High Performance Spectroscopic Observation from Nanosats

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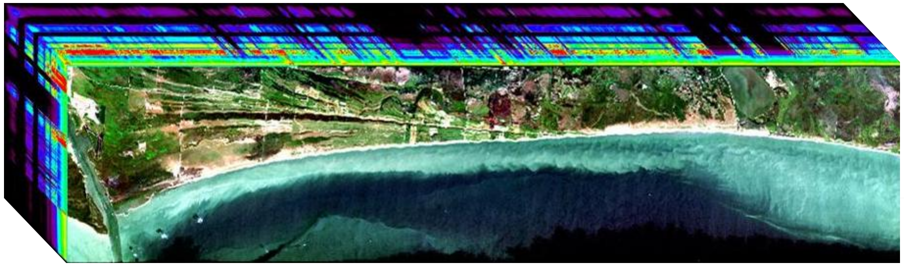
Hyperspectral Imaging

What is HSI

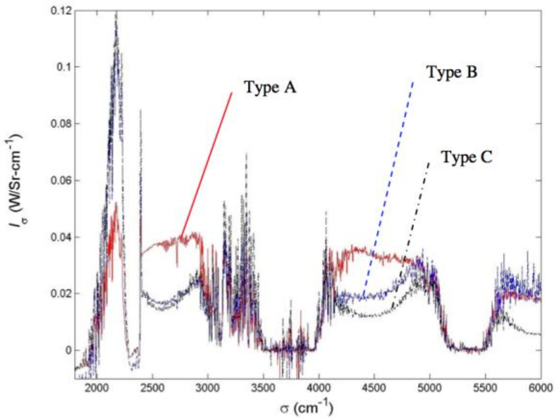
- Hyperspectral data cube: 2D data covering 2 spatial axes and spectrum.
- Wavelength resolution < 1%.

CubeSat HSI Opportunities

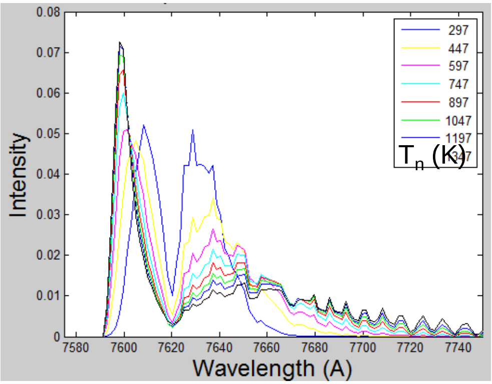
- Agricultural resource monitoring.
  vegetation, stress, mineralogy . . .
- Ocean and litoral monitoring.
  plankton, pollutants, bathymetry . . .
- Temperature profiling of the lower thermosphere.
  high-resolution (< 1 nm) spectroscopy of O2 A-band emission



LA coastline, AVIRIS, 0.4 – 2.5 mm, resolution 17 m x 10 nm



- 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

airglow against the earth limb

Gas Sensing

- Airglow emission lines and bands.

  Spectral features indicative of temperature and dynamic processes in the thermosphere.

  Dominant emission bands from OH, O_2, NO, and N_2^+ occur in the SWIR.

- Molecular absorption bands.

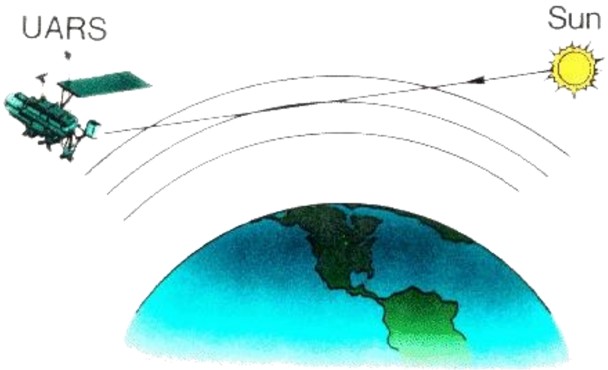
  Trace atmospheric gases indicated by absorption bands in sunlight reflected from the earth.

Spectrophotometery

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

Atmospheric Sounding

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



atmospheric sounding by radiometric solar occultation

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.

