# Hyperspectral Outgoing Longwave Radiation Observatory Payload Concept Study

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# Purpose and Motivation

- A compact thermal-infrared (TIR) imaging spectrometer design was conceived for persistent high-accuracy surveillance of outgoing longwave radiation (OLR) from GEO.
- The proposed spectrometer concept would enable enhanced resolution of the Earth's OLR emission to serve multiple applications.
- Sensor design assumes limited SWAP accommodation resources commensurate with a SmallSat bus.
  - *Compatible with manifesting aboard a GEO constellation as a hosted payload.*
- This concept study is tasked with validating a strawman sensor design and its predicted performance in the GEO environment.

# Crustal Strain and Earthquake Potential

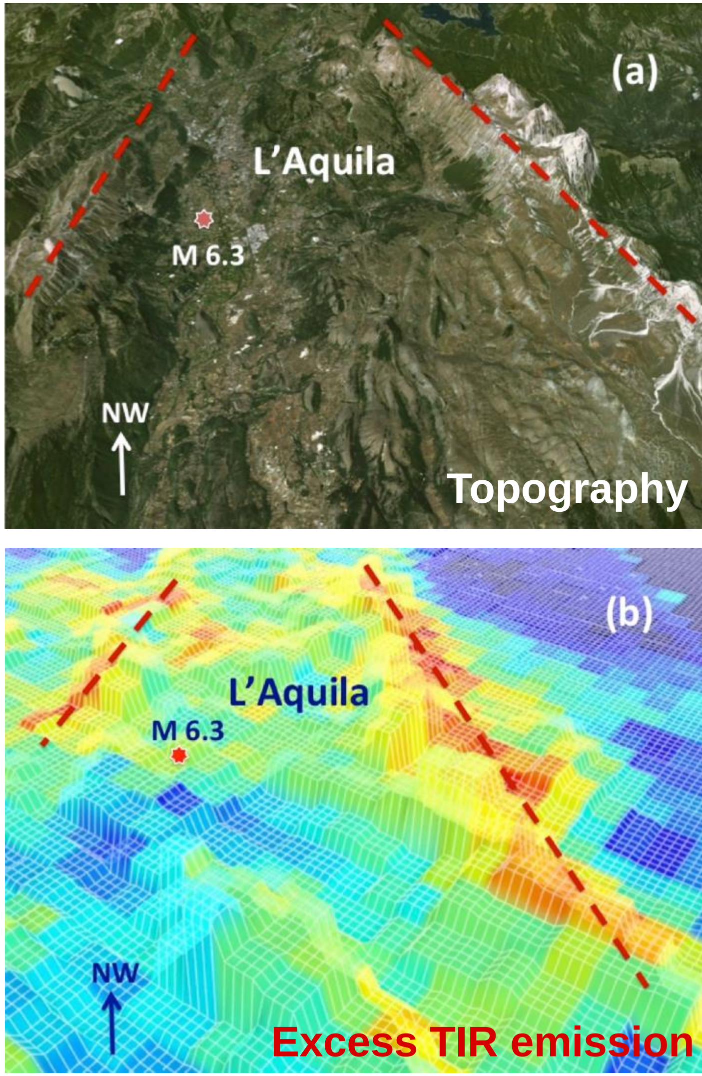
- The proposed spectrometer concept would enable enhanced spectroradiometric resolution of land surface self-emission

  $\Rightarrow$ Characterization of non-thermal IR emissions related to stress build-up within the Earth's crust

