CHAPS-D: The Compact Hyperspectral Air Pollution Sensor–Demonstrator

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Spatial resolution is critical for understanding air pollution emissions and evolution, cloud avoidance

Figure 1: NO$_2$ VCD measured by AirMAP in the morning ($\approx$07:30–09:30 UTC) of April 21, 2016, averaged to a horizontal resolution of (a) 0.1 x 0.1 km$^2$, (b) 0.5 x 0.5 km$^2$, (c) 1 x 1 km$^2$, and (d) 3.5 x 7 km$^2$.

2. Setup for the sensitivity study

To determine the optimal space-based resolution for the estimation of NO$_x$ emissions using the total tropospheric NO$_2$ column amount from urban sources, we adopt a pragmatic approach. This is because the size of NO$_2$ plumes depends on several factors, namely the size and distribution of urban sources, the wind speed and direction, the processes that mix the air from the source into the wind flow, which are in part turbulent, etc. Consequently, to determine the optimal resolution:

- more cloud-free observations
- effectively separate clustered point sources in polluted regions
- understand mixing of emissions, their transport and transformation; short-term evolution of pollution plumes

[CHAPS (~5 kg; 1x1km$^2$) miniaturized, targeted, science-quality]

1 x 1 km$^2$ resolution provides:

- more cloud-free observations
- effectively separate clustered point sources in polluted regions
- understand mixing of emissions, their transport and transformation; short-term evolution of pollution plumes

Fujinawa et al., 2019
Freeform optics enables miniaturization

- **Freeform optics**: An optical surface that lacks translational or rotational symmetry
- Freeform optics offers superior optical aberration correction, compared to spherical and aspherical alternatives
- In an imaging spectrometer, this has several advantages
  - spectral band broadening: increased spectral range
  - spatial broadening: increased slit length (and swath width)
  - increased compactness: unprecedented miniaturization

![Example freeform surface shapes](image)

**TROPOMI (launched 2017)** with TNO optics
Awesome, yes, but big, kitchen sink, global surveys

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**Table 2**

<table>
<thead>
<tr>
<th>Performance metric</th>
<th>Value (max/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal RMS WFE</td>
<td>0.033/0.066</td>
</tr>
<tr>
<td>As-built RMS WFE</td>
<td>0.058/0.066</td>
</tr>
</tbody>
</table>

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**Figure 7**

- Example freeform surface shapes (departures from base spheres) [Reimers et al., 2017]
Proposed investigation

- Design, fabricate, calibrate, and test prototype CHAPS-D, conforming to 6U constraints and space requirements, where reasonable
- Conduct ground-based, zenith-sky measurements as a real-world test of the instrument under controllable conditions and ambient pollution at GSFC
- Fly CHAPS-D on the NASA B200 King Air from LaRC, making nadir observations of tropospheric pollution
- Retrieve tropospheric NO$_2\,*$ vertical column density using well-established techniques, demonstrating end-to-end capability
- Compare retrieved NO$_2\,*$ (and others) with correlative measurements on the ground, potentially from another instrument co-manifested on the aircraft and operational space products from OMI and TROPOMI
- Use lessons learned to improve the CHAPS design and define the spacecraft interface requirements

\*Also SO$_2$, ozone, glyoxal, clouds

CHAPS-D[emonstrator]
(this IIP)
Altitude ~8 km
Spatial resolution ~40 m

CHAPS
(future project)
Altitude 400–600 km
Spatial resolution ~1 km

Driving requirements: Science-quality measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial sampling</td>
<td>&lt;1 km (space) &lt;40 m (aircraft)</td>
<td>Adequate isolation of individual pollution sources</td>
</tr>
<tr>
<td>Swath width (across track)</td>
<td>100 km (space) 400 m (aircraft)</td>
<td>Adequate coverage of urban environments</td>
</tr>
<tr>
<td>Wavelength range</td>
<td>300–500 nm</td>
<td>Retrievals from NO$_2$, SO$_2$, ozone, glyoxal, cloud absorption features in this range</td>
</tr>
<tr>
<td>Wavelength resolution</td>
<td>0.5 nm</td>
<td>Needed to resolve trace species absorption features</td>
</tr>
<tr>
<td>Spectral oversampling</td>
<td>&gt;3x</td>
<td>Needed to resolve trace species absorption features</td>
</tr>
<tr>
<td>Signal-to-noise ratio</td>
<td>500</td>
<td>SNR required for spectral resolution and oversampling of NO$_2$</td>
</tr>
</tbody>
</table>
Preliminary optical layout meets requirements and fits within a 4U (payload) volume

CHAPS-D is a push-broom sensor.
Next steps

• CHAPS-D currently in design phase
  - Working on preliminary optical design and packaging, detector selection
  - CDR Dec 2020

• Exploring the use of additive manufacturing (AM), which provides a number of potential advantages
  - Use topology optimization for mass, thermal, vibration, and (additive) manufacterurability
  - Internal baffling fine structure (critical for stray light control) is very amenable to AM
  - Reduces complexity of housing (idea: AM entire housing and baffling in one go)
  - AM of the mirrors would reduce mass
  - Reduces manufacturing time and cost of future instruments