CHAPS: A COMPACT HYPERSPECTRAL IMAGER FOR AIR POLLUTION REMOTE SENSING

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ABSTRACT

Current and planned low Earth orbiting and geostationary satellite instruments provide global surveys of air quality characteristics and trends. Targeted pollution observations with even finer spatial and potentially temporal resolution could better characterize, quantify, and monitor emissions from urban areas, power plants, and other anthropogenic activities, with both scientific and societal benefits. The Compact Hyperspectral Air Pollution Sensor (CHAPS) is an imaging spectrometer in a CubeSat form factor. The instrument is designed to make measurements of atmospheric composition at 300–500 nm at unprecedented spatial resolution from low Earth orbit (1×1 km^2). The CHAPS–Demonstrator (CHAPS-D) instrument prototype is enabled by freeform optics and additive manufacturing, deriving optical heritage from TROPOMI. Freeform optics has potentially huge advantages over traditional optical designs, including fewer optical surfaces and lower mass and volume, while maintaining optical performance, and CHAPS-D will fit within the design constraints of a 6U CubeSat. The CHAPS-D mechanical structure and some optical elements will be fabricated using additive manufacturing, using a next-generation aluminum alloy. The project will culminate in an airborne demonstration of CHAPS-D, with 40-m spatial resolution. We will retrieve NO_2, SO_2, HCHO, ozone, and other trace species relevant to air quality from solar backscatter measurements.

1 INTRODUCTION

Exposure to ambient air pollution is a leading risk factor in premature death globally [1,2], and air pollution/quality measurement, prediction, and mitigation are therefore essential. The air pollutants linked closely to mortality are PM2.5, ozone, and nitrogen dioxide (NO_2). Nitrogen dioxide is a toxic gas at high concentrations, a marker for combustion-related pollutants and co-emitted air toxins, and is the main precursor of tropospheric ozone and nitrate aerosols. Satellite measurements of NO_2 vertical column density (VCD) have been widely used in studies of atmospheric chemistry, air quality, and climate (through its impact on greenhouse gas trends and lifetimes). Measurements of tropospheric VCDs have also been used to reveal the sources, spatial patterns, and trends of NO_x ($NO+NO_2$) emissions [3,4], NO_x lifetimes [5,6], the impact of population and economic activity on air quality [7], and environmental justice issues [8].

There are structured spectral absorption features at ultraviolet and visible wavelengths between 300 and 500 nm that have been readily exploited for the remote sensing of NO_2 [9,10], water vapor [11], glyoxal [12], and clouds [13]. The first satellite remote sensing of NO_2 was performed by the Global Ozone Monitoring Experiment (GOME) instrument (1995–2003) [14]. Several other satellite missions have since measured NO_2 from low Earth orbit (LEO) as well, most recently the Aura/Ozone Monitoring Instrument (OMI) [15,16] and the TROPOspheric Monitoring Instrument (TROPOMI) [17]. These missions have prioritized global coverage over spatial resolution and diurnal sampling. Satellites in geostationary orbit (GEO) from the U.S., Europe, and Korea (i.e., Tropospheric Emissions: Monitoring of Pollution (TEMPO), Sentinel-4, Geostationary Environment Monitoring Spectrometer (GEMS)) will provide diurnal observations at finer spatial resolution but over limited geographic regions. The finest spatial resolutions of current and planned missions (e.g., 3.5×5.5 km^2 for TROPOMI and >2.1×4.7 km^2 for TEMPO) are a huge improvement over the past generation of instruments but are still insufficient to adequately avoid cloud obscuration and effectively resolve NO_2 point emission sources clustered in urban areas. Finer spatial resolution—of 1×1 km^2—would greatly improve our ability to measure pollution emissions [18].

The Compact Hyperspectral Air Pollution Sensor (CHAPS) is a small imaging spectrometer intended for targeted, science-quality measurements of air pollution at unprecedented spatial resolution from LEO (1×1 km^2) [19], making pushbroom measurements of solar backscattered radiance and using established remote sensing techniques [20]. This would greatly improve our ability to measure pollution emissions and enable detection of emissions plumes directly from a single overpass, without statistical post-processing. The compact size and cost-effectiveness of CHAPS makes a small satellite instrument or hosted payload feasible. As a constellation or in combination with the larger satellites, CHAPS would address such issues as the short-term evolution of pollution, turbulent mixing of air pollution plumes, "top-down" quantification of point-source emissions, and pollution transport and chemical processing. One possible future scenario is a heterogenous constellation of CHAPS instruments, each with optical characteristics (e.g., wavelength range/resolution, spatial resolution, field of view, signal-to-noise ratio) tuned for particular species of interest, including NO_2, SO_2, O_3, CH_2O, methane, CO, aerosols, clouds, or combinations thereof (considering CHAPS instruments making measurements over targeted wavelength ranges between 270 and 2400 nm). CHAPS will complement existing and future trace gas surveyors, such as TEMPO and TROPOMI, with a finer spatiotemporal resolution than is possible currently or otherwise anticipated from other space-based platforms.

