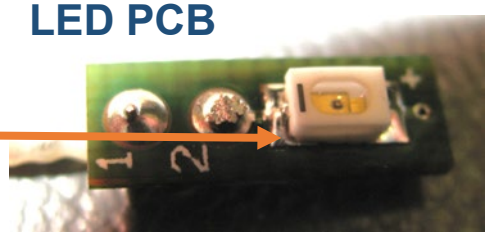
Nicchia NSB100BT Blue LED Spectrum





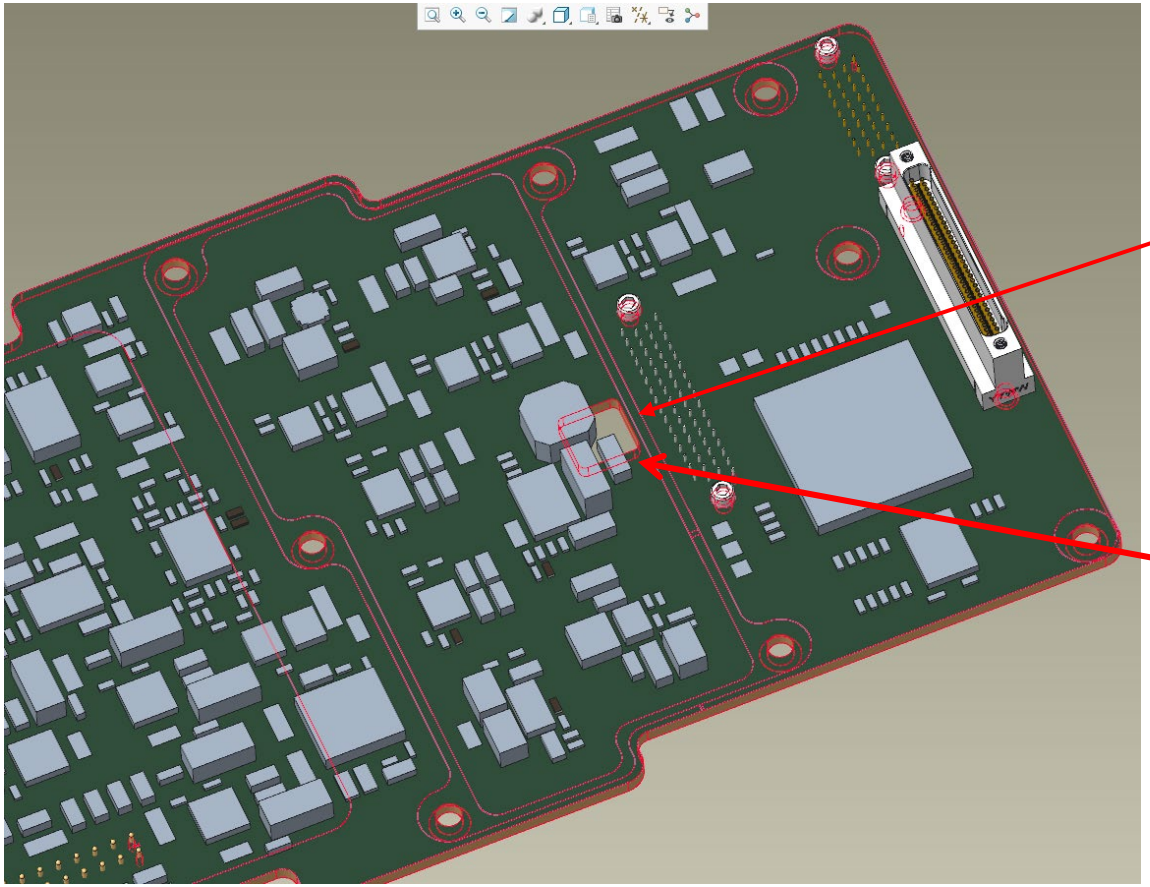


LED PCB

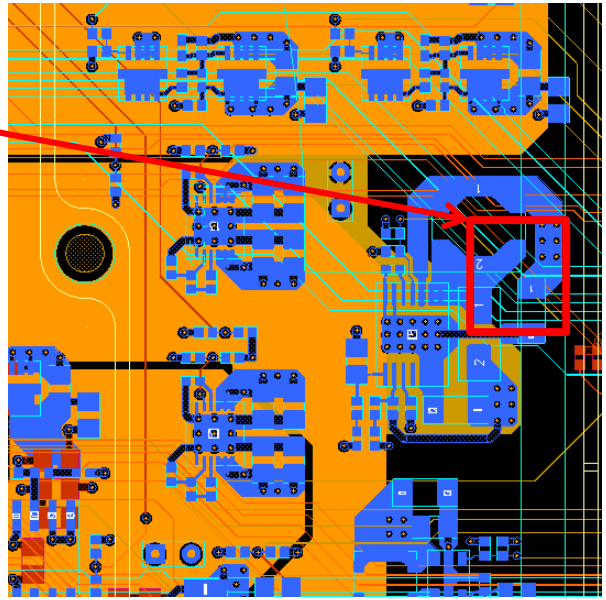


- **Updates during past year**
  - Upgraded to higher bandwidth OpAmp so PWM signal adequate
  - Firmware updated to allow for programmable PWM frequency

