Optical Design of the Snow and Water Imaging Spectroscopy (SWIS) for small satellites and CubeSats

Pantazis Mouroulis
The SWIS Team
Jet Propulsion Laboratory
California Institute of Technology

Earth Science Technology Office

Overview

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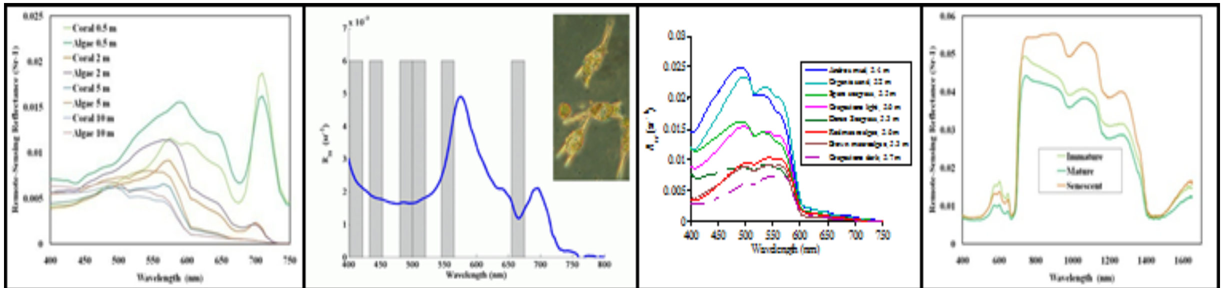
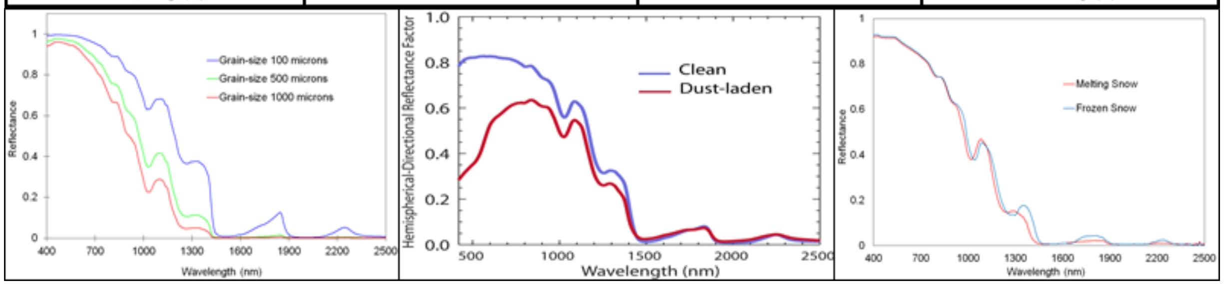
- Optical Design
  - *Spectrometer design*
  - *Telescope design*
- Stray light analysis
- Mechanical and thermal preliminary design
- CubeSat configuration
- Summary and Conclusions

Introduction



Coastal ocean spectral signatures (H. Dierssen), mainly below 900 nm



Snow spectral signatures (T. Painter) contain critical features in 1000-1500 nm range.

- Imaging spectrometry places heavy demands on satellite in terms of aperture size, data volume, and power resources
- Coastal ocean science and snow cover monitoring are two critical niche applications that can be potentially served by CubeSats
- To stay within CubeSat resources
  - No cryogenic temperatures (limits wavelength range)
  - Low data volume and rate (limits area coverage to specific target areas)
  - Limited spatial resolution / telescope aperture

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Research and applications

Utility examples

CubeSat:

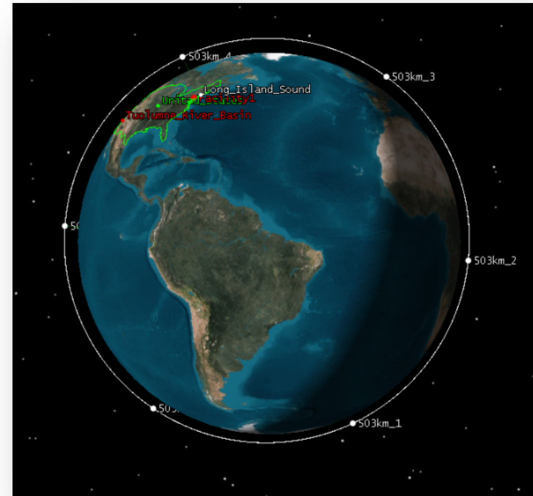
- 160 m resolution from 500 km
- ~2 year mission lifetime with no propulsion.
- Daily coverage with six CubeSats.
- Coasts and snow cover
- Global coverage at low (~1 km) resolution subject to future data transmission rate improvements

Small Sat

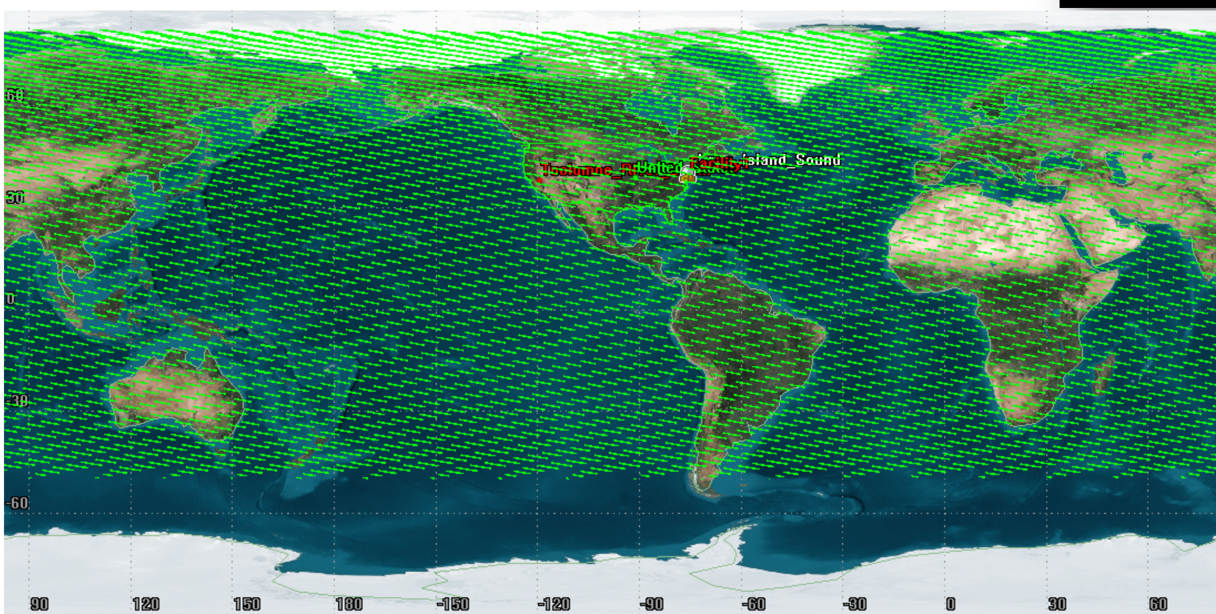
- 30-60 m resolution from 500 km
- 4 year mission lifetime
- Targeted areas only or seasonal variation
- Coasts, inland waters, estuaries, snow cover
- Low resolution global coverage conceivable