CHAPS-D is the CHAPS airborne demonstrator. Although CHAPS-D will focus on the 300–500-nm spectral range, the freeform optics design demonstrated will be generalizable to other wavelengths between 270 and 2400 nm, making it applicable to a wide variety of Earth and space science problems.

2 CHAPS-D

2.1 Requirements

The primary requirements that drive the CHAPS/CHAPS-D design are summarized in Table 1. The signal-to-noise (SNR) requirement of CHAPS is lower than typical surveyors such as Aura/OMI and TROPOMI. Analysis (not shown) indicates that an SNR of 500 would ensure that the absolute noise error in retrieved NO_2 column density along the light path is below 1×10^{15} molecules cm^{-2}, which is considerably lower than typical total NO_2 vertical column density. The fact that CHAPS will target higher concentrations associated with pollution sources will also mitigate the smaller SNR. The SNR requirement is driven by NO_2; spatial binning may be necessary with other trace species to achieve acceptable SNR for high-quality retrievals.

Table 1. CHAPS (space) and CHAPS-D (aircraft) primary requirements.

Parameter	Value	Driver
Spatial sampling	<1 km (space) <40 m (aircraft)	Adequate isolation of individual pollution sources
Swath width (across track)	100 km (space) 400 m (aircraft)	Adequate coverage of urban environments
Wavelength range	300–500 nm	Retrievals of NO_2, SO_2, ozone, glyoxal, cloud absorption features in this range
Wavelength resolution	0.6 nm	Needed to resolve trace gas absorption features
Spectral oversampling	>3×	Needed to resolve trace gas absorption features
Signal-to-noise ratio	>500 @ 405–460 nm	Spectral resolution and oversampling needed for NO_2 retrieval

2.2 Technologies

CHAPS-D leverages two emerging technologies, to enable the needed miniaturization for CHAPS: freeform optics and additive manufacturing (AM, or 3-D printing). Freeform optics is an emerging technology with potentially huge advantages over traditional optical designs, including fewer optical surfaces, lower mass and volume, and improved image quality [21,22]. Freeform optics have been flown in space, in the TROPOMI telescope. An all-reflective design based entirely on freeform mirrors has been chosen for CHAPS-D—a much smaller instrument. Freeform optics allows us to achieve a very compact design and accommodate the anamorphism resulting from the instrument viewing requirements.

Our approach with CHAPS-D is to additively manufacture the entire mechanical housing, including optical mounting fixtures and light baffles. Traditional, subtractive machining methods (milling, turning, etc.) impose design limitations; small increases in geometric complexity cause large increases in fabrication cost and lead time. Additive manufacturing can produce very complex shapes impossible to make using traditional approaches. AM also has a number of potential advantages when combined with topology optimization. These include reduced mass, greater simplicity (fewer sub-parts or assembly steps), greater mechanical strength/stiffness, the ability to tune the design for vibration resonance and thermal properties (conductivity/insulation), and manufacturability. Next-generation aluminum alloys were evaluated for CHAPS-D, to extend the structural performance beyond that of typical aluminum–silicon while maintaining compatibility with conventional optical processes. Our design includes internal light baffles, which ideally are black, either by painting or anodization. We would also like the option of additively manufacturing the optical mirrors themselves, which requires compatibility with NiP plating and single-point diamond turning to produce a smooth, high-quality optical surface. With a mix of traditional and AM components, a coefficient of thermal expansion close to that of 6061 Al is also required.

The CHAPS-D instrument design is shown in Figure 1. We imposed the design constraints for the payload of a 6U CubeSat (4U payload volume). The instrument itself is printed in two pieces: telescope and spectrometer. The freeform mirrors are fabricated from wrought aluminum. After machining, the mirrors receive NiP plating, followed by single-point diamond turning to achieve the desired freeform shapes, and are finally coated with optical coatings. Although the baseline design uses conventionally manufactured freeform mirrors, we are exploring the use of AM mirrors as well, with an internally latticed structure, to reduce mass. If they perform as anticipated, two of the mirrors in CHAPS-D will be AM mirrors.