Possible Spectrum Electronics Changes

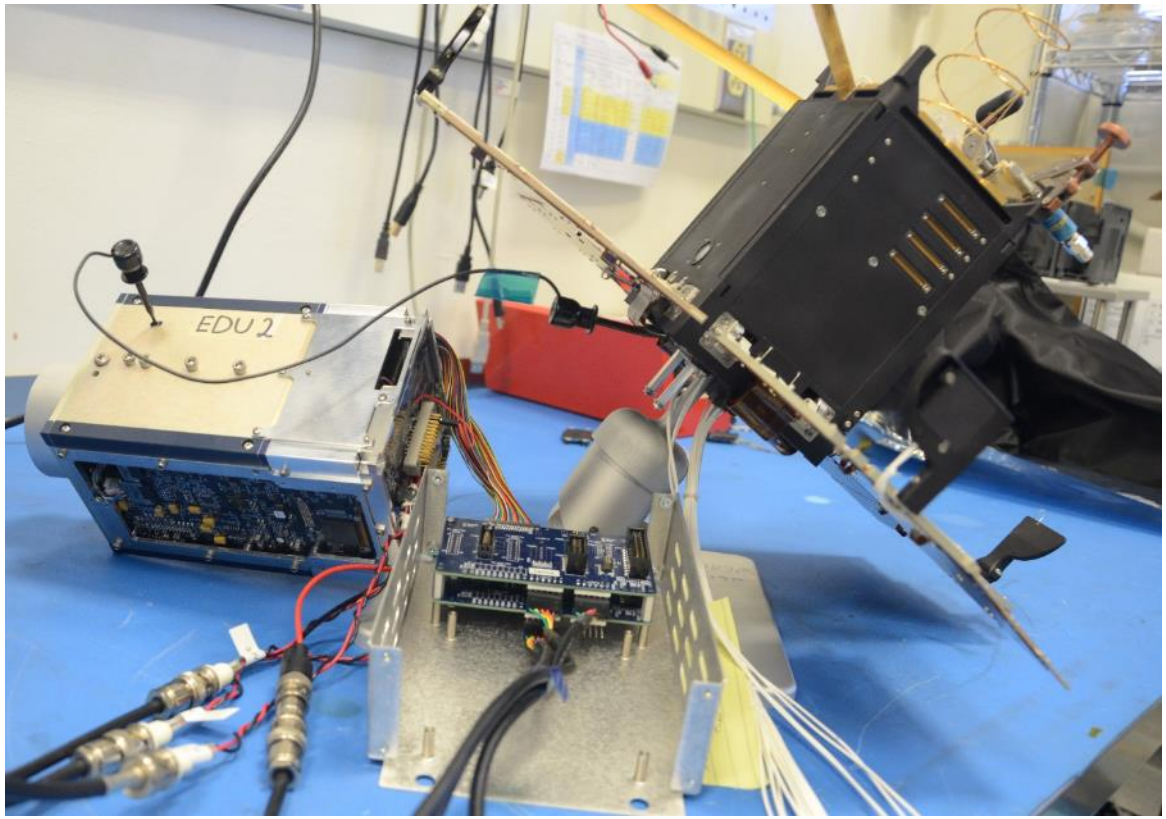


- **Required to Improve of Mirror Mount Stability**
  - Requires additional hardware that results in hole in PCB
  - Hole is right in CCD power supply region.
    - difficult but possible



EMI/EMC Tests

- **Host issues are mostly radiated emissions. Other payload is RF and so highly sensitive to this.**
- **Ran host through various operation regimes while looking for changes to CCD image (at low voltage range) and SOH**



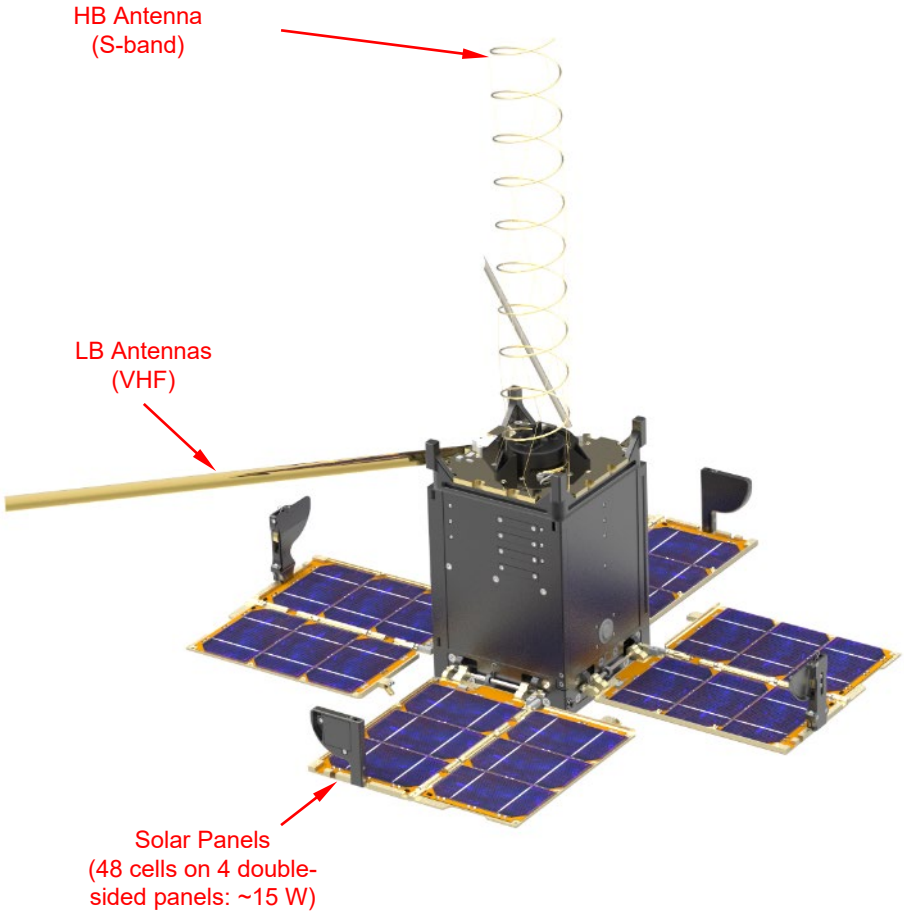
NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