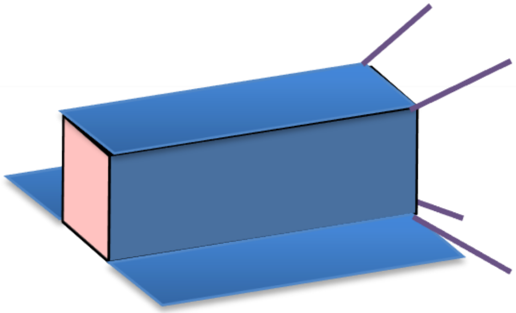
Need: miniaturized sensors for radiometric or Doppler observation at target wavelengths.

Design Challenges

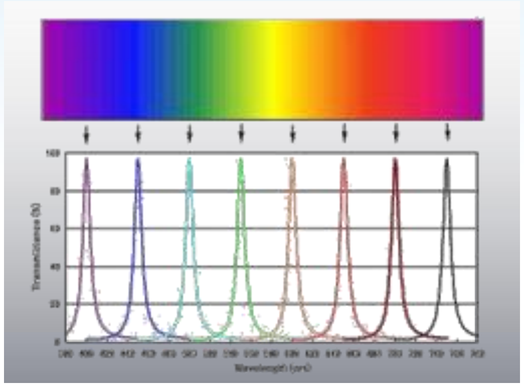
Architecture Constraints for a Nanosat Instrument

- 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

simplified ConOps



Filter-based Instruments

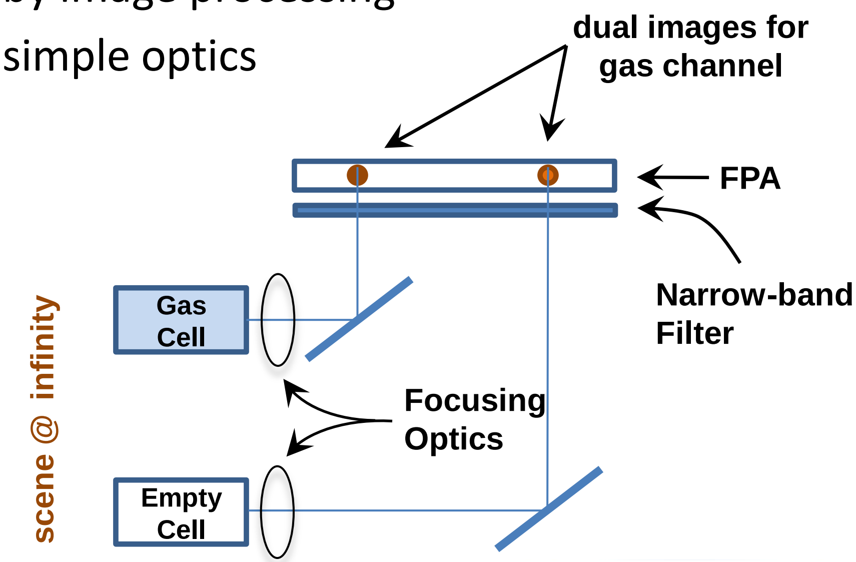


Linear Variable Filter (LVF) Spectrometer

- 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#, $\Delta\lambda/\lambda \sim 0.05/F\#^2$

Gas Filter Correlation Radiometer (GFCR)

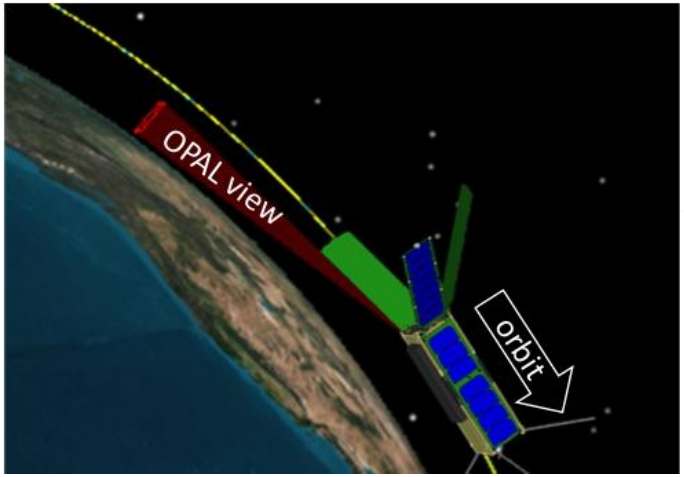
- ratio two images, with/without a gas filter
- sensitive to trace gas concentrations in the scene
- signal combines effects of multiple lines in a molecular band
- requires radiometric SNR ~ 1000, enhanced by image processing
- simple optics



