DEVELOPMENT AND ON-ORBIT OPERATION OF THE NACHOS CUBESAT-BASED TRACE-GAS HYPERSPECTRAL IMAGER

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ABSTRACT

The Nano-satellite Atmospheric Chemistry Hyperspectral Observation System (NACHOS) consists of 3U CubeSats hosting high-throughput (f/2.9), high spectral resolution (1.3 nm optical, 0.57 nm sampling) UV/Visible hyperspectral imagers that cover the 300-515 nm spectral region in 350 spectral bands. Complementing spectroscopically similar large-satellite instruments, NACHOS performs targeted measurements at a much higher spatial resolution of ~0.4 km/pixel from 500 km altitude over its ~130 km across-track field of view. With its high spectral resolution, NACHOS is aimed at observing trace gases such as anthropogenic NO_2, SO_2 and other volcanic gases, and CH_2O from wildfires. NACHOS incorporates highly streamlined onboard gas-retrieval algorithms, alleviating the need to routinely downlink massive hyperspectral data cubes. This paper discusses the development, ground-based operation, and initial on-orbit results of the NACHOS instrument and onboard processor.

Index Terms — Hyperspectral imaging, UV, Visible, remote sensing, CubeSat, NO_2, SO_2

1. INTRODUCTION

Hyperspectral imagers of sufficient spectral resolution and sensitivity for space-based trace gas imaging have traditionally been heavy and power-hungry, requiring expensive large-satellite platforms for deployment in space. The advent of the CubeSat standard for very small satellites, and the associated low-cost launch opportunities that are becoming ever more readily available, together with continuing progress in the miniaturization of electronics and instrumentation, has made it possible for many types of instrument to transition from large-satellite platforms to far less expensive CubeSats. Of the various remote-sensing technologies being adapted to the tiny CubeSat form factor, however, hyperspectral imaging (HSI) of trace gases at scientifically useful sensitivity levels is one of the most challenging. Hundreds of spectral bands are typically needed, as opposed to tens of bands for applications such as vegetation monitoring or geologic mapping. Achieving the gas detection sensitivities necessary to address key scientific questions is already challenging even for traditional large-satellite instruments for which volume and mass constraints are relatively relaxed. A further challenge of performing trace-gas HSI on a CubeSat is the intrinsically large size of the raw hyperspectral datasets. This volume of data would be difficult to impossible to downlink on a routine basis given the limited communications bandwidth typical of today's CubeSats, which necessitates performing the bulk of the chemical retrieval processing onboard the satellite to reduce the downlink data volume to manageable levels.

The Nano-Satellite Atmospheric Chemistry Hyperspectral Observation System (NACHOS) was conceived to address these many challenges and open the way to a new approach to space-based trace-gas remote sensing, with inexpensive constellations of CubeSats performing much of the work of far more expensive large-satellite instruments being ultimately envisioned. The NACHOS project recently deployed into low earth orbit two UV/Visible CubeSat hyperspectral imagers having trace-gas imaging and rapid onboard processing capabilities [1,2]. The NACHOS instruments cover the 300-515 nm spectral range in 350 spectral bands, 0.6 nm per channel, with optical spectral resolution of 1.3 nm, making them spectroscopically similar to NASA's large-satellite Ozone Mapping Instrument (OMI) [3]. With this spectral range and resolution, NACHOS can detect a variety of gases, including NO_2, SO_2, BrO, IO, OClO, and CH_2O, making them applicable to urban air pollution, wildfire, and volcano observations.

NACHOS-1 launched February 19, 2022 aboard the NG-17 Cygnus International Space Station resupply mission, and was deployed to a 400-km altitude, 51.6-degree inclination orbit on June 28, 2022. Shortly thereafter, on July 2, NACHOS-2 was launched to a 500 km altitude, 45-degree inclination orbit aboard a Virgin Orbit aircraft-deployed rocket. From these low earth orbits, the NACHOS CubeSats provide imagery at ~0.4 km spatial resolution, 1-2 orders of magnitude finer than existing large-satellite instruments currently in orbit. With a swath width of roughly 130 km, NACHOS is aimed at targeted observations at this relatively high spatial resolution, complementing the wide-coverage measurements of its large-satellite cousins.

2. THE NACHOS HYPERSPECTRAL IMAGER

This work was initially inspired by the development at LANL of a new CubeSat system [4,5] offering a robust payload hosting capability. This 1.5U satellite bus (a 'U' being the basic 10x10x10 cm^3 building block of the CubeSat standard, making the LANL bus's dimensions 10x10x15 cm^3) provides the basic infrastructure of power generation, communications, an attitude determination and control system (ADCS), and data handling, and is capable of hosting a 1.5U instrument payload, to produce a 3U (10x10x30 cm^3) complete satellite.