Research and applications: Mission example

Access any point on the globe on any given day



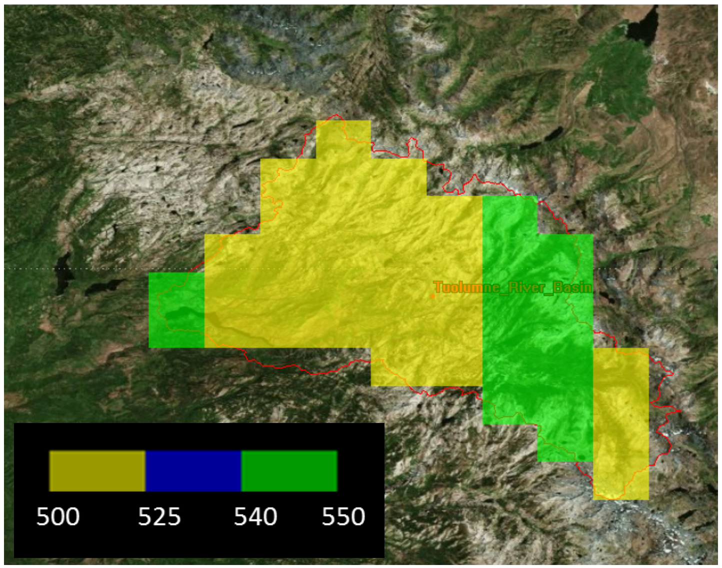
- Six CubeSats, 500 km orbit
- 10° Field of view
- 50° Field of regard with pointing

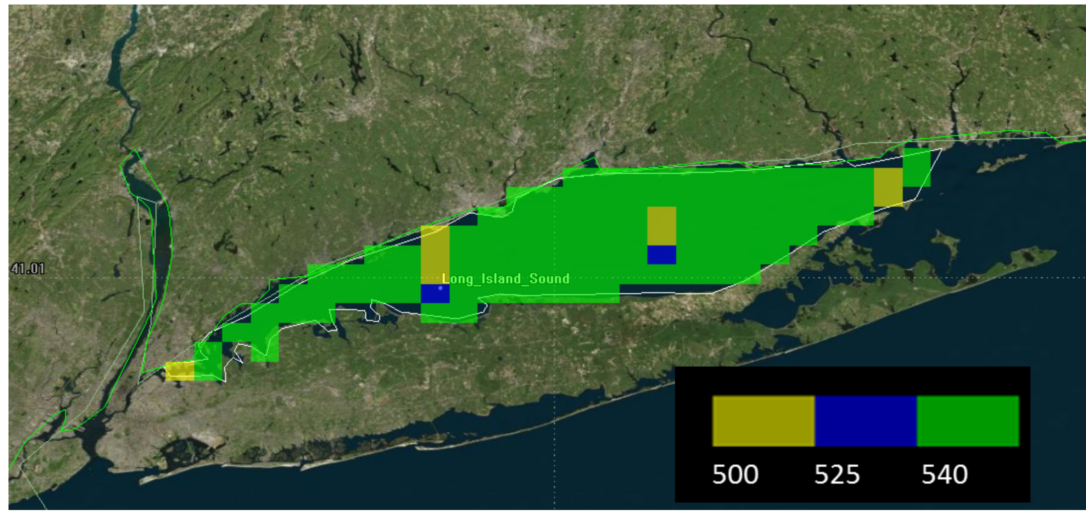


Daily coverage

Research and applications: Mission example

Coverage of Tuolumne River Basin (snow) and Long Island Sound (water)





TRB

LIS

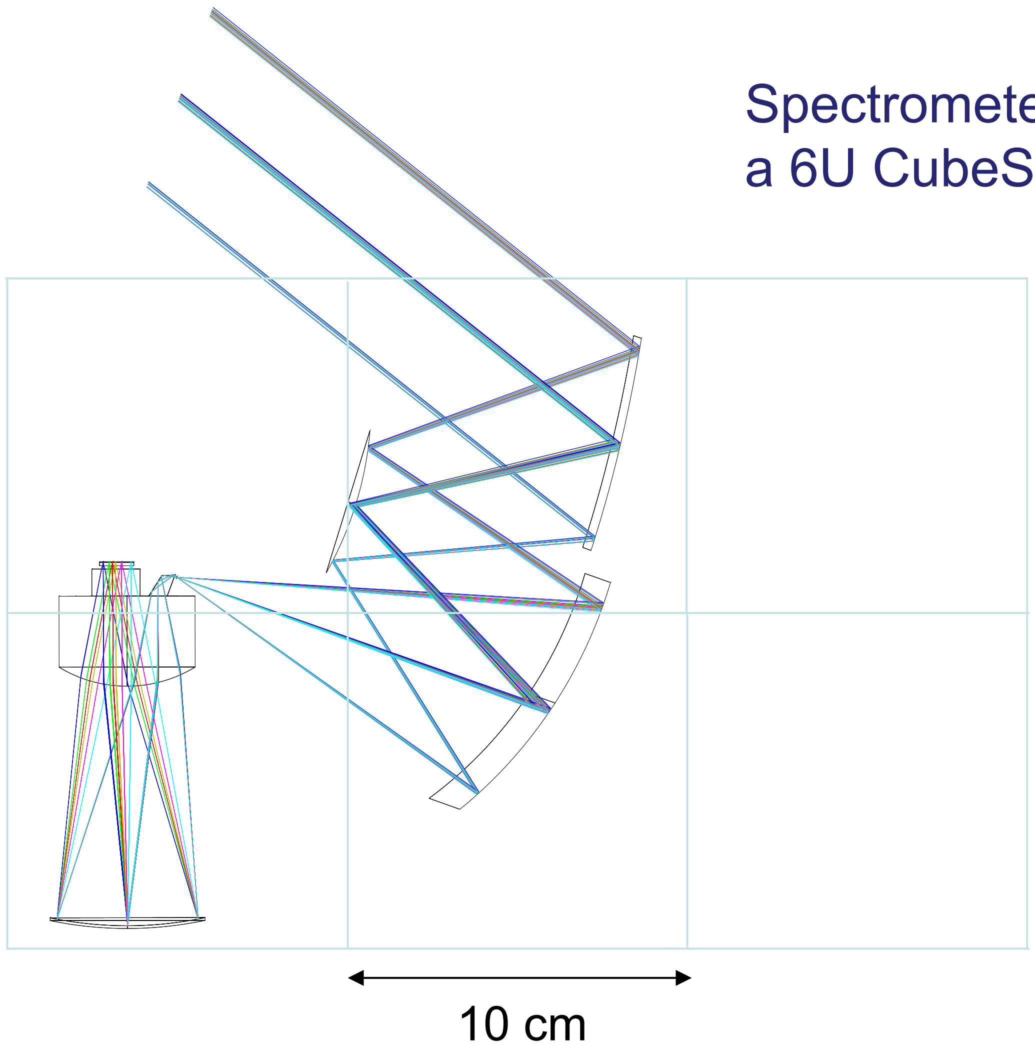
Maximum number of views per year with 50^o FOR