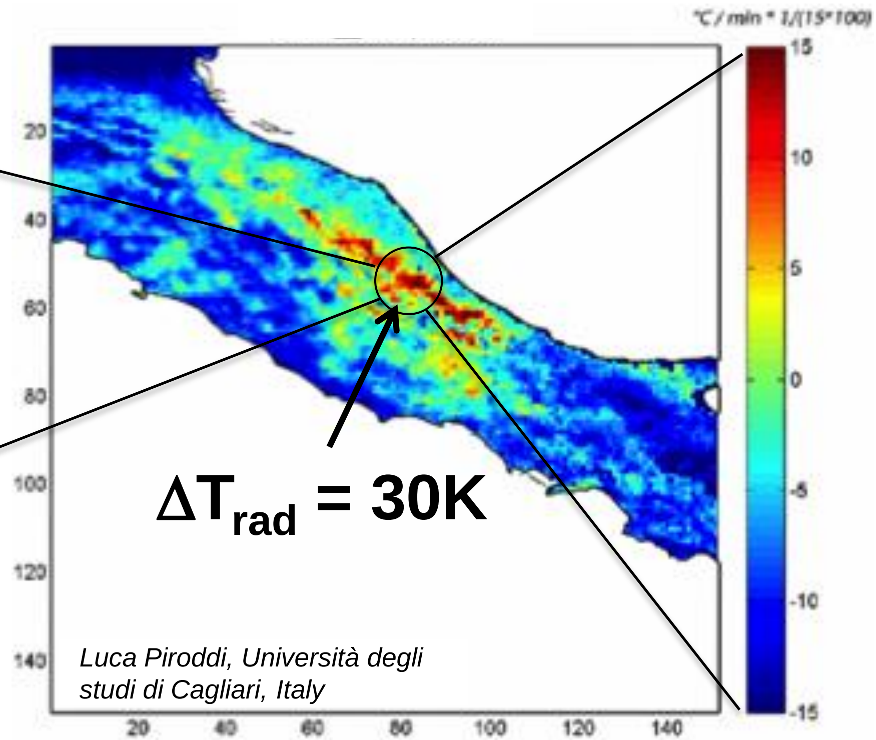
- Definitive determination of spectral content would help to resolve competing theories of anomalous TIR generation observed prior to some earthquake events

  $\Rightarrow$ Opens up possibility of alternative earthquake early warning (EEW) approach