The 1.5U volume constraint for the instrument payload presents a serious challenge for the optical design of a high-resolution hyperspectral imager, particularly since 0.5U of this volume is needed for electronics, leaving only 1U for the actual optical instrument. After exploring various strategies, we settled on an Offner-type [6] design, which consists of two concave spherical focusing mirrors and a convex spherical grating, all roughly concentric with each other, a configuration in which spherical aberrations cancel. Importantly for our application, Offner spectrometers can be made optically fast (*i.e.* small focal ratio) and still maintain high image quality, with a near complete absence of geometrical "smile" and "keystone" distortions. The NACHOS spectrometers have an f/2.9 effective focal ratio, which, coupled with high-efficiency ruled and blazed diffraction gratings, provides the high optical throughput needed for sensitive HSI.

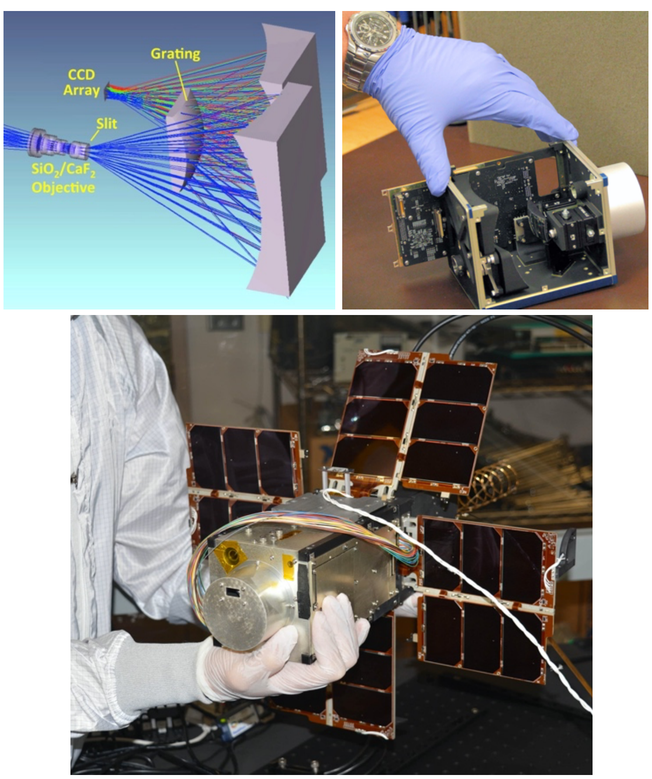

Figure 1. The NACHOS hyperspectral imager. Top: Optical layout and assembled optical package. Bottom: The complete integrated satellite.

The reflective spectrometer is fed by an eight-element CaF_2/SiO_2 objective lens, which images the scene onto the spectrometer slit. The entire reflective spectrometer – mirror and grating substrates and optical bench – is made from a single material, aluminum, so that all elements expand and contract proportionally, and thus remain in focus independent of temperature. For the objective lens, athermal focus stability is achieved using a bi-material Al/polymer lens mounting scheme.

The NACHOS detector array is a UV-optimized, back-illuminated version of the extensively space-validated Teledyne/e2v CCD47-20 CCD array. This CCD supports high frame readout rates and has quantum efficiency greater than 70% over the entire 300-500nm spectral range of interest. For the brightest anticipated scenes and f/2.9 optics, nearly full-well capacity (100ke-/pixel, shot noise limited SNR~300) can be reached through most of the spectrum at this frame rate. Pixel-to-pixel nonuniformities in the CCD response and dark-current offset, which would otherwise manifest as effective noise in the spectra, are calibrated out using an LED-based onboard calibration system. In this no-moving-parts system, four LEDs residing immediately in front of the CCD, mounted in the final stray-light baffle, provide a highly uniform illumination field having better than 0.01% fine-scale smoothness and coarse-scale uniformity of ~1%. To perform the calibration, the spacecraft points at deep space, whereupon dark and LED-illuminated CCD frames are collected. This is done prior to each data collection pass over a target.

Temperature control of the CCD is completely passive, achieved through careful engineering of the thermal conduction between the CCD and the satellite structure, and judiciously chosen surface treatments on the satellite exterior radiating surfaces. The major challenge is achieving a CCD temperature <0˚C to keep dark current low, while maintaining satellite electronics and batteries in the required ~20˚C range. In practice, our scheme worked extremely well, with on-orbit CCD temperatures in the -5˚C to -20˚C range, rendering dark current shot noise essentially negligible, while the other electronics remain in the desired ~+20˚C range.