Over 100 views obtained for both cases without pointing (10^o FOV)

- **Episodic events can be covered with better than daily frequency**
- **Slower events (snow) can be covered without pointing**

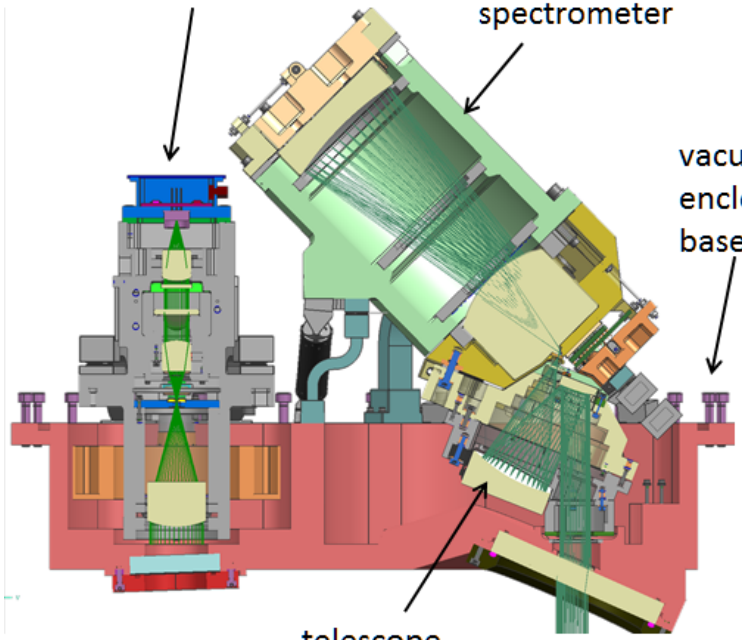
Optical Design

Spectrometer and telescope inside a 6U CubeSat frame



Prior work

- The Portable Remote Imaging Spectrometer (PRISM) is a state-of-the-art coastal ocean airborne sensor that provides a starting point and a demonstration of the challenges to be faced.

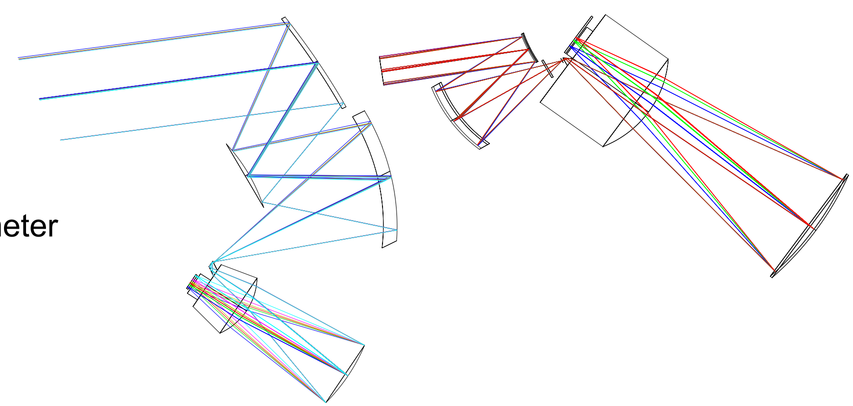


PRISM Airborne Imaging Spectrometer

Comparison

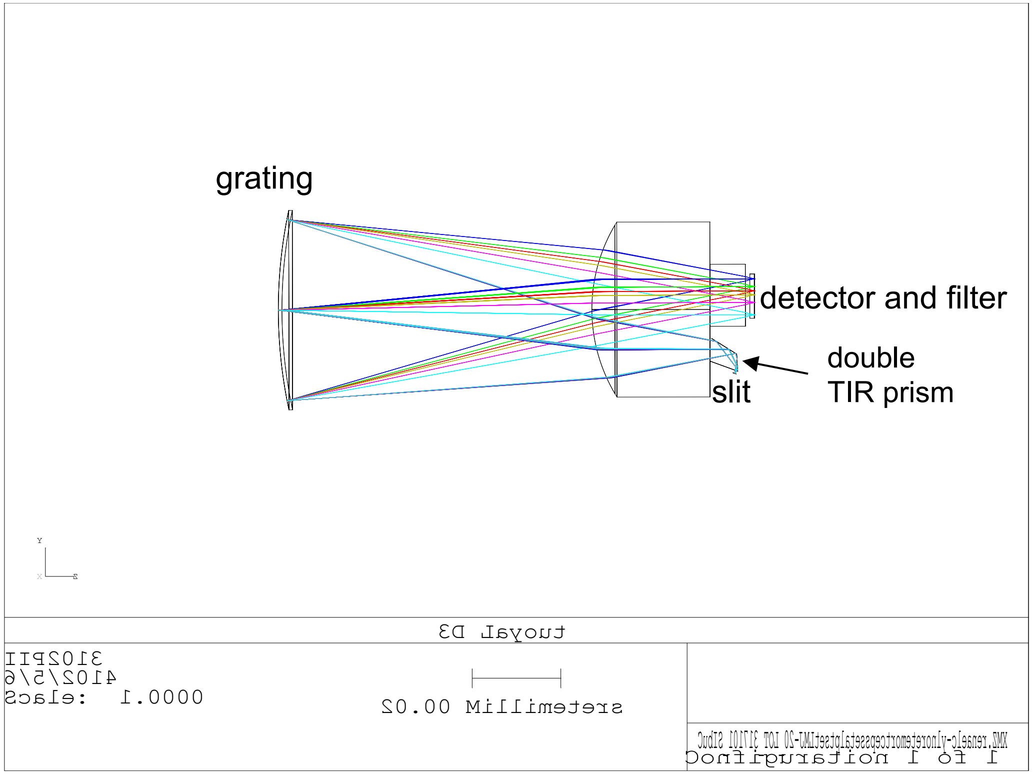
PRISM	SWIS
350 – 1050 nm, 1240nm, 1610 nm	350 – 1700 nm contiguous
Spectrometer + SWIR radiometer	Single FPA, SWIR inherently co-registered
2.9 nm sampling	5.7 nm sampling
608 cross-track pixels	Same
Compact F/1.8 Dyson	Reduced size F/1.8 Dyson
2-mirror telescope	TMA telescope
30^{o}, 0.9 mrad	10^{o}, 0.3 mrad
18 mm aperture	54 mm aperture