Optical Profiling of the Atmospheric Limb (OPAL)

Mission:

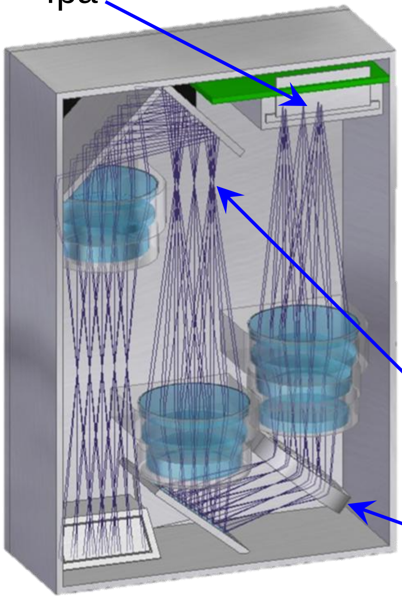
- dynamic profiling of the lower thermosphere, 90 – 160 km
- resolve detail of the O2 A-band emission line
- OPAL constellation with overlapping FOVs



Snapshot HIS

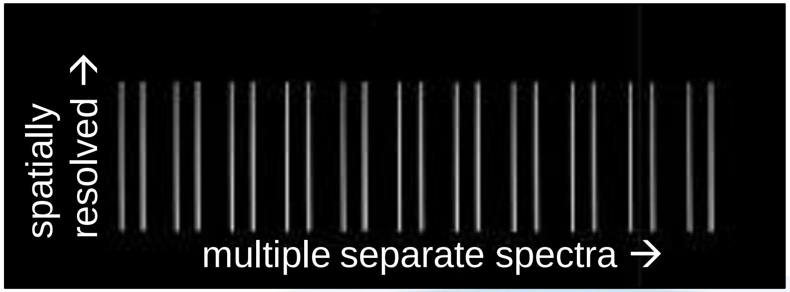
- complete (sparse) HSI datacube in one frame
- resolution tradeoff: 9 horizontal samples; limited spectrum (12 nm / 1.64 Å/pixel = 73 pixels)

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

lab demo, viewing Hg 577 nm doublet



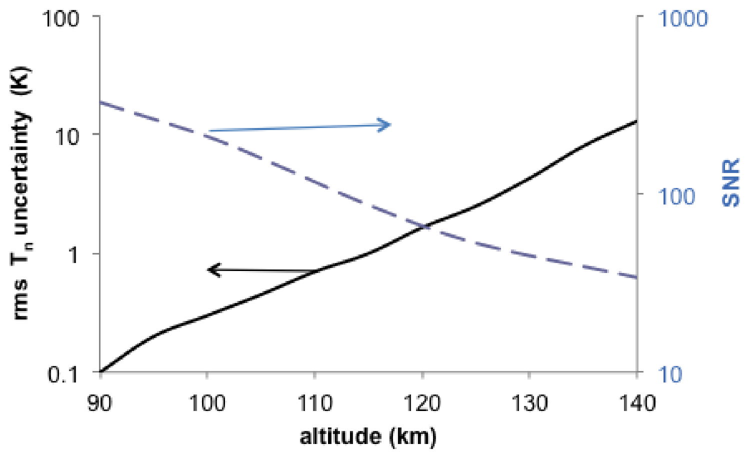
OPAL Performance and Missions

Sensor Performance

spectral band	758 – 770 nm
focal length	50 mm
spectral resolution	0.25 - 0.5 nm slit-width dependent
vertical FOV	2.5 deg
vertical IFOV	0.3 mrad
horizontal FOV	11 deg
horizontal sampling	1.4 deg
sampling period	20 s
size	3U spacecraft

Mission Capabilities

- thermosphere temperature profiling, 90 – 160 km
- neutral temperature resolution altitude dependent



- thermosphere dynamics, Δt ~ 10 min (from a constellation)
- science questions: solar storm energy coupling; dynamics of atmospheric waves

Stray Light Control

OPAL as an example

The stray light problem:

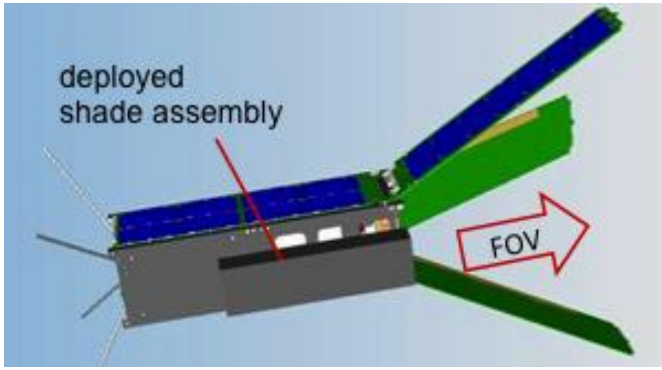
- limb brightness in the O2 A-band (758 – 760 nm) @ 100 km tangent height ~ 5,000 kRayleigh = 4.0E8 photon/cm^2/s/sr
- brightness of sun-illuminated cumulus cloud (same spectral band) ~ 15,000,000 kRayleigh
- cloud spectrum includes A-band absorption
- earth limb only ~ 2° above the cloud layer for sensor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

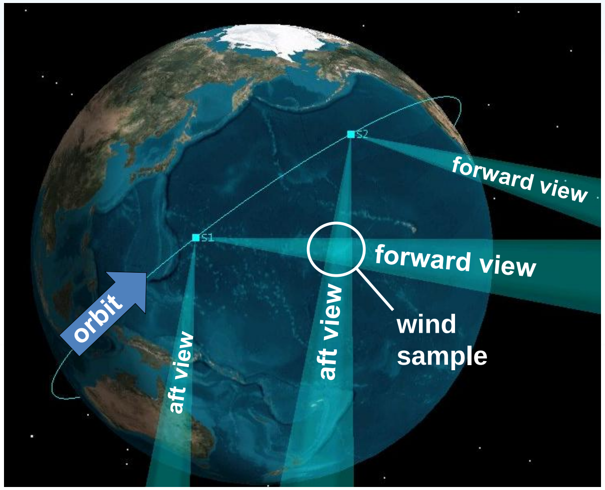
- dominated by small angle scattering (veiling glare) due to surface roughness
- one mirror is 8x worse than two lens surfaces
- ghost analysis and AR coating for refractive surfaces
- defective area on a 40/20 surface is < 0.1%; problematic only when surface is near focus



Split-field Etalon Doppler Imager (SEDI)

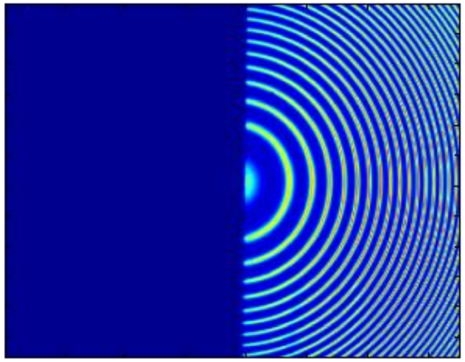
Wind profiling by passive Doppler imaging