3. ON-BOARD HYPERSPECRTRAL PROCESSING

In order to perform CubeSat-based hyperspectral gas detection on a routine basis, an onboard processing scheme is needed that reduces the downlinked data volume by at least 2 orders of magnitude, and is also computationally efficient enough to run quickly on the CubeSat's small onboard processor. The approach that we developed [7,8] to achieve both these aims is to produce (with on-board processing) a set of 2D grayscale images (up to ten, at most) using the covariance-matrix-based adaptive matched filter (AMF) approach, along with a small sample (up to a thousand or so) of unprocessed full-spectrum pixels, all of which comprise an easily downlinked small data set. These 2D images are matched-filter outputs for each target gas of interest, plus a Mahalanobis distance (MD) image. The sample full-spectrum pixels will include random background pixels, in addition to pixels corresponding to high matched filter values and high Mahalanobis distance values. The individual gas AMF images and the MD image can be utilized together in ground processing to implement more sophisticated gas detection algorithms to achieve even higher gas detection sensitivity than the straightforward AMF.

While our AMF-based approach is computationally far less demanding than a full physics-based radiative transfer retrieval, it is still challenging for the small processor on board our CubeSat. Processing a 2000 x 350 spatial pixel data cube takes roughly four hours on the CubeSat processor if the full AMF and MD algorithms are performed in the standard manner without any approximations. As we described in detail in an earlier paper [7], this unacceptably long processing time can be drastically reduced, with negligible loss of gas detection sensitivity or increase in false detection rate, by applying judicious approximations to streamline the calculation. The first of these is very straightforward, and that is to approximate the full covariance matrix using a small subset of the total spatial pixels. In tests using real-world OMI data, we find that a subset representing less than one percent of the total pixels still provides a covariance matrix of sufficient fidelity to enable accurate gas retrievals. The second streamlining approximation deals with the calculation of the Mahalanobis distance, and is accomplished via the sparse matrix transformation and Givens rotations, as detailed in [7]. With these streamlining approximations, processing time for this large data cube is reduced from four hours to under nine minutes, with the resulting gas-retrieval maps virtually indistinguishable from the full AMF/MD calculation. [1,7]

4. GROUND-BASED MEASUREMENTS

While designed for space, the NACHOS instrument is also a highly portable hyperspectral imager suitable for ground-based measurements. Figure 2 shows NACHOS gas-detection imagery of a local coal-fired power plant, the Four Corners Power Plant near Farmington, New Mexico in December 2021, taken from a site roughly 2 km north of the plant. The left image shows a single-wavelength (473 nm) grayscale image, similar to the visual appearance of the plume. The visible plume here is the condensed water-droplet cloud. The image on the right shows the result of Adaptive Matched Filter (AMF) processing tailored to detect NO_2, from the same hyperspectral data cube as used for the upper image. The detected NO_2 plume extends far beyond the visible water droplet plume and shows complex turbulent

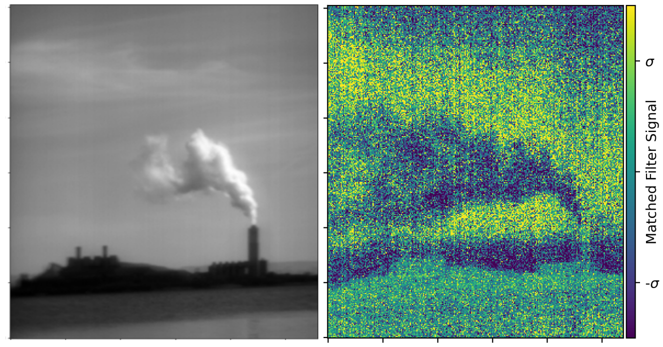

Figure 2. NACHOS images of the 4-Corners Power Plant plume. Left: Single-wavelength image from the NACHOS 473 nm band. Right: NO_2 matched-filter image produced using the AMF algorithm; high NO_2 amounts appear as dark blue.

structure. Also visible along the horizon is a very prominent NO_2 detection corresponding to the regional accumulation of NO_2 due to local topography and meteorological conditions, *i.e.* part of the regional smog caused by the power plants and the nearby city.

5. SPACE-BASED MEASUREMENTS

Following deployment of the two NACHOS satellites to their final orbits in mid-2022, commencement of hyperspectral data collection was delayed for several months by various issues with the satellites' attitude determination and control systems. Figure 3 shows the first fully successful hyperspectral acquisition, a hyperspectral image of the Naples, Italy area obtained by NACHOS-2 on Aug. 18, 2023. The image spans approximately 100 km x 130 km. The single-channel 473 nm image on the left shows the Naples metropolitan area and coastline, with the Miseno promontory