SWIS:
larger telescope
smaller spectrometer



PRISM:
smaller telescope
larger spectrometer

Spectrometer design



Spectrometer specifications

Parameter	Value
Spectral range	350-1700 nm
Spectral sampling	5.7 nm
Cross-track spatial elements	600 (+40 monitor)
Uniformity	95%
Detector pixel size	30 mm
F-no	1.8

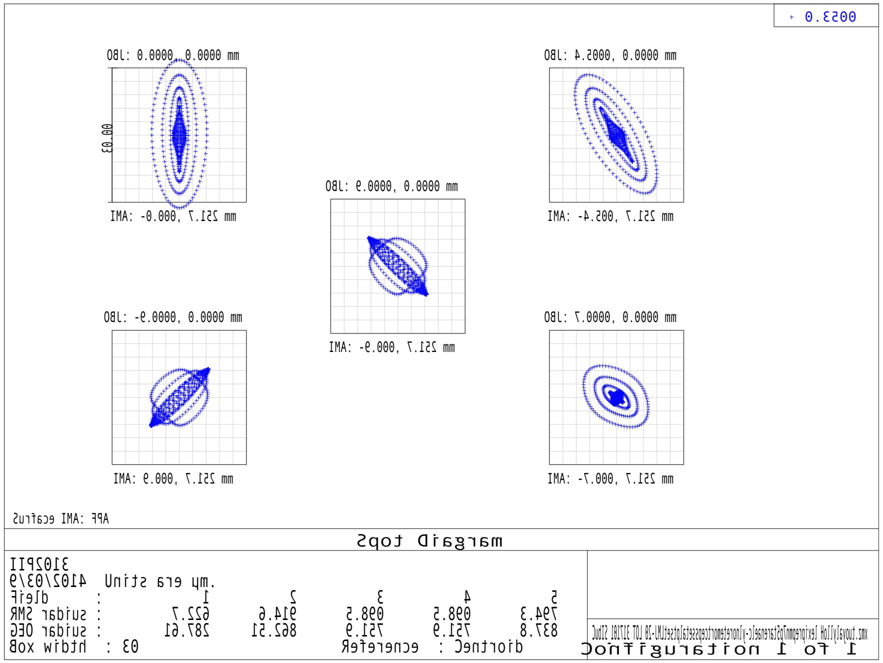
Construction:

- two spherical surfaces with common axis of symmetry
- double TIR prism
- two cemented interfaces for ease of fabrication

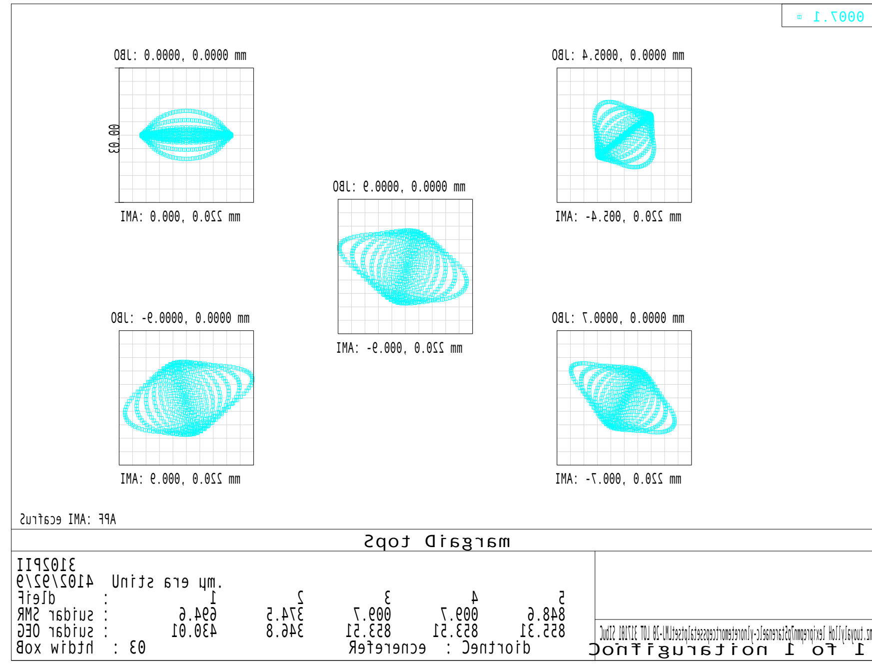
Spectrometer performance

Spot Diagram examples

350 nm



1700 nm

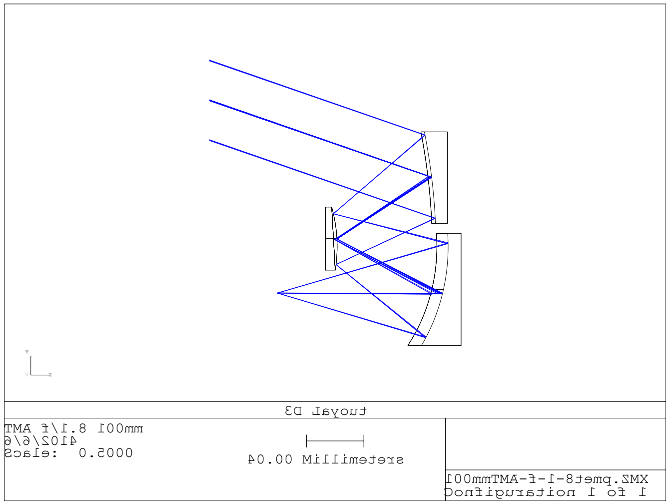


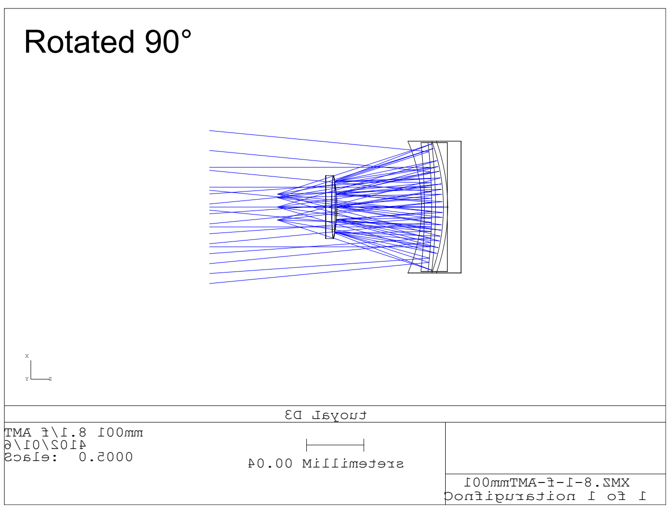
Spots well contained in 1 pixel (30 μm box size)