# TIR Anomaly Case Study: L'Aquila, Italy, 2009

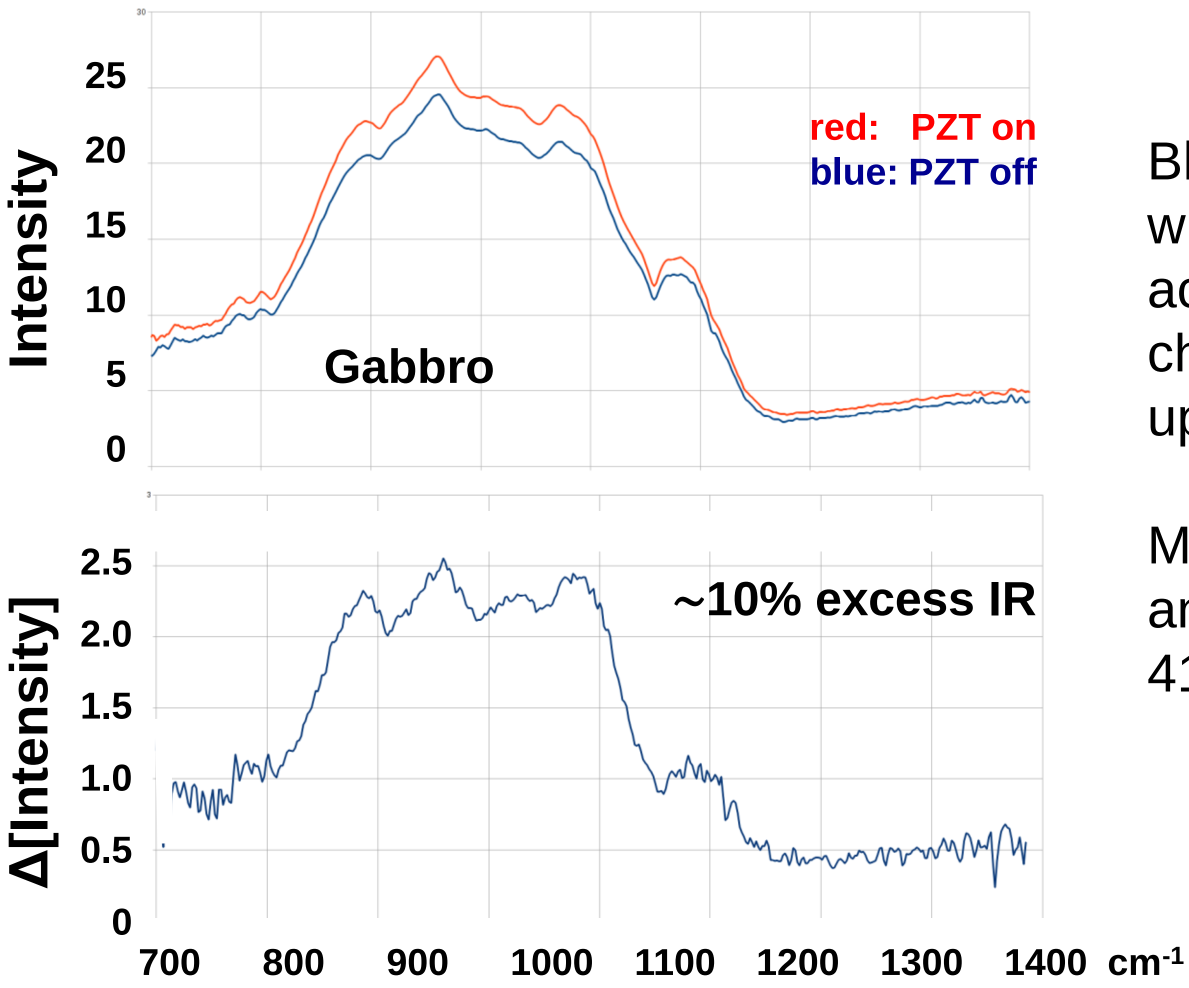



**M6.3 earthquake, 06 April 2009**




Excess TIR emission prior to L'Aquila earthquake derived from MeteoSat time series night-time thermal gradient.

# Strain-Induced Self-Emission Lab. Measurements




Black gabbro, excited with 40-kHz ultrasound to activate positive hole charge carriers, exhibits up to 10% excess TIR.

Measurements made with an Agilent ExoScan™ 4100 FTIR spectrometer.

# Terrestrial Hydrology Processes

- The proposed spectrometer concept would enable enhanced resolution of land surface spectral emissivity

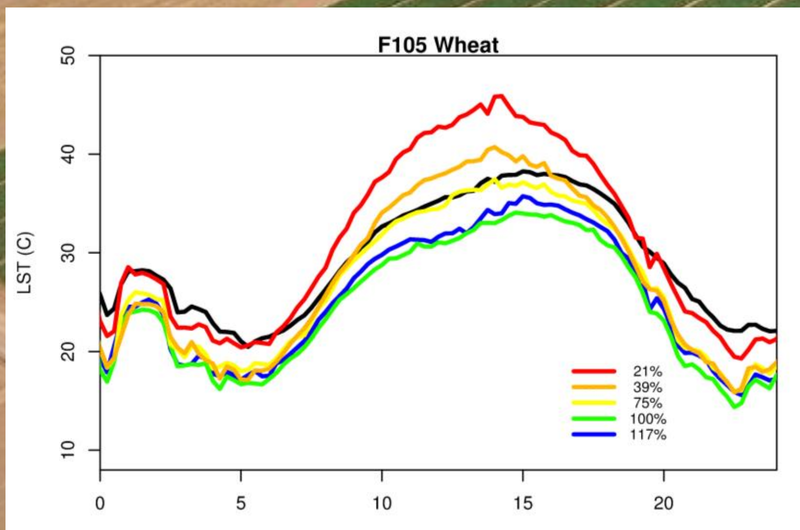
  ⇒ *More accurate land surface temperature (LST) retrievals*

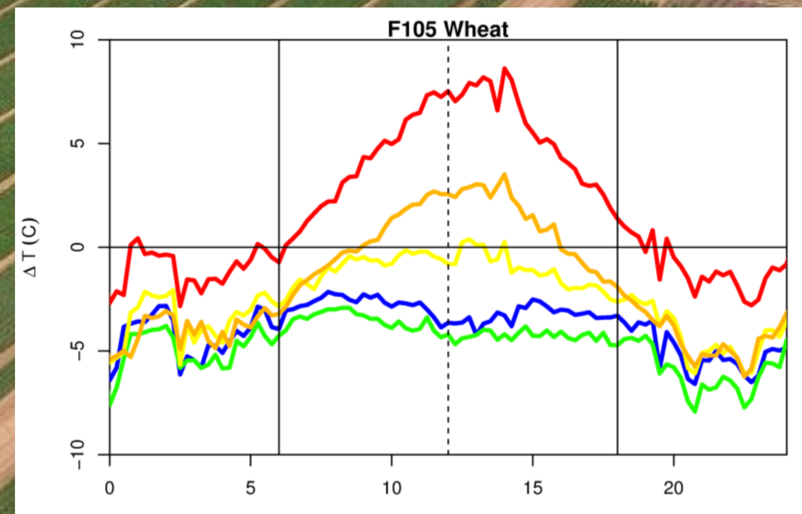
  ⇒ *Improved estimates of local- to regional-scale evapotranspiration (ET)*

