High Performance Spectroscopic Observation from Nanosats

Chad Fish  
Alan Marchant*  
Erik Stromberg  
Stephanie Sullivan

*Utah State University
Hyperspectral Imaging

What is HSI

- Hyperspectral data cube: 2D data covering 2 spatial axes and spectrum.
- Wavelength resolution < 1%.

CubeSat HSI Opportunities

- Agricultural resource monitoring.
  vegetation, stress, mineralogy . . .
- Ocean and litoral monitoring.
  plankton, pollutants, bathymetry . . .
- Temperature profiling of the lower thermosphere.
  high-resolution (< 1 nm) spectroscopy of O2 A-band emission

- Monitoring of energetic events.
  * e.g. explosions or ordinance
  * MWIR signatures w/ moderate resolution
  * “snapshot hyperspectral”
  * high frame rate for hypertemporal signature

- Spatial resolution < 20 m

Need: miniaturized HSI instruments w/ high spectral resolution.
Other Spectroscopic Observations

Gas Sensing
- Airglow emission lines and bands.
  - Spectral features indicative of temperature and dynamic processes in the thermosphere.
  - Dominant emission bands from OH, O₂, NO, and N₂⁺ occur in the SWIR.
- Molecular absorption bands.
  - Trace atmospheric gases indicated by absorption bands in sunlight reflected from the earth.

Spectrophotometery
- Radiometrically accurate w/ calibrated bandpass.
- Thermometry and mixed surface modeling.

Atmospheric Sounding
- Solar occultation of the earth limb for trace gas profiling.

Doppler Sensing
- Wavelength precision ±0.03 pm.
- Thermosphere wind observation from passive observation of an atomic airglow line.
- Lower atmosphere winds based on molecular band.

Need: miniaturized sensors for radiometric or Doppler observation at target wavelengths.
Design Challenges

Architecture Constraints for a Nanosat Instrument

- Instrument Cost
  consistent with mission budget; COTS components incl. FPA

- Instrument Size
  e.g. 10x10x15 for a 3U CubeSat
  stray light control in a small package

- Power Consumption, avg. and peak
  6 W OAP from 5 panels on a 3U CubeSat

- Restrict Downlinked Data
  < 1 GB/day

- Static Instrument Attitude
  avoid high-speed slewing or scanning
  no precision mechanisms

- Low-power thermal control
  passive spacecraft thermal control
cryocoolers – size, cost, power, thermal, vibration
Filter-based Instruments

Gas Filter Correlation Radiometer (GFCR)
- ratio two images, with/without a gas filter
- sensitive to trace gas concentrations in the scene
- signal combines effects of multiple lines in a molecular band
- requires radiometric SNR ~ 1000, enhanced by image processing
- simple optics

Linear Variable Filter (LVF) Spectrometer
- narrow-band filter with graded layer thicknesses
- apply filter to FPA or an intermediate focal surface
- scan target scene parallel to filter gradient; accumulate a skewed HSI cube
- limited spectral resolution at high F#, $\Delta \lambda / \lambda \sim 0.05/F#^2$

![Diagram of filter-based instruments](image-url)
Optical Profiling of the Atmospheric Limb (OPAL)

Mission:
- dynamic profiling of the lower thermosphere, 90 – 160 km
- resolve detail of the O2 A-band emission line
- OPAL constellation with overlapping FOVs

Snapshot HIS
- complete (sparse) HSI datacube in one frame
- resolution tradeoff: 9 horizontal samples; limited spectrum (12 nm / 1.64 Å/pixel = 73 pixels)

Refractive Dispersive Spectrometer
- wide field of view
- achromatic correction not required
- holographic grating provides strong dispersion
- bandpass filter passes 750 – 770 nm
- slit array defines the horizontal FOV

9-slit array

Holographic grating

Lab demo, viewing Hg 577 nm doublet

Spatially resolved
Multiple separate spectra

SmallSat, Aug 2013
OPAL Performance and Missions

Sensor Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>spectral band</td>
<td>758 – 770 nm</td>
</tr>
<tr>
<td>focal length</td>
<td>50 mm</td>
</tr>
<tr>
<td>spectral resolution</td>
<td>0.25 - 0.5 nm</td>
</tr>
<tr>
<td>vertical FOV</td>
<td>2.5 deg</td>
</tr>
<tr>
<td>vertical IFOV</td>
<td>0.3 mrad</td>
</tr>
<tr>
<td>horizontal FOV</td>
<td>11 deg</td>
</tr>
<tr>
<td>horizontal sampling</td>
<td>1.4 deg</td>
</tr>
<tr>
<td>sampling period</td>
<td>20 s</td>
</tr>
<tr>
<td>size</td>
<td>3U spacecraft</td>
</tr>
</tbody>
</table>

Mission Capabilities

- thermosphere temperature profiling, 90 – 160 km
- neutral temperature resolution altitude dependent
- thermosphere dynamics, $\Delta t \sim 10$ min (from a constellation)
- science questions: solar storm energy coupling; dynamics of atmospheric waves
The stray light problem:

- limb brightness in the O2 A-band (758 – 760 nm) @ 100 km tangent height
  ~ 5,000 kRayleigh = 4.0E8 photon/cm^2/s/sr
- brightness of sun-illuminated cumulus cloud (same spectral band)
  ~ 15,000,000 kRayleigh
- cloud spectrum includes A-band absorption
- earth limb only ~ 2° above the cloud layer for sensor at LEO
- Will the A-band emission spectrum be overwhelmed by day-time stray light?