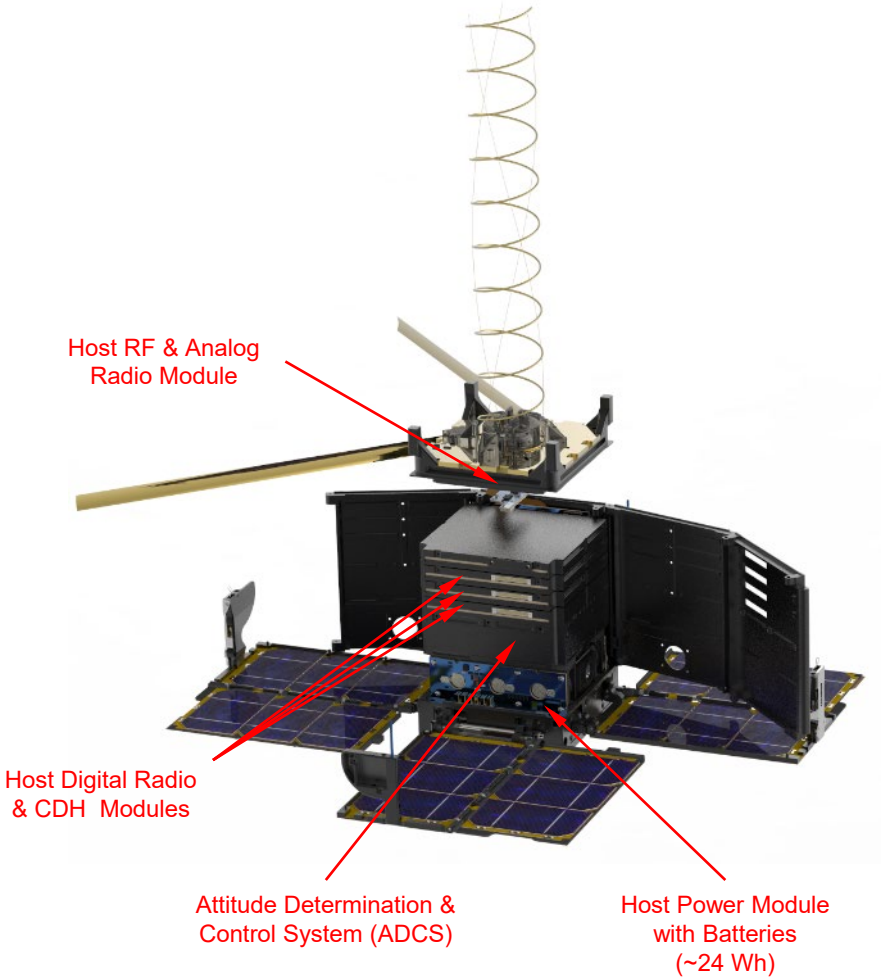
First Annual Review - 1/21/2020

Host Bus Status

Markus P. Hehlen (ISR-2)

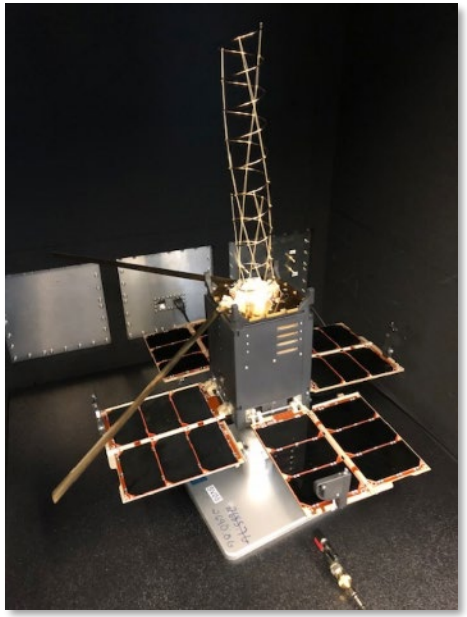
Bus Status


HB Antenna
(S-band)
LB Antennas
(VHF)
Solar Panels
(48 cells on 4 double-sided panels: ~15 W)

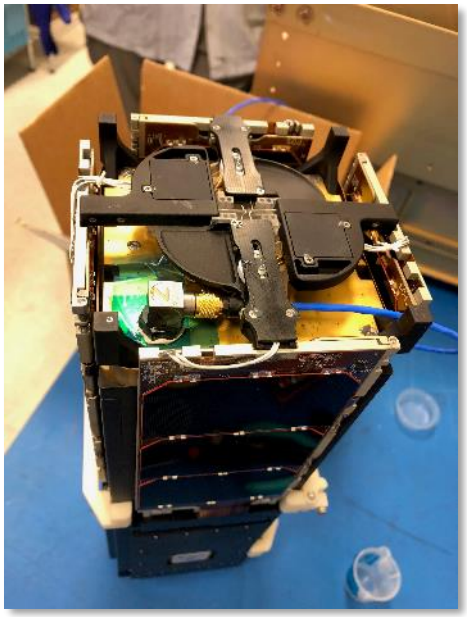

Host RF & Analog
Radio Module
Host Digital Radio
& CDH Modules
Attitude Determination &
Control System (ADCS)
Host Power Module
with Batteries
(~24 Wh)

Bus Status

- **Host bus for NACHOS**
  - Host bus: power, C&DH, comms, ADCS, and interface to PIP
  - Design heritage: 4 versions (Block 1, 2, 2A, & 2B) of LANL cubesat bus and 1 other project payload
  - On-orbit heritage: 12 Block-1, 2 Block-2 (SV-1&3), & 2 Block-2A (SV-7&9) LANL cubesat buses
  - NACHOS will use latest Block 2B host bus featuring new F7 processor
  - NACHOS EDU (received) and Flight (in final assembly & testing) host bus are produced by DOE Kansas City National Security Center (KCNSC)



Block 2B



Stowed for vibe test

Bus Status

- **Recent modifications to Block 2B**
  - Modifications based on other project payload testing to improve both performance and reliability:
    - Full grounding of card cages to reduce EMI
    - Modified springs and perimeter of solar panels to ensure full deployment
    - Grounding tab for stowed high-band antenna to ensure reliable TX inhibit
    - Removed inductors on backplane to eliminate transient-induced failure mode
  - Block 2B host bus and associated modifications currently undergoing extensive functional and environmental testing as part of other project payload.
  - NACHOS EQM and FM will directly benefit from this design and testing heritage

- **Remaining risk items**

LANL cubesat bus and other project payload heritage and associated on-going on-orbit and flight-unit developments are buying down risk for NACHOS

Power module: other project payload observed two failures in October 2019 during testing with an external power supply connected. A formal root cause analysis in progress (other project payload). A procedural rather than a design issue is suspected.

High-band analog radio: other project payload observed a failure of the high-power amplifier in the HB analog radio module during testing in October 2019. A formal root cause analysis in progress (other project payload). A procedural rather than a design issue is suspected.

Bus Status

- **Remaining risk items (continued)**

ADCS wheels:

- other project payload observed increased friction in 1 of 4 wheels at cold temperatures in TVAC.
- LANL cubesat bus SV-7 shows increased friction in 1 of 4 wheels on orbit, but it is still performing well with regards to pointing accuracy
- A set of individual candidate ADCS wheels for NACHOS were therefore tested extensively over a –20 to +40 °C range in a thermal chamber (December 2019)
- Four flight quality ADCS wheels were selected and sent to KCNSC for integration.
- The NACHOS ADCS unit will be tested again as part of the environmental tests of the integrated NACHOS space vehicle at LANL (vibe, TVAC)
- In parallel, other project payload is assessing possible modifications to the motor/wheel coupling mechanism in order to reduce loads on the motor bearing.

Thermal performance:

- The goal is to achieve a compromise between keeping the battery temperature at ≥0 °C while keeping the internal operating temperature of the digital radio FPGAs at ≤65 °C.
- Can be realized with appropriate (spacecraft specific) tape-out design. Analysis for other project payload using a high-fidelity thermal model is currently underway. These results can inform the tape-out design for NACHOS.

Bus Status

- **Remaining risk items (continued)**

Unknown unknowns:

  - SV-6 for other project suffered an unknown fatal on-orbit failure on Mission Day 18 (July 2019).
  - The likely cause was an inductor failure on the backplane.
  - This root cause has since been eliminated by a modification to the backplane.