  ⇒ *Higher fidelity water usage determination and drought susceptibility forecasting in agricultural regions and sensitive ecosystems*

- Multiple time-of-day acquisitions made possible by GEO orbit enable the diurnal variation of LST to be tracked

# Radiometric Canopy Temperature Closely Related to Plant Water Status




- ET depends upon LST/air temperature difference.
- Surface (colors) and air (black) temperatures of wheat were observed continuously to monitor ET in 15-minute time steps.
- To demonstrate LST/ET relationships, soil moisture contents were controlled by irrigation and measured continuously.
- Diurnal LST variation over wheat crop a strong function of soil moisture content.
- At night crop is nearly isothermal except for severely water-stressed plants.
- Differentiation of soil moisture contents varies throughout the day with greatest spread in afternoon.

# Sensor Design Philosophy

- Choice of near-ambient temperature detector operating point puts sensor cooling requirements within the capability of passive thermal control schemes.
  – *Eliminates need for high-SWAP cryocoolers, but at the cost of reduced heat-lift capacity.*
  – *GEO vantage point enables integration times sufficient to overcome resulting radiometric sensitivity reduction.*
- Spectrometer based on a dispersive pushbroom hyperspectral design coupled to a 2-D microbolometer focal-plane array.
- 10-km ground-sample distance (GSD) at nadir permits acquisition of full disk at 1-hour cadence.
- Modular design will allow ready substitution of higher GSD fore optics to address other applications.

# Microbolometer Sensor Requirements

*Sensor requirements are set by science goals*

$$\underset{(K)}{NE\Delta T} = \frac{4(f\#)^2\sqrt{\Delta f}}{\pi\sqrt{A_d}\int_{\lambda_1}^{\lambda_2} d\lambda\, D^*_{sys}(\lambda)\tau_o(\lambda)\tau_{ATM}(\lambda)\frac{\partial L}{\partial T_B}(\lambda, T_B)}$$

$$\text{where } D^*(\lambda) = \frac{R_I(\lambda)\sqrt{A_d\Delta f}}{\bar{\sigma}_I} = \frac{R_V(\lambda)\sqrt{A_d\Delta f}}{\bar{\sigma}_V}$$

| Sensor requirements | |
|---|---|
| Spectral Range | 7-14 µm |
| Spectral Channels | 64 |
| NEΔT at 10 µm | <1 K |

$$\Delta f = \frac{1}{2 * T\_int} \text{ and } \int_{\lambda_1}^{\lambda_2} d\lambda = \Delta\lambda$$

| Sofradir-EC Pico640 Microbolometer Array | |
|---|---|
| Spectral Range | 8-14 µm (3-dB points) |
| NEΔT at 10 µm | <75 mK @ f/1, 300 K, 30 Hz |
| Estimated D* | 4.6 x $10^8$ cm $Hz^{½}$ $W^{-1}$ |
| Array Format | 640 x 480, 17-µm pitch |

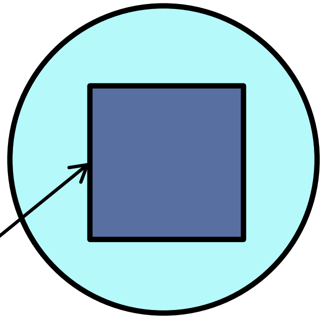
Number of spectral channels and number of co-added samples determine the achievable NEΔT. All other parameters are fixed or optimized.

# Predicted Microbolometer Performance

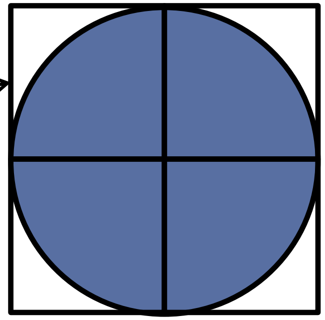
*Coverage at 40 sample coadds*

10-km GSD at nadir permits acquisition of a square frame with sides half the length of the Earth's diameter. This square image results from a linear array of 640 pixels for each wavelength band and collection of 640 frames along-track.

40-sample co-adds yields this square image in 14 min.



Full disk image of Earth is possible in 56 min.