Smile and keystone negligible (<1%)

Telescope

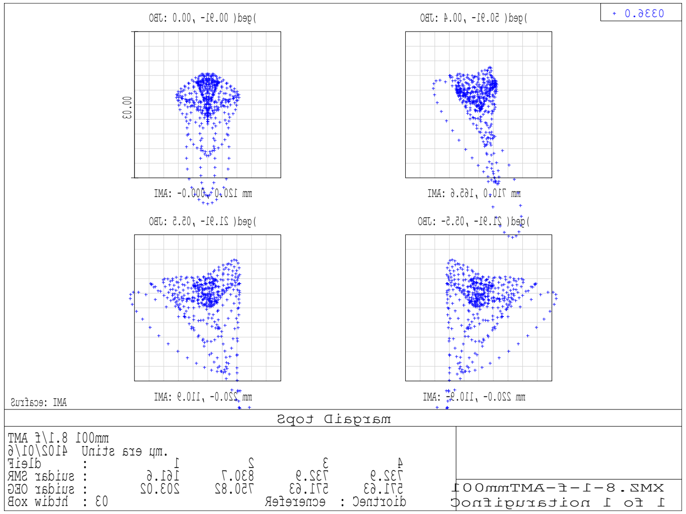
TMA telescope layout





Parameter	Value
Focal length	100 mm
Cross-track FOV	10^{o}
Resolution	0.3 mrad

Spot diagram:



Spots across the field in 30 mm box

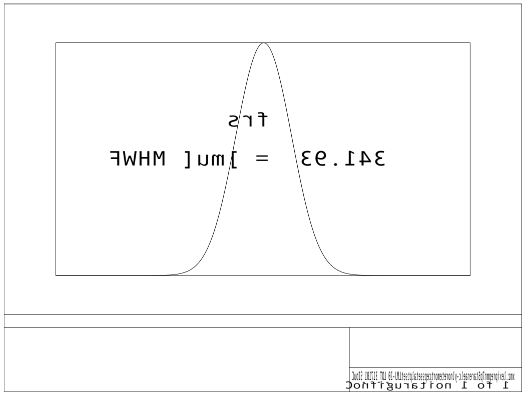
Construction:

- three conics
- common axis of symmetry

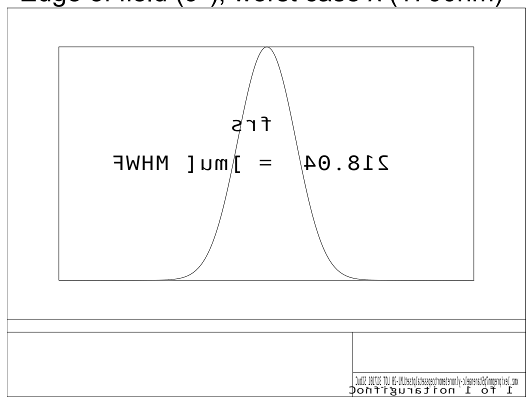
Optical design performance

Spectral response function uniformity (SRF):

On-axis field (0°); worst case λ (1700nm)



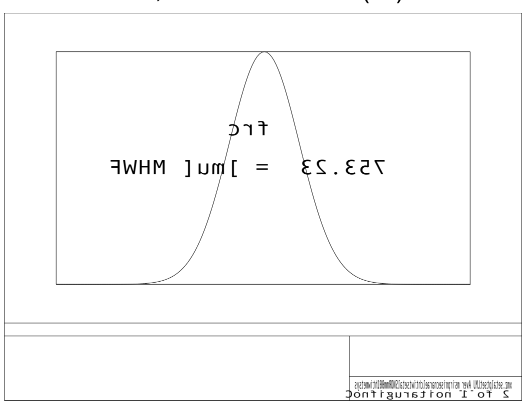
Edge of field (9°); worst case λ (1700nm)



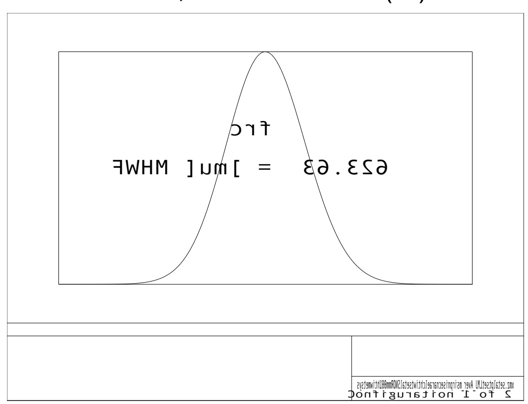
Max SRF FWHM variation with field negligible.

Cross-track spatial response function uniformity (CRF):

350 nm; worst case field (9°)



1700 nm; worst case field (9°)