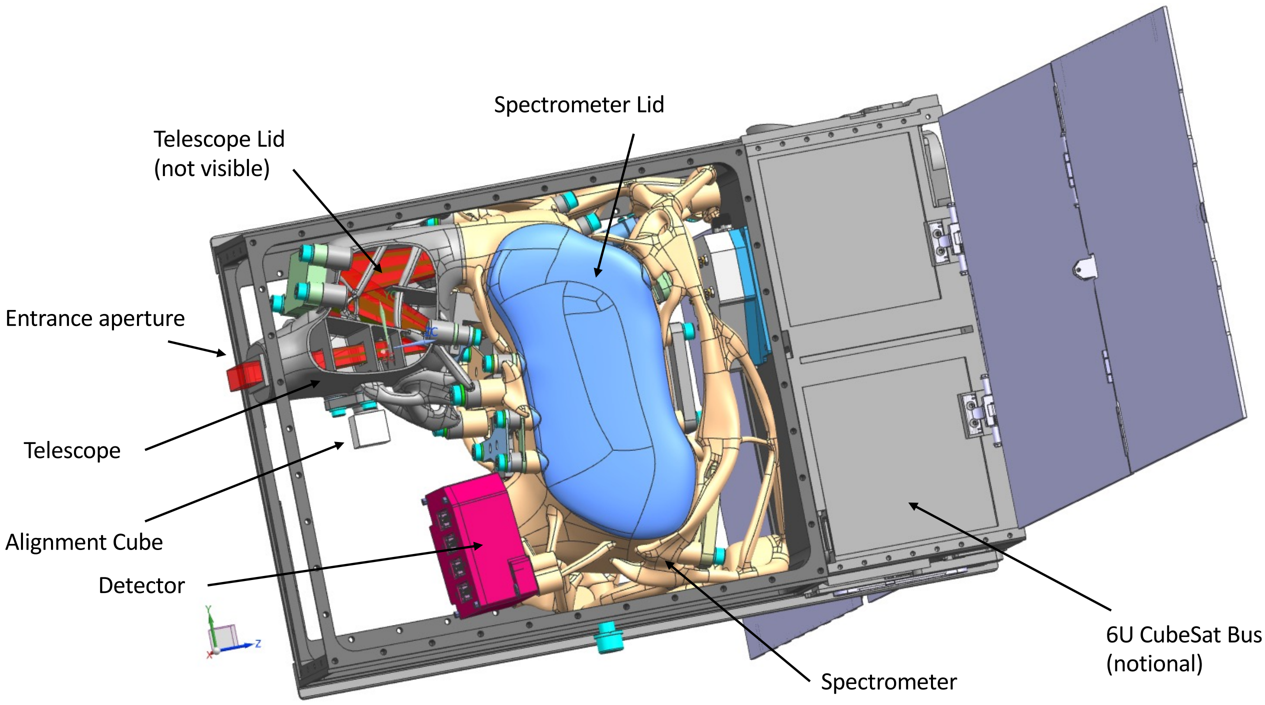

Figure 1. CHAPS-D instrument design, contained within a notional 6U CubeSat. The telescope (gray) and spectrometer (yellow) are additively manufactured, following topology optimization.

To meet CHAPS/CHAPS-D requirements, we found Scalmalloy to be the best AM aluminum alloy candidate among those tested. In addition to meeting our tensile property, print quality, and thermal requirements, Scalmalloy is also compatible with Aeroglaze Z306 paint (not shown) and optical mirror post-processing. In Figure 2, a series of one of CHAPS-D's mirrors, additively manufactured, is shown. Both solid and internally latticed variants are being tested, and preliminary results indicate that the AM mirrors will meet CHAPS-D requirements.

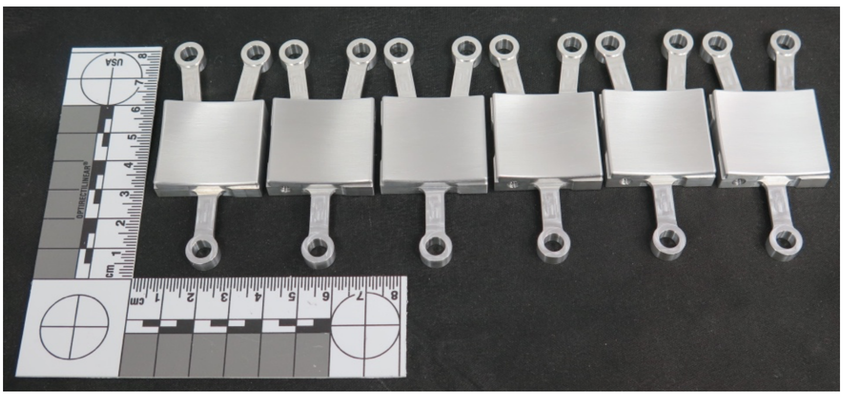

Figure 2. Additively manufactured CHAPS-D optical mirrors, after 3-D printing and coarse machining; before NiP plating and single-point diamond turning.

3 CONCLUSIONS

CHAPS is a hyperspectral imaging spectrometer for measuring atmospheric trace gases from low Earth orbit. It will characterize, quantify, and monitor emissions from urban areas, power plants, smelters, oil and gas refineries, and other anthropogenic activities. With an initial primary focus on

NO_2, CHAPS-D will measure the spectrum of the Earth-reflected radiance from 300 to 500 nm. The instrument development, flight demonstration, and validation (ultimately the retrieval of vertical column densities of NO_2 and comparison with independent correlative measurements) at airborne altitude will provide both the proof-of-concept and costing history necessary for future application of such sensors.

Compared to current and planned spaceborne air pollutions sensors, the CHAPS instrument has finer spatial resolution and represents a significant reduction in the size, mass, power, and cost of a hyperspectral imaging spectrometer—suitable for deployment in a 6U CubeSat. As a result, it can be flown on a much smaller platform than has been realized previously, with substantially lower cost, greater ease of use, and/or with a lower deployment risk posture. This makes a multiple-instrument satellite constellation feasible, with much higher spatial resolution.

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