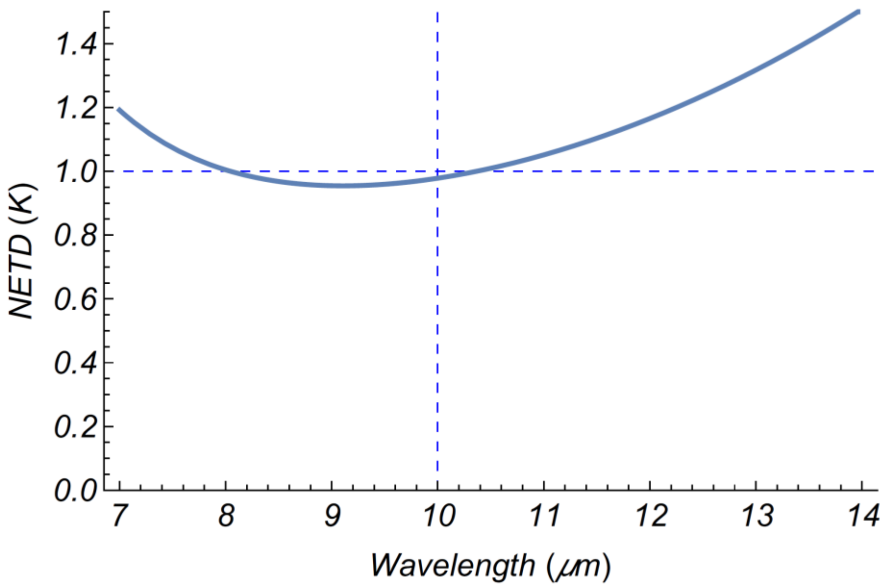


# Predicted Microbolometer Performance

*NE$\Delta$T behavior as a function of wavelength*

10-km GSD at nadir and 40 sample co-adding permits acquisition of full Earth disk image in 56 minutes.

| | |
|---|---|
| f/# | 0.7 |
| Sample rate (Hz) | 30 |
| Atmospheric transmittance | 0.9 |
| Ground temperature (K) | 265 |
| Optical transmittance | 0.5 |
| Estimated D* (cm Hz$^{1/2}$ W$^{-1}$) | 4.6 x $10^8$ |
| Sample co-adds | 40 |