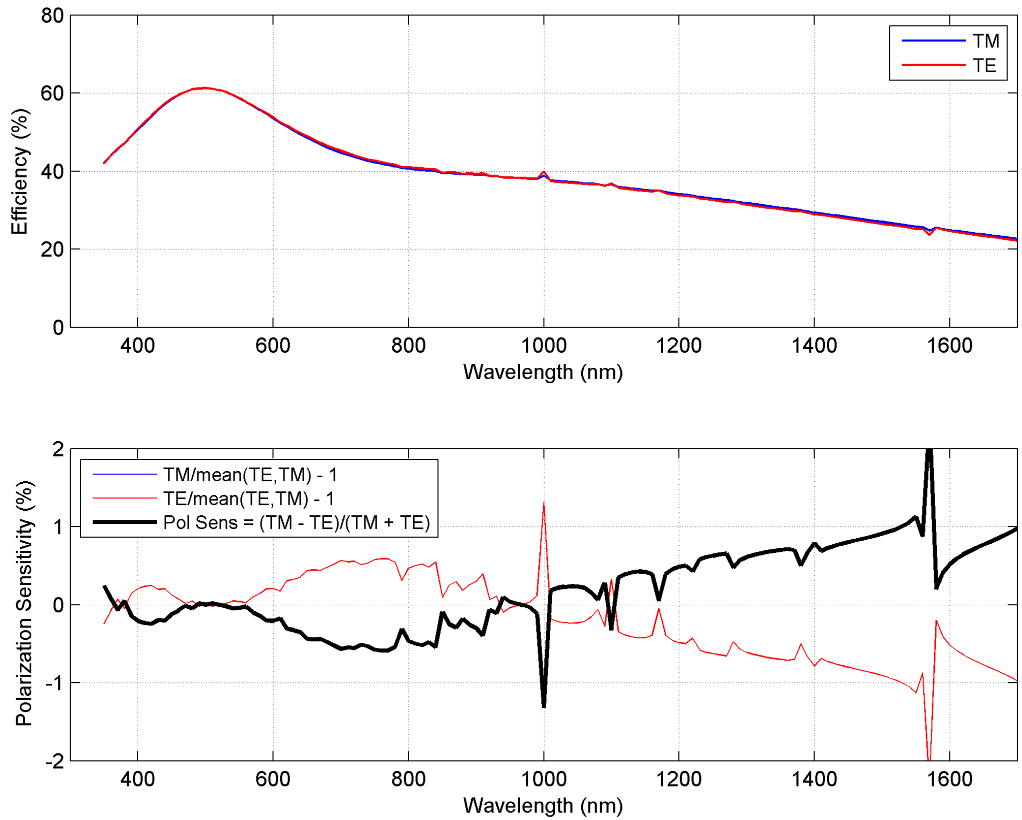


From complete system PSF along X direction, max variation is ~12%.

With anticipated detector wavelength dependence folded in, the maximum FWHM variation should be <10%.

Optical Design: Diffraction Grating

Broadband, polarization-insensitive diffraction grating fabricated via e-beam lithography.



Stray Light Analysis

Stray Light Model includes

- Grating efficiency in multiple orders
- A/R coatings
- Detailed slit assembly model
- Order-sorting filter and detector reflectivity
- Preliminary baffle positions and shapes
- Lambertian scatter properties for ground glass surfaces
- Black paint scattering

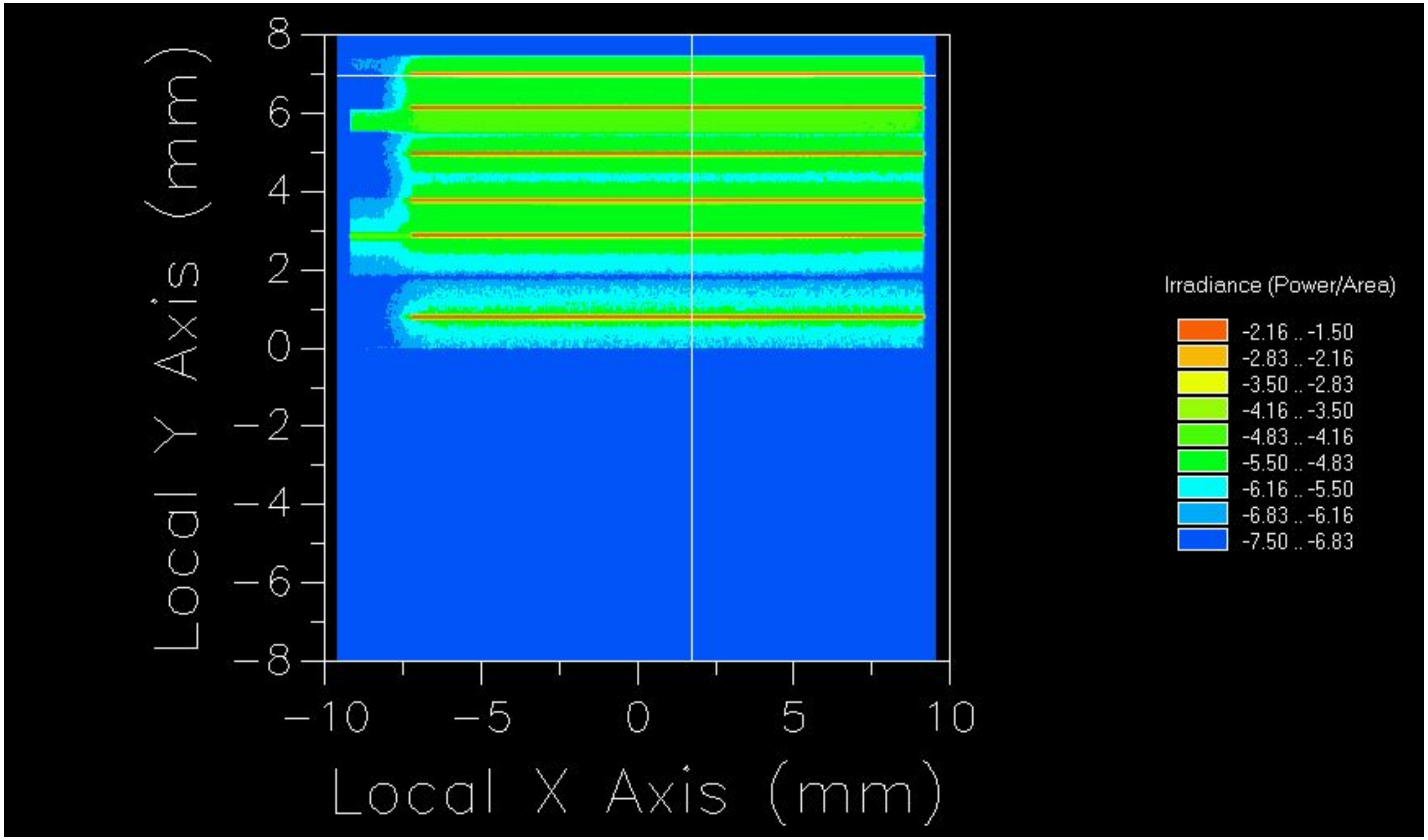
Not included:

- Polished surface scatter model (surfaces specified to <0.5nm rms)
- Surface cleanliness model
- Grating Scatter

Ghost reflections and detector/OSF etalon reflections are the main effect by significant margin