- **Delivery status**
  - Host bus for Engineering Qualification Model (EQM): received
  - Host bus for Flight Model (FM):
    - Final assembly in progress at KCNSC
    - Functional testing at KCNSC: Jan 27 – Feb 7, 2020
    - Expected delivery date: Feb 10, 2020

Bus Path to Meet Schedule

Milestone	Date	Effort Level	Can Meet?
Project Start	Jan 2019		
Environmentally Tested EDU TACOS Completed	Jan 2020		
EQM NACHOS Instrument Complete (Redesign of EDU)	April 2020		
EQM NACHOS Instrument and TACOS CubeSat Host Integration Complete	May 2020	Low	Yes
Qualification Level Environmental Testing of Integrated EQM Instrument and Host Complete	July 2020		
Resolution of any Anomalies from EQM Testing Complete	Sept 2020		
FM Instrument and NACHOS Host Build Complete	Nov 2020	Medium	Yes
Acceptance Testing of FM Instrument and Host Complete	Dec 2020		
Pre-Shipment Review	Dec 2020		
Delivery to Launch Site for Integration	Jan 2021		
Launch	April 2021		
Minimum Criterion for Success Completed	August 2021		
Desired, Best-Case Criterion for Success Completed	Dec 2021		

EDU = Engineering Design Unit
EQM = Engineering Qualification Model
FM = Flight Model

NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)

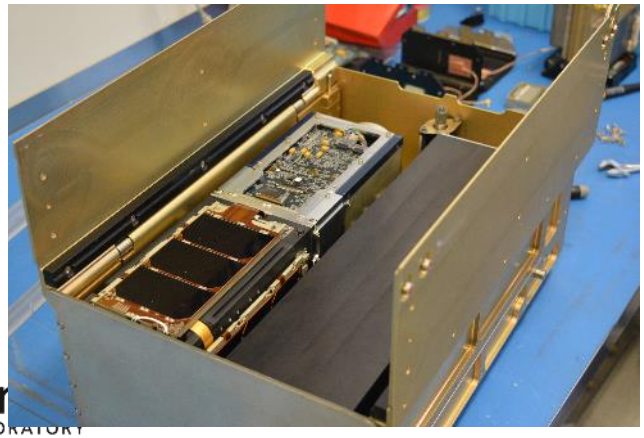
First Annual Review - 1/21/2020

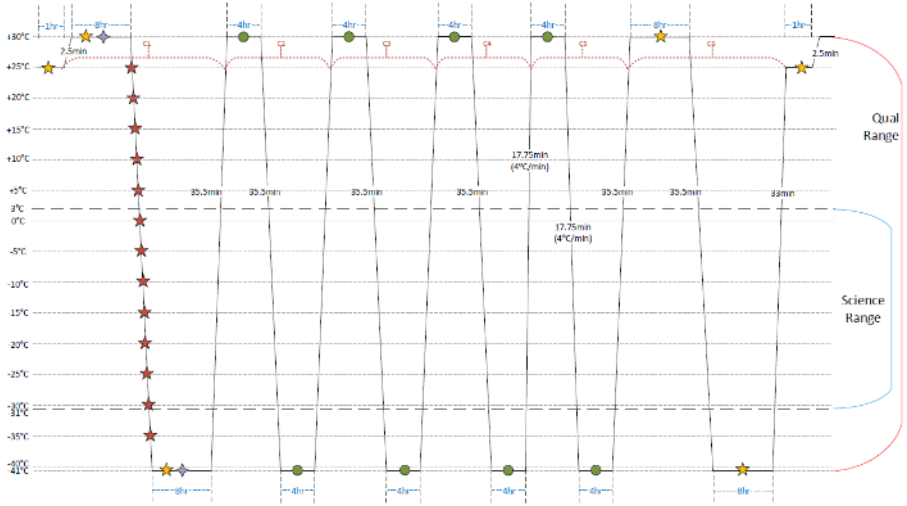
Systems – Budget – Schedule

M. Dale, A.Guthrie, L. Ott

Systems Status & Plans

- **TRL level 6** – expect to reach in Feb 2020 when successful vibration testing complete
- **Numerous recent environmental tests**
  - Thermal, vibration, and basic host EMI-EMC effects completed
  - Thermal test confirmed operational temperature range (-31ºC to 3ºC) and system survival at bakeout (60ºC)
- **Payload & host integration**
  - Test fit payload with EQM host and in P-Pod. EQM host initial functionality confirmed.
- **Future Plans:**
  - Planning for defining CONOPS and host+payload interactions
  - Incorporating launch requirements into EQM &FM build and test plans
  - Resolving frequency allocation issues





NACHOS Power, Mass, & Volume History

	LANL Funded - TACOS		NASA Funded - NACHOS	
	PDR (7/2017)	CDR (7/2018)	Kickoff (1/2019)	Annual Review (1/2020)
Power				
CCD Collect (peak 2min)	10W	15.8W	15.8W	16.5W
Image Processing (25min)	5.7W	5.1W	5.1W	5.1W
Nominal (10min)	2W	2 W	2 W	3W
Mass (Total)	4.18kg	4.18kg	4.12kg	4.12kg
Host	2.7kg	2.7kg	2.7kg	2.7kg
Payload	1.48kg	1.48kg	1.42kg	1.42kg

Volume has remained 3U+ across the design evolution

Risk Items

- **Risks Items**

Limited systems level documentation and analysis

Per NASA launch service provider requirements need to address

- Tin removal or mitigation was required for contamination purposes
- NASA Debris Assessment Software (DAS)

Frequency allocation for on-orbit communications (NTIA)

- Need to work with AF and DOE to understand best path forward

Launch: CSLI seems likely, should we apply for others?

Optics vibration survival: how likely for us to get a ISS Cygnus launch

System integration with bus ground and on-orbit (electrical, thermal, software). The first time a payload will be operated on this newly revised bus will be Fall 2020.