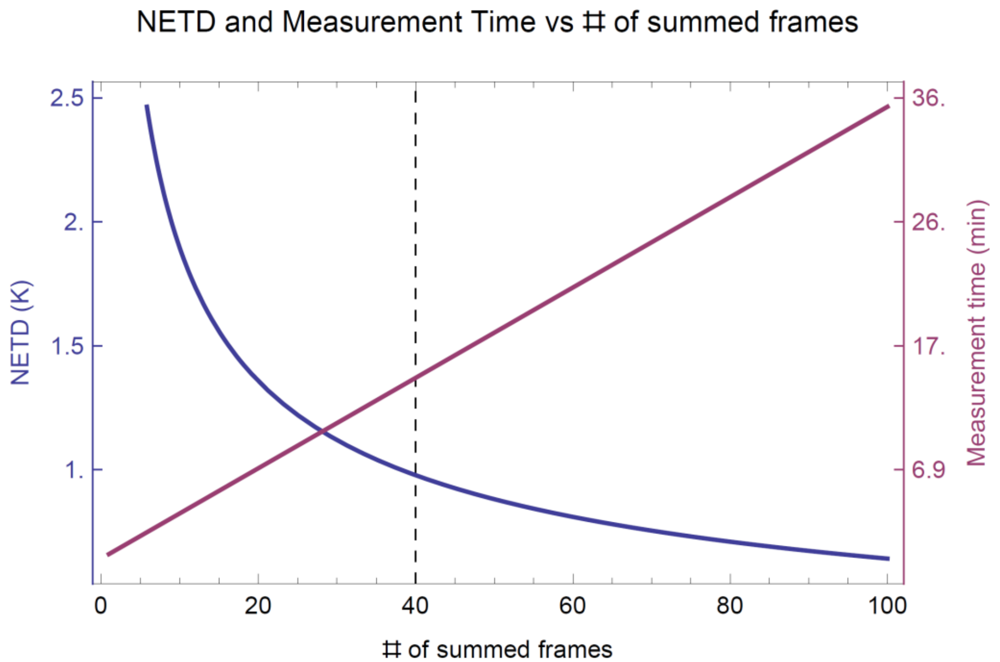



***At 10 µm, 1-K NE$\Delta$T is achievable with 64 spectral channels and 40 sample co-adds***

# Predicted Microbolometer Performance

*NE$\Delta$T behavior as a function of sample co-adds*

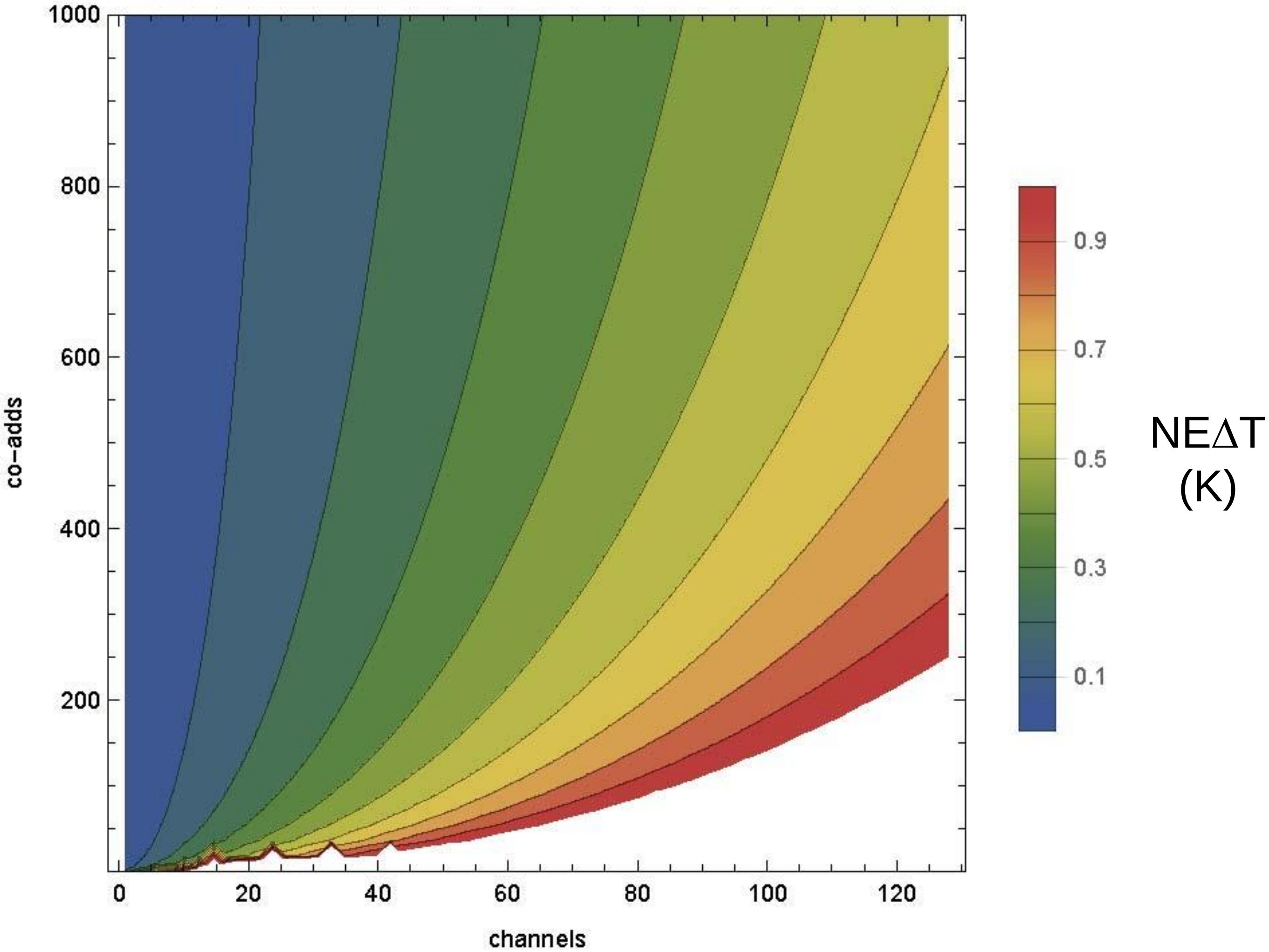
Smaller NE$\Delta$T is achievable with higher coadding if more limited areal coverage is desired.