Stray Light Analysis

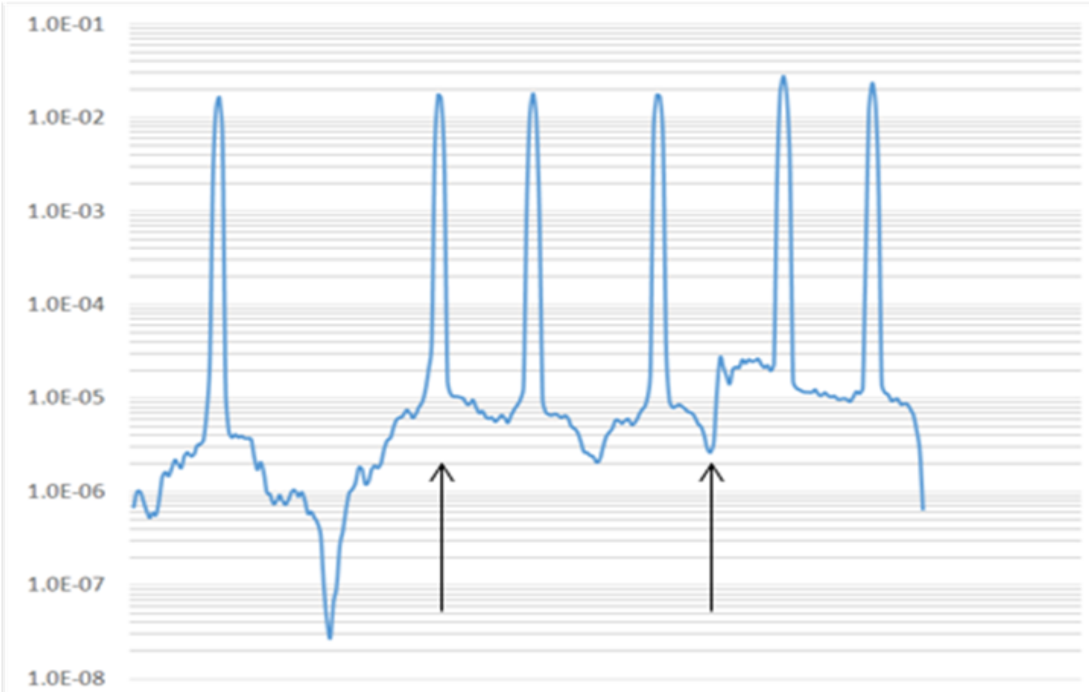
Example FRED output for six finely sampled 10 nm bands covering most of the slit



Spatial ghosts remain below 1e-3, depend critically on detector and OSF reflectivity

Undispersed spatial ghost at ~1140 nm handled by appropriate positioning of OSF.

Stray Light Analysis



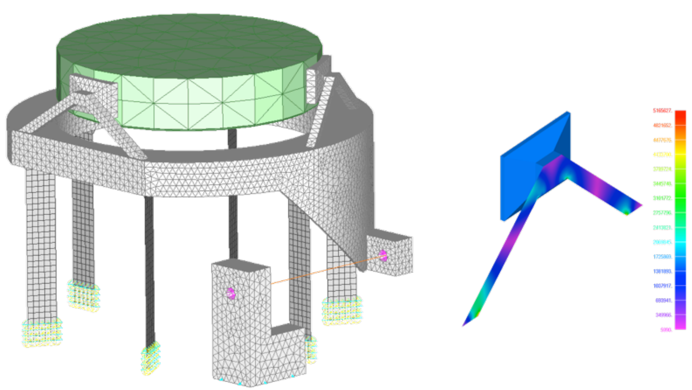
Arrows indicate OSF seam locations.

Ghosts have been minimized by

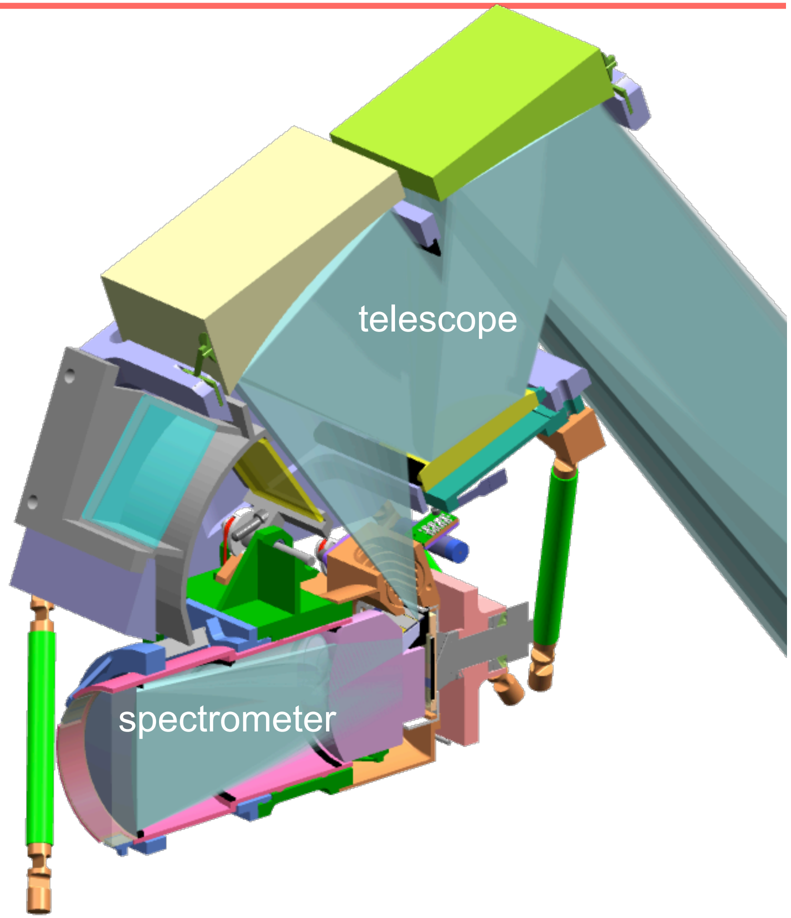
- Judicious positioning of the slit
- Optimization of dispersion to exclude zero order reflected ghosts
- Ensuring that all reflected ghosts are returned in negative (weak) grating orders
- Bandpass OSF regions
- Development of special detector A/R coating to be undertaken.

Optomechanical design

- Telescope housing designed for ease of machining and assembly
- Spectrometer assembly leverages airborne Dyson spectrometer designs with enhancements to grating mount
- Common materials and relatively simple fabrication
- Mounts and flexures analyzed for buckling and thermo-mechanical stress