- **First four items discussed in following slides**

Systems Level Documentation

- **Systems Requirements**
  - 10Y1749147-D400_NACHOS_System Requirements.xlsx
  - Status: Last updated 7/2018 with requirements flowed down to individual systems
- **Verification & Validation Matrix**
  - 10Y1749147-D404_NACHOS_V&VMatrix_OI.xlsx
  - Status: populated with launch and overall requirements
- **Actions & Risk Tracking**
  - 10Y1749147-D408_NACHOS_Actions-Risk_Status.xlsx
  - Status: Up to date. Tracked RFAs since initial TACOS PDR
- **Environmental Testing & Reports**
  - 10Y1749147-D401-NACHOS Payload Test Plan.doc, 10Y1749120-D403-NACHOS Thermal Test Plan.doc, 10Y1749147-D404-NACHOS EM vibe test 060619.doc
  - NACHOS Thermal Test Report, NACHOS payload & host EMI-EMC, NACHOS Shake Test Results
- **Concept of Operations**
  - 10Y1749147-D406_NACHOS_Concept_of_Operations.doc Determination of documentation and format needed in process with team.
- **Document Number Control & PCB Revision Tracking**
  - Electrical documentation maintained in Team Forge. Test Plans and Reports maintained in Team Forge. Mechanical documentation maintained in WindChill (CREO)

Risk and Watch Items (10Y1749147-D408_NACHOS_Actions-Risk_Status.xlsx)

NACHOS Request For Actions, Watch, & Risk List

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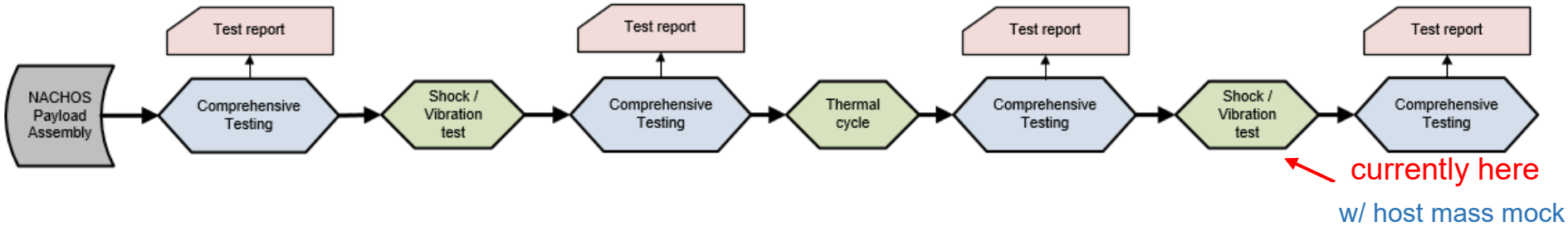
Item	Person(s) Il	Date Initiate	Title	Request/Action	Rationale/Reviewer Comments	System	Resp Persol	Statu	Plans & Outcome
22	NASA-Goddard	3/13/2019	Frequency Allocations	LANL needs to complete NTIA application		System	Mags	In Process	Working with LANL frequency manager to submit application.
23	NASA-Goddard	3/13/2019	Launch Applications	Missed CSLI deadline for FY19, will apply this coming November FY20		System	Mags	In Process	Submitted Application 11/1, typically 6mo to hear back
27	LDRD Final Review	7/22/2019		Is there coherent noise over long integration times? The SNR shown on slide 15 is not quite sqr(n).		Optics		In Process	
34	Risk	10/24/2019	Host Integration Issues (EMI/EMC)	tape PIP interface with metal tape to help reduce EMI/EMC. Check CCD performance with various systems on and operating. Consider options to shield CCD with metal box around sides that doesn't interfere with optics?	Bus has EMI issues, luckily CCD is farther away.	Electrical	Mags	In Process	May need to add in mechanical shielding within payload. Does this need to be tested out (ie host+payload) before mech EQM revs or can this be added in later? Completed basic EMI-C testing and no image interference noted.
35	Risk	10/24/2019	Spectral Resolution Improvements		Still room for improvement in optical alignment and consequent spectral resolution. Affect on validation mission minimal, but would like to achieve high SO2 sensitivity for potential bonus science results. Desired improvements expected as flight instrument is optimized.	Optical/Mechanical	Steve/Kirk	In Process	minimum spectral resolution achieved, work proceeding towards further improvements.
36	Risk	10/24/2019	Optical Mount Stability		Original tertiary mirror mount failed vibration test. New improved mount expected to pass, but test has not yet been conducted.	Mechanical	Logan	In Process	Still not passing (12/19) redesign in progress and testing in ppod with mass mock
37	CSLI Feasibility Review	10/29/2019	Optical Mount Stability		1) Mirror mount change, re-design recently completed. At risk with late change. 2) Optical mounts still need work and a vibe has not yet shown them to be viable. The host dispenser is not known and this could impact the optical mount likelihood of success. Have a new design and a good test plan.	Mechanical	Logan	In Process	Performance in optics lab is encouraging. Vibe test to occur prior to EQM redesign.
40	Watch	10/24/2019	PIP envt'l reliability	Final Payload Interposer (PIP) design will be validated in thermal/vibe testing in EQM not EDU. Interposer redesign needs verification that power supply can work. Do TC before TVAC		Electrical	Kerry	In Process	
41	Watch	10/24/2019	SDRAM - PDH	FPGA control of SDRAM fails to stall processor requests over memory bus for data during SDRAM refresh cycles VHDL fix may be possible. Other mitigations include patching data with redundant reads, reduced refreshes		Software	Claira	In Process	
42	Watch	10/24/2019	NAND Flash - PDH	Potentially SW error in initialization order of NAND flash, write protection, and file system. SW fix implemented, currently on watch to ensure issue was purely software and is not tied to PDH design as originally thought		Software	Claira	In Process	
45	Risk	10/24/2019	ADCS integration	Integrating SFS with payload and ADCS		Electrical/Software	Hannah	In Process	may not be needed for 25deg pointing accuracy but not much time and effort, so low priority to complete
46	Watch	10/24/2019	ADCS clock sync	Image readout experiencing clock synchronization issue		Software/ADCS	Hannah	In Process	
47	Watch	10/24/2019	ADCS on-orbit operation	On-orbit checkout schedule slip Lifetime		Software/ADCS	Hannah	In Process	
50	CSLI Feasibility Review	10/29/2019	ADCS on-orbit operation	The differences in ADCS performance between SV7 & SV9 are unknown at this time.		ADCS	Hannah	In Process	**Continue testing the on-orbit sensors using data getting down to resolve. Can likely achieve SV9 having similar pointing as SV7**
51	CSLI Feasibility Review	10/29/2019	Bus Modifications Confirmed Effectiveness	Keep tabs on GS-J and current on orbit Block 2B bus operations. Confirm new changes improve performance as expected.	The fixes to the latest bus revision won't be known until further into the GS-J schedule. 1) Full grounding of card cages to reduce EMI 2) Modified springs and perimeter of solar panels to ensure full deployment 3) Grounding tab for stowed high-band antenna to ensure reliable TX inhibit 4) Removed inductors on backplane to eliminate transient-induced failure	Bus		In Process	Keep tabs on GS-J and current on orbit Block 2B bus operations.Confirm new changes improve performance as expected. Launch is expected July 2020 (likely slip) but definitely Fall 2020.
55	LDRD Final Review, CSLI Review, NASA-Goddard	7/22/2019	Thermal analysis of CCD and payload	How to go about improving likelyhood of successful thermal performance on orbit Performance of the passive cooling seem to be unverified assertions at this point. 'Need to understand targeted setpoint for host+payload Need to confirm thermal is fine by validating models in TVAC tests	Performance of CCD is strongly dependent on temperature, with a nonlinear increase in noise with increasing temperature. Passive cooling of the CCD may improve CCD performance without significant increase in SWAP. '1) Thermal analysis/testing of payload & payload/host interface wrt CCD 2) Thermal incomplete. T-vac incomplete. Thermal management at risk 3) Not enough resources to do full testing as would fly, best to just understand heat loads and than the model works. 4) Consider looking at self generated heat only and how to get heat out. Insturment to look at this test data and then relate back to model. 5) Look at on-orbit telemetry thermal data vs orbit/pointing/location and understand why temps are this way. 6) Look at TVAC data from GSJ 7) If redesign needed for internal thermal issues is this a big deal? 8) I encourage team to consider how good the thermal model needs to be (+/-5 degrees? 10?) and then develop a model to match, rather than dedicate time to the best model possible. 9) Critical thermal model maturation plan can be improved 10) Recommend against tuning up expensive thermal modeling, simple analysis can be done. 11) Concern is thermal management: addressed by team. Battery and CCD temperature requirements are disparate, thermal model needs to be more mature in order to have confidence that both temperature requirements can be met. '1) Achieve compromise between keeping the battery temperature at ≥0 C while keeping the internal operating temperature of the digital radio FPGAs at ≤65 C. Can be realized with appropriate (SV specific) tape-out design. Analysis using a high-fidelity thermal model (GS-J) is currently underway. 2) Consider putting thermal design point towards the mid-point of minimum battery and maximum CCD. Trying to get too close to the battery to improve CCD noise may not be in line with minimizing risk to hit the threshold objectives. 3) Given lifetime of project and low temp effect on battery not a big deal to run batteries cold.	Thermal/Mechanical	Logan	In Process	1) complete subsystem tests to quantify thermal peformance in TVAC 2) Correlate empirical thermal performance back to model 3) Use thermal images to determine where to investigate heat loads (already ongoing)
58	LDRD Final Review & CSLI Review	10/29/2019	CONOPS		Would like to see more clarity on dependency between pointing accuracy and CONOPS Although this isn't required for the current NASA proposal, understanding the real world targets, how the payload instrument will engage and acquire data from these targets wasn't well described and doesn't seem to be part of testing. Would this be an appropriate project for a student? The project seems to have many opportunities for additional student engagement.	System		In Process	Inlcuding this in CONOPS Ability to due science target is dependent on bus performance. CONOPS for science targets have been considered in some detail. Student/Postdoc engagement is planned.
59	CSLI Feasibility Review	10/29/2019	EQM-FM Testing		Plan for a proper bus characterization and run the full system as it would be on orbit in TVAC and on bench	System		In Process	This is already in our NACHOS Qualifiction Test Plan
60	CSLI Feasibility Review	10/29/2019	Bus+Payload power margins budget	Complete a full power margins budget.	Complete a full power margins budget understanding the bus' various modes or operation (comms transmit/receive, peak power, orbit averages). Figure out ~6-7 orbits to recharge amount of time in sun/dark. Pointing power is high, hard to determine full ADCS power draw on the ground. Understand how to monitor power telemtry from bus on orbit	Systems/Electrical	Mags	In Process	A preliminary version has already been done but host power availability has since been updated. A complete analysis will be done as part of our CONOPS documentation.