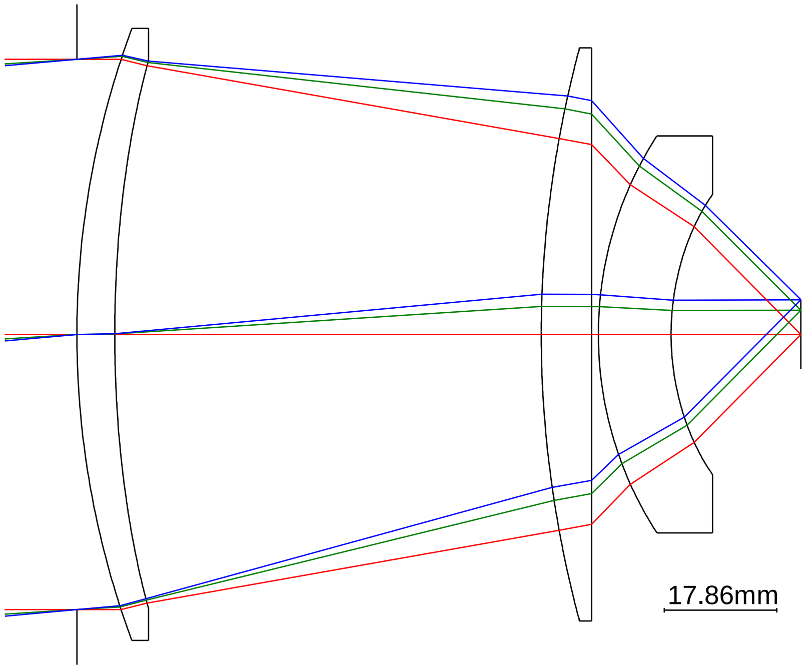

| | |
|---|---|
| f/# | 0.7 |
| Sample rate (Hz) | 30 |
| Atmospheric transmittance | 0.9 |
| Ground temperature (K) | 265 |
| Optical transmittance | 0.5 |
| Estimated D* (cm $Hz^{1/2}$ $W^{-1}$) | $4.6 \times 10^8$ |
| Sample co-adds | 6 – 100 |