Grating mount and flexure stress analysis



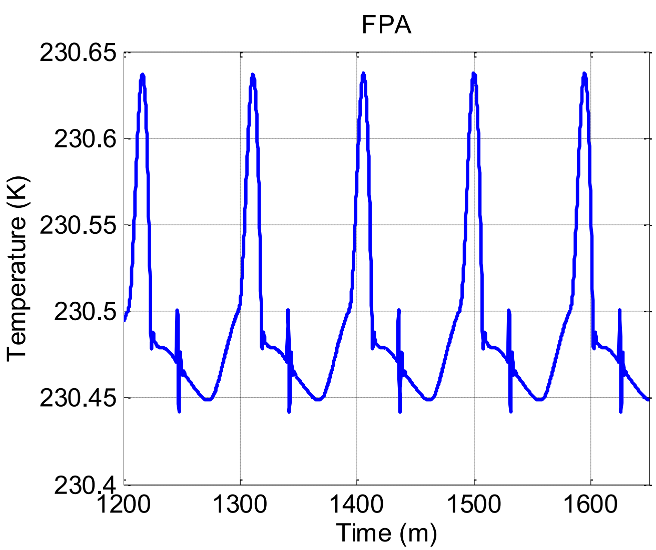
Cross section of optomechanical design

Preliminary thermal analysis

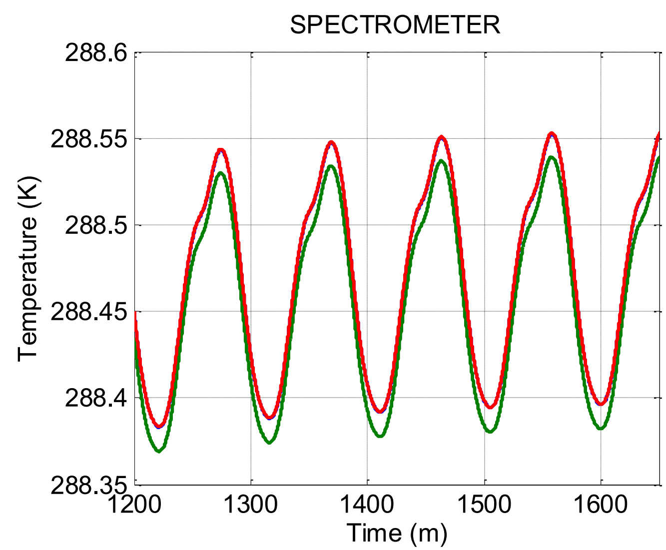
- A preliminary thermal analysis supports the required detector and spectrometer temperature stability

Temperature requirements

	Op. Temp. (K) / stability (± K)	Op. min. (K)	Op. max. (K)	Non-op. min. (K)	Non-op. max. (K)
FPA	230 / 0.1	NA	250	135	310
Spectrometer	290 / 1	280	295	155	310

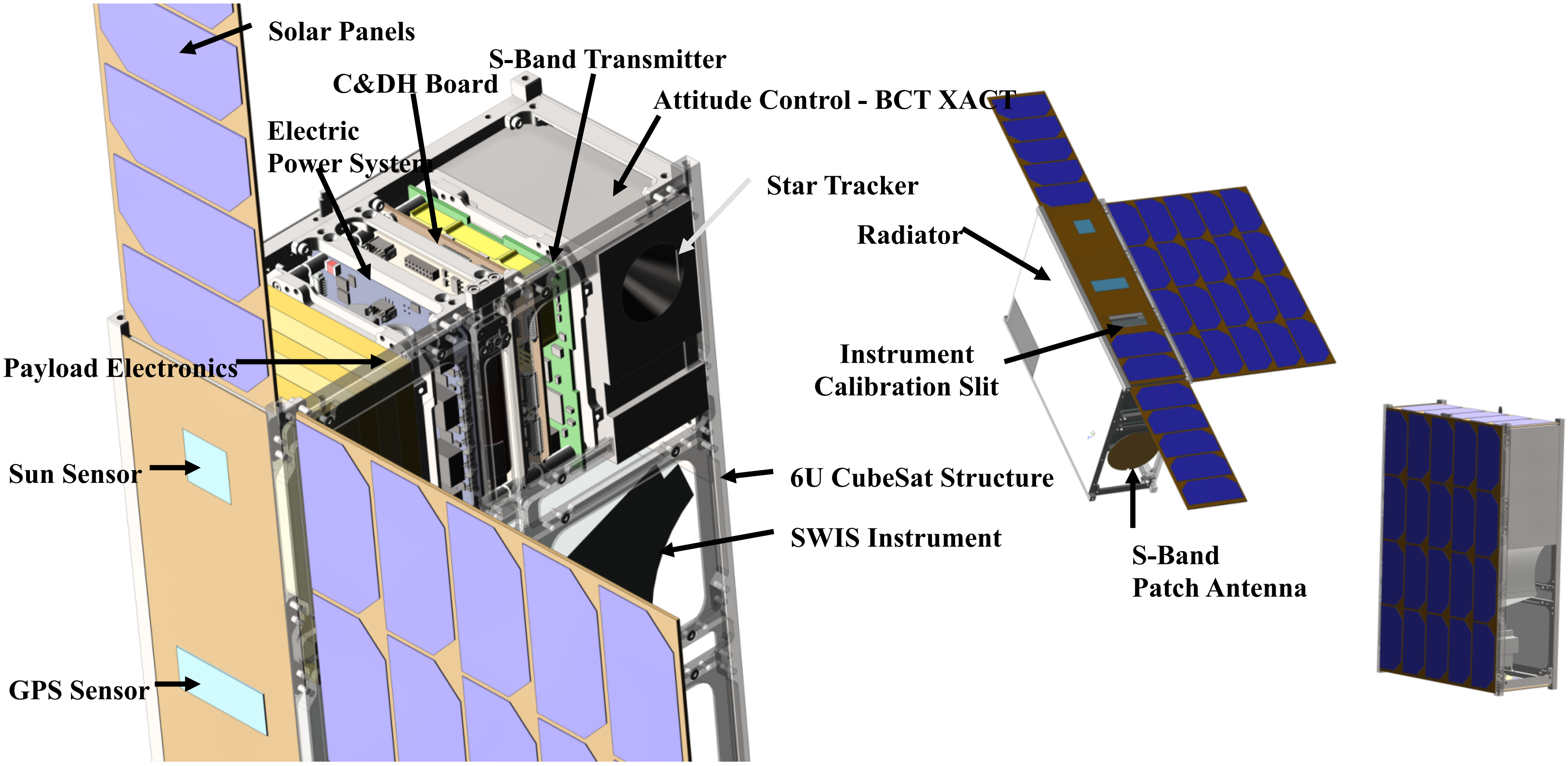


Design target: 230K
FPA stability achieved with a 1.5 W heater



Design target: nominal 290K
Stability requirement is met

CubeSat configuration



Complete CubeSat configuration with commercial 6U structure, attitude control unit, radio, power electronics, and custom FPA electronics.

Summary & Conclusions

- An imaging spectrometer design suitable for CubeSat applications requiring high throughput (SNR) has been demonstrated.
- The design advances the state of the art in compact sensors of this kind in terms of size and spectral coverage.
- The design has been optimized to minimize ghost reflections and stray light in conjunction with vendor-supported efforts in detector coating and OSF production.
- Preliminary mechanical, thermal, and spacecraft design favorable for accommodation in 6U CubeSat frame and capabilities
- Useful missions can be designed with high spatial and temporal resolution to address targeted areas of the Earth's surface.

Acknowledgments

The SWIS Project Team:

PI: Pantazis Mouroulis
Task Manager: Holly Bender

Co-Is: Rob Green, Tom Painter, Heidi Dierssen (UConn), Byron Van Gorp, Dan Wilson, Michael Eastwood, Jose Rodriguez

Engineering Team: Dan Preston, Colin Smith, Chris Smith (ATK), Paula Pingree, Ernie Diaz, Johannes Gross

Industrial Partner: Teledyne (Jianmei Pan, task manager)