- 73 items watched since TACOS project started
- 53 items completed
- 20 items are still in process and are discussed in this review

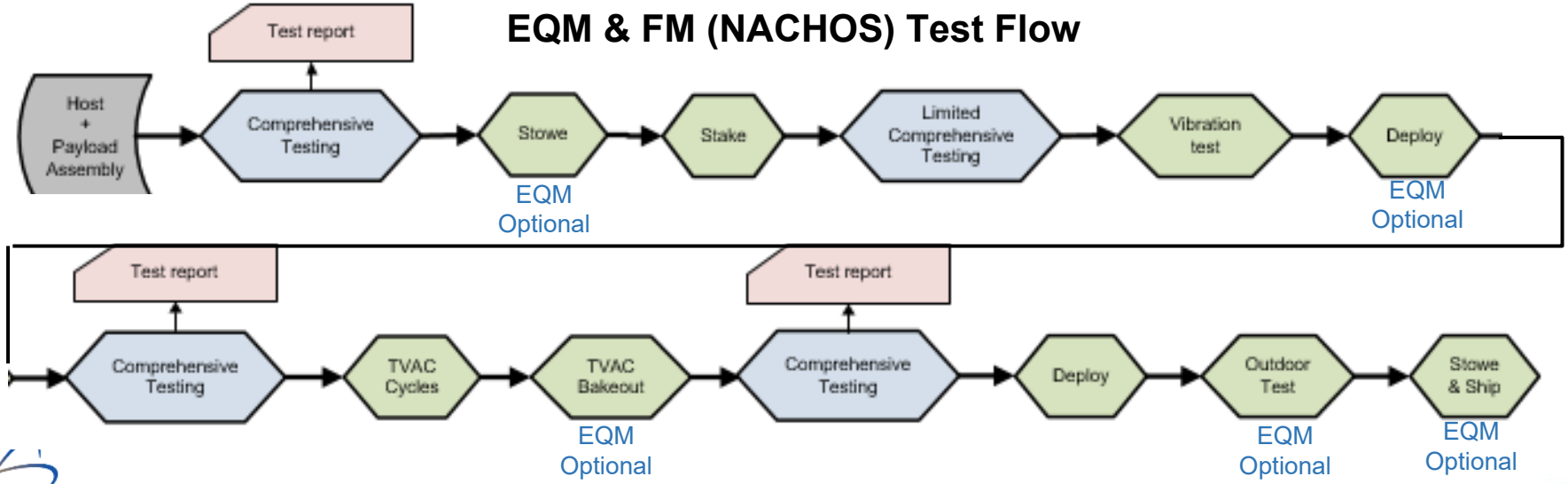
Systems Level Testing

- Testing to GEVS and/or AF SMC and using previous payloads test flow as guideline for various tests
- EQM & FM - All testing done with flight software, FM will have reduced TVAC cycle temperatures & times