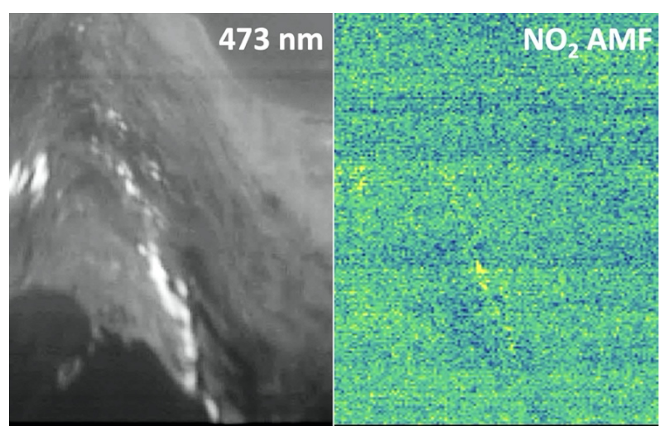

Figure 3. NACHOS imagery of the greater Naples, Italy area. Left: Image from the NACHOS 473 nm channel. The Naples coastline, including the isle of Ischia, can be seen at lower left. Right: NO_2 adaptive matched-filter image generated by the NACHOS onboard processor. Urban NO_2 appears as the dark blue region over the Naples metro area, to the left of the bright cloud band.

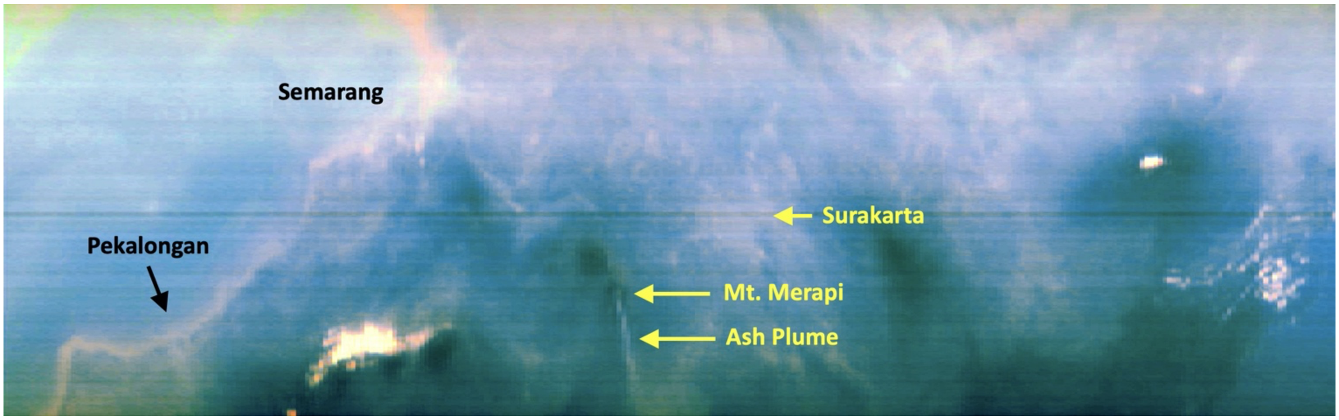

Figure 4. NACHOS-2 false-color image of central Java, Indonesia, showing the Mt. Merapi volcano, emitting a plume of ash, and the cities of Semarang, Pekalongan, and Surakarta. Image is approximately 340 km x 90 km, and is constructed from the NACHOS-2 511 nm, 402 nm, and 321 nm channels.

and isles of Procida and Ischia clearly visible (for scale, Procida is ~1 km x 2.5 km and Ischia is ~ 5 km x 8 km). Shown on the right is the NO_2 matched-filter image (AMF algorithm) produced by the NACHOS onboard processor. Higher NO_2 densities appear dark in this image, with the most prominent feature being the large NO_2 plume over Naples in the lower left portion of the image.

Figure 4 shows a NACHOS-2 false-color image generated from its 511 nm, 402 nm, and 321 nm channels, from a hyperspectral data cube obtained Sept. 5, 2023 over the Mt. Merapi volcano in central Java, Indonesia. The volcano, emitting a distinctive ash plume blowing to the south, can clearly be seen here, as well as the cities of Semarang, Pekalongan, and Surakarta. The SO_2 matched-filter image from this data set showed no discernable SO_2, however, likely because the dense ash was opaque enough to obscure the SO_2 spectrum. Nevertheless, this image demonstrates the spatial resolution of NACHOS, with features as small as 0.5 km, such as individual factory complexes on the outskirts of Semarang, discernable in the image.

6. SUMMARY AND THE FUTURE

The NACHOS project has performed high spectral- and spatial resolution hyperspectral imaging, with integrated onboard chemical retrieval processing, all on 3U CubeSats weighing only 6 kg apiece, demonstrating that constellations of hyperspectral nano-satellites could be a viable approach to future gas-sensing remote sensing. The technologies developed here are applicable not just to earth observation, but to planetary missions as well. Because of the aforementioned difficulties with satellite attitude control, the NACHOS scientific mission, at the time of this writing, is only just getting started. We are hopeful that the coming year of observations will see many more exciting results.

Acknowledgments

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