- 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



calibration source illuminating the aft view

Split-field optics

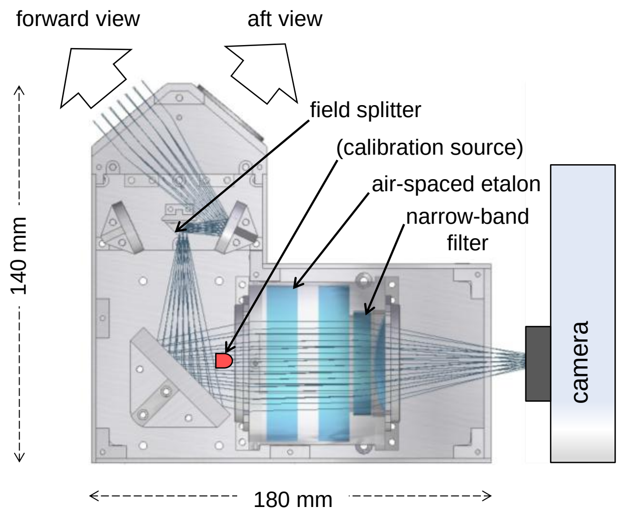
- two Doppler images, simultaneously

On-board calibration

- neon glow-lamp Jones source, 630.5 nm

EMCCD

- faint emission requires a photon-sensitive camera

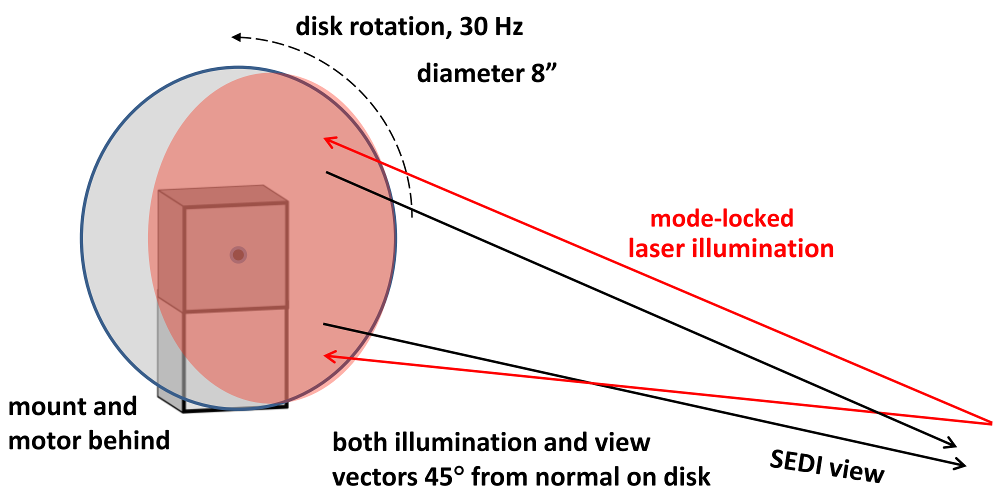


SEDI Performance and Missions

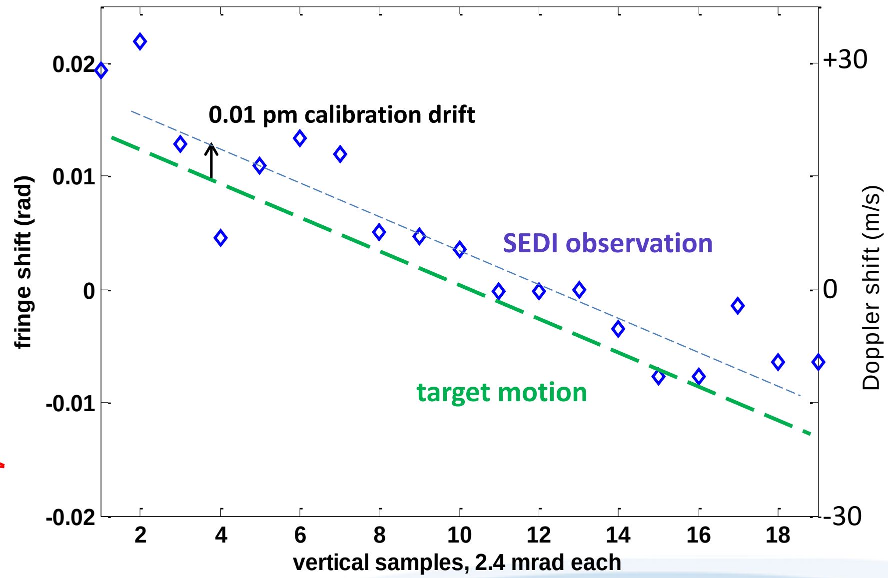
Sensor Performance	
Doppler resolution	±10 m/s
Doppler range	±1,000 m/s
vertical FOV	4.1 deg
vertical resolution	2.4 mrad
horizontal FOV	2.6 deg (fore & aft)
sampling period	70 s
size	6U spacecraft