Solution:

- minimal aperture size; pop-up baffle tube; flip-up fold mirror; moderate attitude control
- daytime stray light reduced to < 1%

Stray light principles:

- dominated by small angle scattering (veiling glare) due to surface roughness
- one mirror is 8x worse than two lens surfaces
- ghost analysis and AR coating for refractive surfaces
- defective area on a 40/20 surface is < 0.1%; problematic only when surface is near focus
Split-field Etalon Doppler Imager (SEDI)

Wind profiling by passive Doppler imaging
- OI-630, day/night emission, 200 – 350 km
- narrow atomic line, thermal width ~ 6 pm
- imaging interferometer
- triangulate wind from fore and aft limb views

Imaging through a Fabry-Perot etalon.
- gap ~ 10 mm with moderate finesse to resolve line
- air gap with ULE spacer stabilizes the modes
- position etalon in collimated space then focus onto an FPA; image is a product of interferogram x scene
- spatial shift of fringes → Doppler shift

Split-field optics
- two Doppler images, simultaneously

On-board calibration
- neon glow-lamp Jones source, 630.5 nm

EMCCD
- faint emission requires a photon-sensitive camera
Sensor Performance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Doppler resolution</td>
<td>±10 m/s</td>
</tr>
<tr>
<td>Doppler range</td>
<td>±1,000 m/s</td>
</tr>
<tr>
<td>vertical FOV</td>
<td>4.1 deg</td>
</tr>
<tr>
<td>vertical resolution</td>
<td>2.4 mrad</td>
</tr>
<tr>
<td>horizontal FOV</td>
<td>2.6 deg (fore &amp; aft)</td>
</tr>
<tr>
<td>sampling period</td>
<td>70 s</td>
</tr>
<tr>
<td>size</td>
<td>6U spacecraft</td>
</tr>
</tbody>
</table>

Mission Capabilities

- wind profiling, 200 – 250 km (2D horizontal velocities)
- neutral temperature profiling (based on line width)
- wind dynamics (SEDI constellation)

![Diagram showing sensor orientation and modes of operation](image)
CubeSat Form Factor for SEDI + OPAL

Operational synergy
- Combined dynamics of energy input and driven atmospheric flows.
- Temperature profiling in lower and middle thermosphere.
- Multiple constraints on space weather models.

Two instruments in a 6U payload
- common orbit requirements, mid-inclination LEO
- fixed attitude
- no moving parts (after shade deployments)
Energetic Event Spectral Imager (EESI)

Spatial Heterodyne Interferometer

- FTS with no moving parts
- OPD varies along one axis
- spectral resolution limited by FPA size
- no slit; high optical efficiency

Snapshot or scanned collection

- cylinder lens used to image pupil at focal plane (1D or 2D)
- collect simultaneous spectrum
- one spatial axis

Two orthogonal instruments (X & Y)

- match events wrt time & spectrum
- intersection → 2D location
- multiple events are distinguishable
- energetic events are sparse in the SWIR band
## EESI Capabilities and Missions

### Mission Capabilities
- simultaneous hyperspectral and hypertemporal characterization of energetic events
- localization of multiple simultaneous target events
- analysis of event size, temperature, dynamics, and chemistry
- suggested applications:
  - battlespace monitoring
  - lightning dynamics
  - cosmic ray showers

### Sensor* Performance

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>spectral band (SWIR)</td>
<td>1 – 5 μm</td>
</tr>
<tr>
<td>spectral resolution</td>
<td>&lt; 30 nm</td>
</tr>
<tr>
<td>FOV</td>
<td>1.4°, 12 km</td>
</tr>
<tr>
<td>spatial resolution</td>
<td>40 μrad, 20 m</td>
</tr>
<tr>
<td>temporal resolution</td>
<td>5 ms</td>
</tr>
<tr>
<td>size</td>
<td>3U spacecraft</td>
</tr>
</tbody>
</table>

* tactical sensor @ LEO, 8 cm aperture

Note: spatial heterodyne spectroscopy is applicable generally to light-starved HSI missions.
Sophisticated optical instrumentation can be packaged into a nanosat payload.

Select from many options to achieve high spectral resolution.

A broad range of earth observation missions are enabled:

- atmospheric sounding (composition, temperature, clouds, etc)
- trace gas detection
- thermosphere science
- Doppler wind profiling
- hyperspectral earth monitoring
- tactical and strategic application