EDU (TACOS) Test Flow



EQM & FM (NACHOS) Test Flow



EDU = Engineering Design Unit (LANL-LDRD) TACOS
EQM = Engineering Qualification Model (NASA) NACHOS
FM = Flight Model (NASA) NACHOS

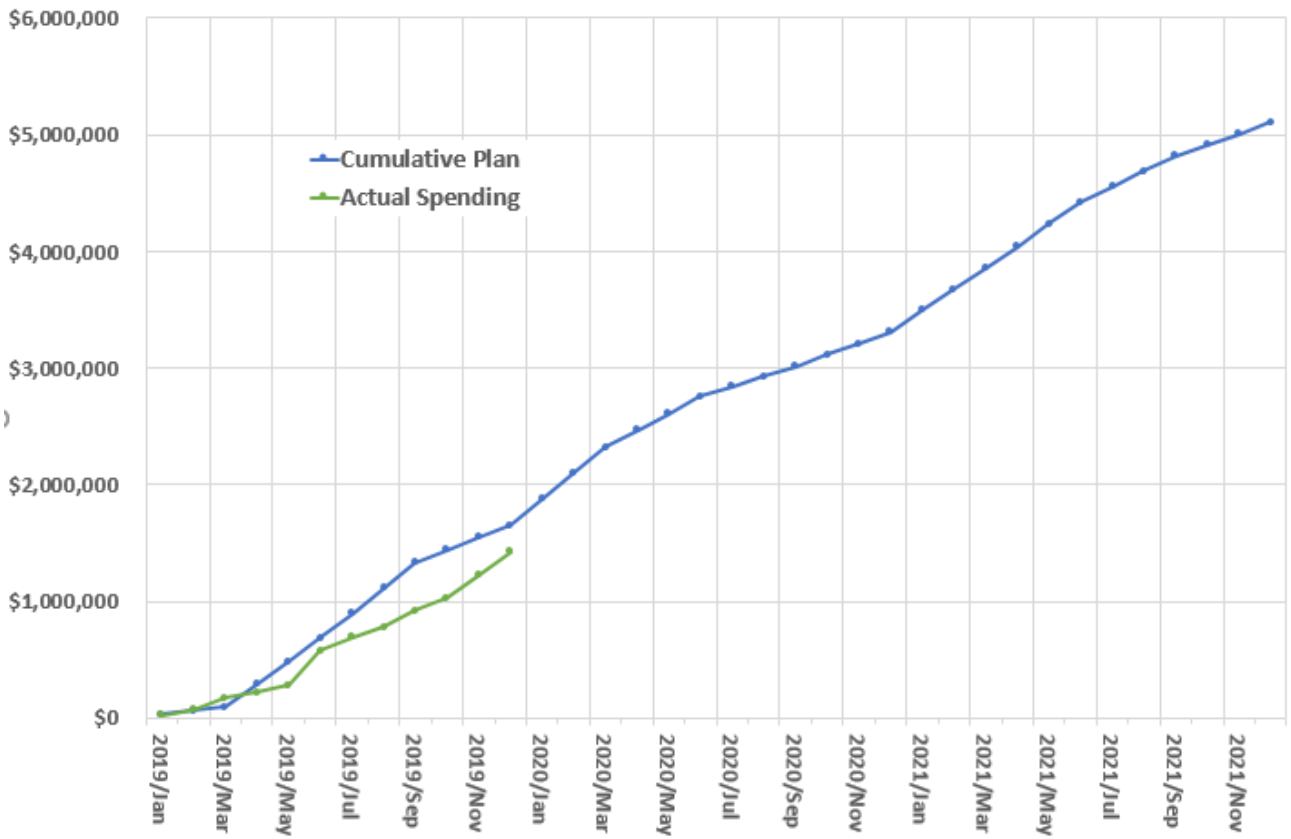
Frequency Allocation & Launch

- **National Telecommunications and Information Administration (NTIA)**
  - Application was submitted by DOE and reviewed at Spectrum Planning Subcommittee (SPS) on 1/6/2020 but was soon after removed due to identical hardware submitted by Air Force and operation of the low band radio in a military range.
  - We are currently working with the AF sponsor to understand if:
    - NACHOS can have a waiver to operate our low band radio in the military range
    - OR if additional frequencies can be added to the recent AF application
  - Backup plan is to use existing DOD sponsor NTIA allocated frequency bands
- **Launch**
  - CSLI application submitted 11/1/2019
  - Issues brought up during application:
    - Tin removal or mitigation was required for contamination purposes
      - Need to confirm this is required. This has not been done on previous launches of this host and would require unplanned cost and schedule impact.
    - NASA Debris Assessment Software (DAS)
      - LANL could not obtain NASA DAS software for orbit decay analysis. This is due to LANLs request terms changes for removal of FFRDC (Federally funded research and development centers) as LANL is also an FFRDC.

Systems Level Plans

- **Concept of Operations Development**
  - Image capture and calibration operations have been documented
  - Mission manager (autonomous operation software) is being developed by software team
  - Working with NACHOS and other cubesat payload team members to plan and document system on-orbit operational plan, scenarios, conditions, constraints, etc.
- **Payload Power Budget Review**
  - The original power budget analysis was based on previous bus power specification
  - Design changes to the bus have resulted in an increase in the recharge time resulting in a longer recharge duty cycle.
  - Plan to look into host power use throughout operations and recharge time. Mission requirements will still be met.
- **Star Field Sensor MOU from previous sponsor**
  - SFS hardware was developed by previous payload sponsor and is available for use by NACHOS.
  - An official MOU is needed from this sponsor to use this hardware and needed before launch. This targeting to be completed by the end of February