Mission Capabilities

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



laboratory demonstration



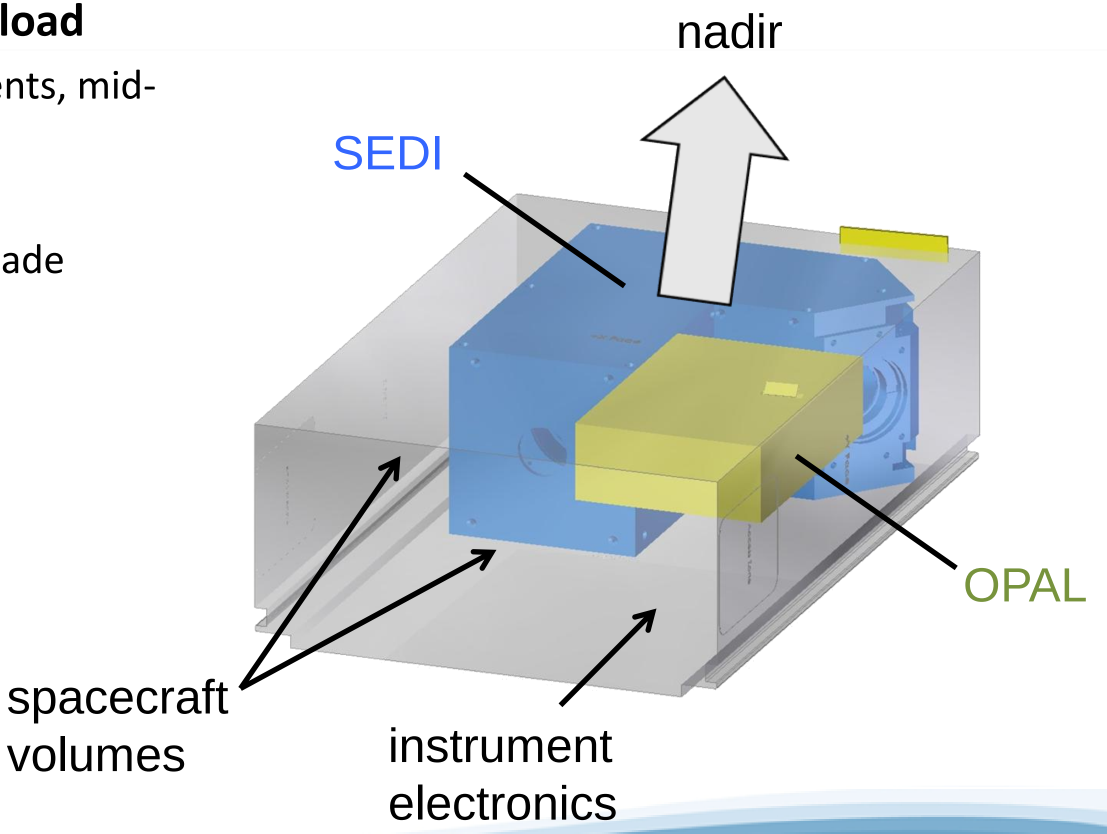
CubeSat Form Factor for SEDI + OPAL

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)



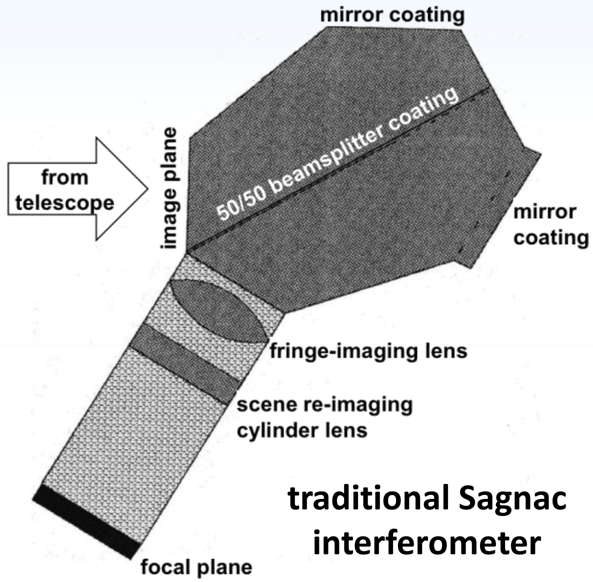
Energetic Event Spectral Imager (EESI)

Spatial Heterodyne Interferometer

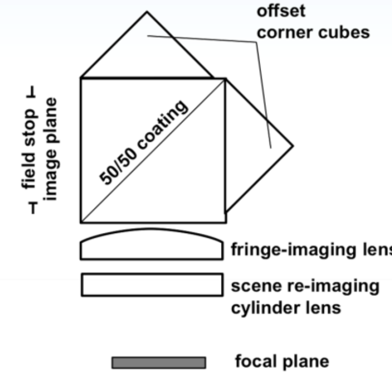
- FTS with no moving parts
- OPD varies along one axis
- spectral resolution limited by FPA size
- no slit; high optical efficiency

Snapshot or scanned collection

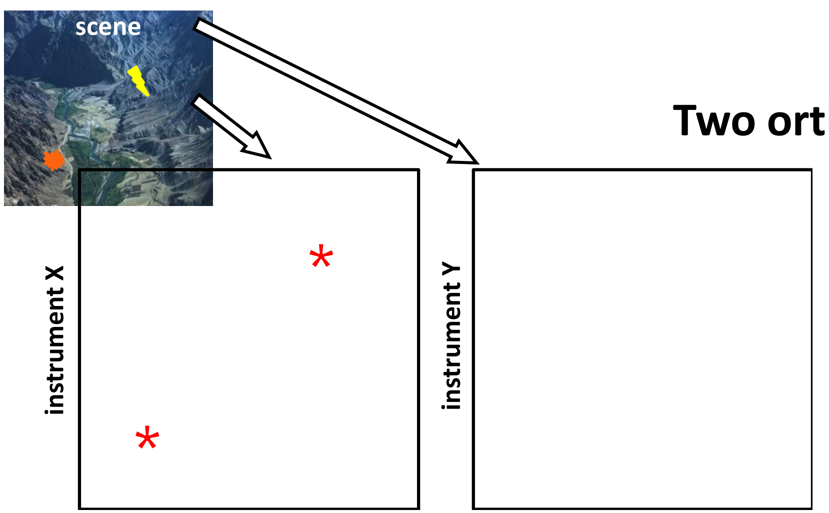
- cylinder lens used to image pupil at focal plane (1D or 2D)
- collect simultaneous spectrum
- one spatial axis



traditional Sagnac interferometer

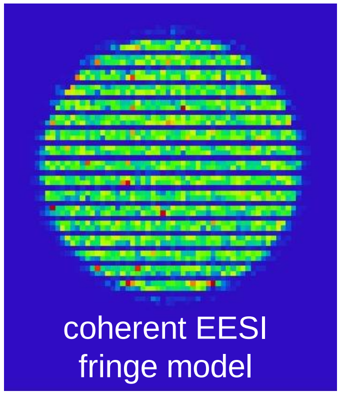


offset corner-cube interferometer
(compact / COTS components)



Two orthogonal instruments (X & Y)

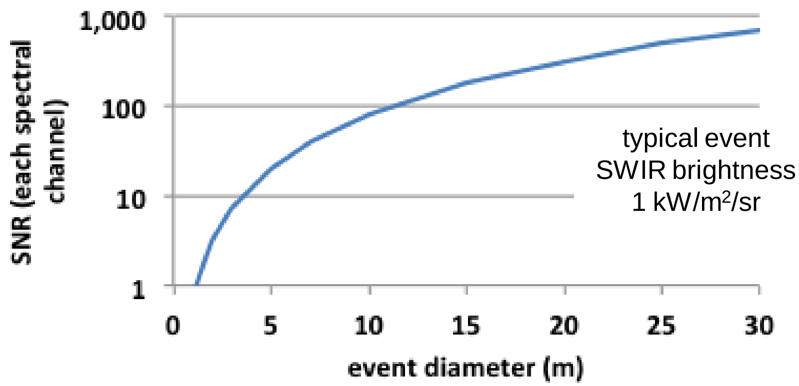
- match events wrt time & spectrum
- intersection → 2D location
- multiple events are distinguishable
- energetic events are sparse in the SWIR band



EESI Capabilities and Missions

Sensor* Performance	
spectral band (SWIR)	1 – 5 µm
spectral resolution	< 30 nm
FOV	1.4°, 12 km
spatial resolution	40 µrad, 20 m
temporal resolution	5 ms
size	3U spacecraft
issue: deployment & ConOps for continuous coverage	

* tactical sensor @ LEO, 8 cm aperture



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

Note: spatial heterodyne spectroscopy is applicable generally to light-starved HSI missions.

Summary

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