Overall Spending



	Monthly plan	Cumulative Plan	Actual Spending
2019/Jan	$ 31,519.83	$ 31,519.83	$ 19,964.85
2019/Feb	$ 31,519.83	$ 63,039.65	$ 68,457.30
2019/Mar	$ 31,519.83	$ 94,559.48	$ 170,762.82
2019/Apr	$ 195,584.97	$ 290,144.45	$ 219,217.81
2019/May	$ 195,584.97	$ 485,729.41	$ 276,222.36
2019/Jun	$ 195,584.97	$ 681,314.38	$ 574,123.98
2019/Jul	$ 216,758.23	$ 898,072.61	$ 691,679.66
2019/Aug	$ 216,758.23	$ 1,114,830.85	$ 777,594.90
2019/Sep	$ 216,758.23	$ 1,331,589.08	$ 919,473.46
2019/Oct	$ 107,482.18	$ 1,439,071.26	$ 1,025,209.35
2019/Nov	$ 107,482.18	$ 1,546,553.43	$ 1,220,006.40
2019/Dec	$ 107,087.57	$ 1,653,641.00	$ 1,420,833.80
2020/Jan	$ 223,225.15	$ 1,876,866.15	
2020/Feb	$ 223,225.15	$ 2,100,091.31	
2020/Mar	$ 223,225.15	$ 2,323,316.46	
2020/Apr	$ 144,012.54	$ 2,467,329.00	
2020/May	$ 144,012.54	$ 2,611,341.55	
2020/Jun	$ 144,012.54	$ 2,755,354.09	
2020/Jul	$ 85,328.90	$ 2,840,682.99	
2020/Aug	$ 85,328.90	$ 2,926,011.88	
2020/Sep	$ 85,328.90	$ 3,011,340.78	
2020/Oct	$ 99,934.66	$ 3,111,275.44	
2020/Nov	$ 99,934.66	$ 3,211,210.11	
2020/Dec	$ 100,014.89	$ 3,311,225.00	
2021/Jan	$ 181,935.03	$ 3,493,160.03	
2021/Feb	$ 181,935.03	$ 3,675,095.06	
2021/Mar	$ 181,935.03	$ 3,857,030.09	
2021/Apr	$ 187,307.41	$ 4,044,337.50	
2021/May	$ 187,307.41	$ 4,231,644.91	
2021/Jun	$ 187,307.41	$ 4,418,952.32	
2021/Jul	$ 133,463.74	$ 4,552,416.06	
2021/Aug	$ 133,463.74	$ 4,685,879.79	
2021/Sep	$ 133,463.74	$ 4,819,343.53	
2021/Oct	$ 95,305.67	$ 4,914,649.20	
2021/Nov	$ 95,305.67	$ 5,009,954.86	
2021/Dec	$ 95,110.14	$ 5,105,065.00	

- Below budget because some mechanical and electrical procurements have not yet been made.

Schedule Milestone (1/3)

- **Table modified to show change in milestone dates and change in task duration**
- **Change explanations on following slides**

Milestone	Original Date (Kickoff)	New Date	Milestone Date Δ	Original Duration	New Duration
1- Project Start	Jan 2019	Jan 2019	0		
2- Environmentally Tested EDU TACOS Completed	July 2019	Jan 2020	+6	6mo	12mo
3 - EQM NACHOS Instrument Complete (Redesign of EDU)	Nov 2019	April 2020	+5	4mo	3mo
4 - EQM NACHOS Instrument and TACOS Host Integration Complete	Jan 2020	May 2020	+4	2mo	1mo
5 - Qualification Level Environmental Testing of Integrated EQM Instrument and Host Complete	March 2020	July 2020	+4	2mo	2mo
6 - Resolution of any Anomalies from EQM Testing Complete	May 2020	Sept 2020	+4	2mo	2mo
7 - FM Instrument and NACHOS Host Build Complete	August 2020	Nov 2020	+3	3mo	2mo
8 - Acceptance Testing of FM Instrument and Host Complete	Sept 2020	Dec 2020	+3	1mo	1mo
9 - Pre-Shipment Review		Dec 2020		--	0mo
10 - Delivery to Launch Site for Integration	Sept 2020	Jan 2021	+4	0mo	1mo
11 - Launch	Jan 2021	April 2021	+3	4mo	3mo
12 - Minimum Criterion for Success Completed		August 2021		--	8mo
13 - Desired, Best-Case Criterion for Success Completed	Dec 2021	Dec 2021	0	12mo	4mo

EDU = Engineering Design Unit (LANL)
EQM = Engineering Qualification Model (NASA)
FM = Flight Model (NASA)

Schedule Milestones (2/3)

Milestone	Original Date (Kickoff)	New Date	Milestone Date Δ	Original Duration	New Duration
1- Project Start	Jan 2019	Jan 2019	0		
2- Environmentally Tested EDU TACOS Completed	July 2019	Jan 2020	+6	6mo	12mo
3 - EQM NACHOS Instrument Complete (Redesign of EDU)	Nov 2019	April 2020	+5	4mo	3mo
4 - EQM NACHOS Instrument and TACOS Host Integration Complete	Jan 2020	May 2020	+4	2mo	1mo
5 - Qualification Level Environmental Testing of Integrated EQM Instrument and Host Complete	March 2020	July 2020	+4	2mo	2mo
6 - Resolution of any Anomalies from EQM Testing Complete	May 2020	Sept 2020	+4	2mo	2mo

- Delay from Milestone 1-2
  - More issues were found during EDU testing than had been anticipated. Resolving these took much more time than had been allocated. However doing so should result in an improved EQM that requires less anomaly resolution.
    - Grating manufacturing error required new procurement and mechanical mount redesign required
    - Focus unexpectedly difficult, delay in electronics LED calibration, and software GUI
  - Personnel not available due to other project commitments. Some of those projects were resolving current CubeSat issues, which benefits NACHOS
- Mitigation Strategy
  - Used 3 month reserve
  - Redesign is being done in parallel so EQM design to build can be shorter.

Schedule Milestones (3/3)

Milestone	Original Date (Kickoff)	New Date	Milestone Date Δ	Original Duration	New Duration
7 - FM Instrument and NACHOS Host Build Complete	August 2020	Nov 2020	+3	3mo	2mo
8 - Acceptance Testing of FM Instrument and Host Complete	Sept 2020	Dec 2020	+3	1mo	1mo
9 - Pre-Shipment Review		Dec 2020		--	0mo
10 - Delivery to Launch Site for Integration	Sept 2020	Jan 2021	+4	0mo	1mo
11 - Launch	Jan 2021	April 2021	+3	4mo	3mo
12 - Minimum Criterion for Success Completed		August 2021		--	8mo
13 - Desired, Best-Case Criterion for Success Completed	Dec 2021	Dec 2021	0	12mo	4mo

- Changes in Milestones 7-12
  - Delay carried over from initial EDU work. Added in time for acceptance testing and pre-shipment review
- Mitigation Strategy - Reduced time needed from launch to on-orbit validation
- Possible other Mitigation Strategies:
  - What is typical time between delivery and launch (3 or 4 months)?
  - If concerns regarding timing of EQM development could consider no-cost extension
  - Delay launch to allow for additional development
- Conclusion
  - Mitigation strategy has made up significant time in the schedule by executing critical tasks in parallel and reducing time for on-orbit validation. Achieving on orbit minimum mission criterion for success is still achievable.