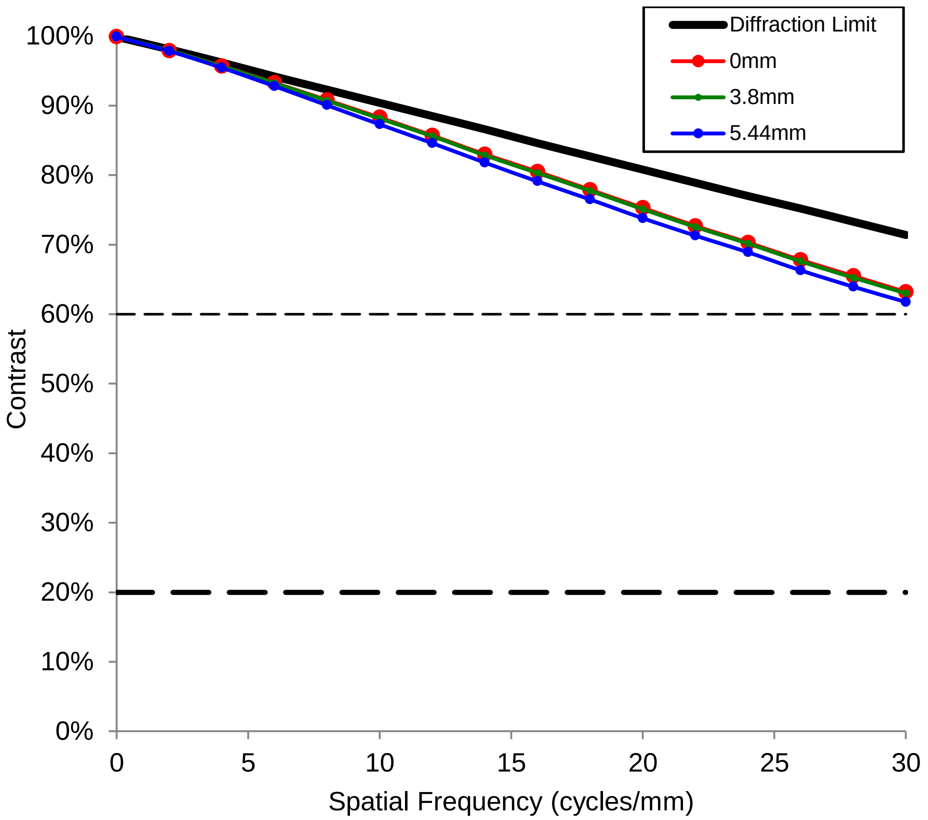
# Spectrometer Performance Tradespace

*NE∆T as a function of sample co-adds and channel count*



# Optical Objective Schematic and Performance: MTF



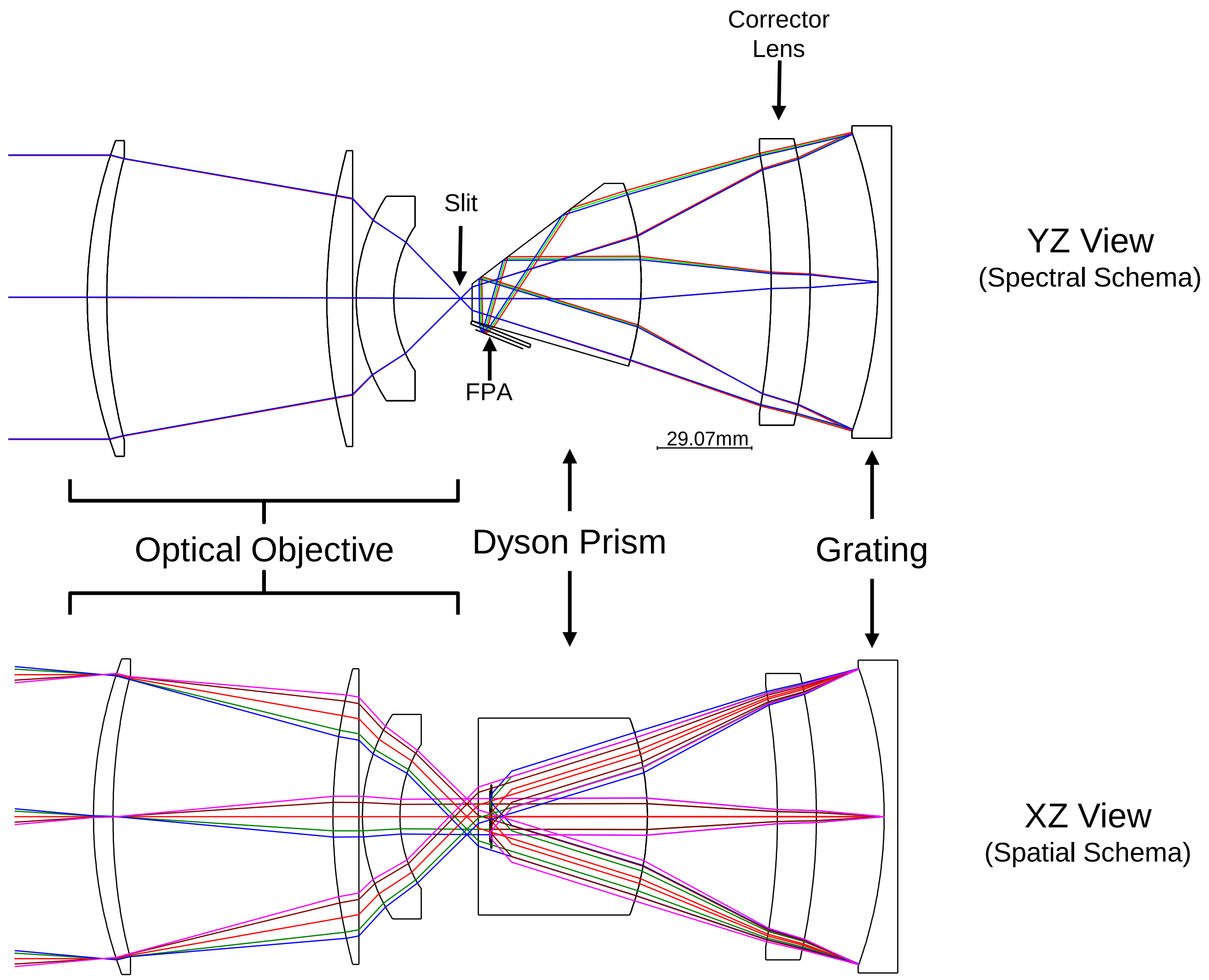




With end goal of >20% contrast at Nyquist (30 cycles/mm) for objective, lens has ample margin to accommodate imperfections.

# End-to-End Optical Schematic

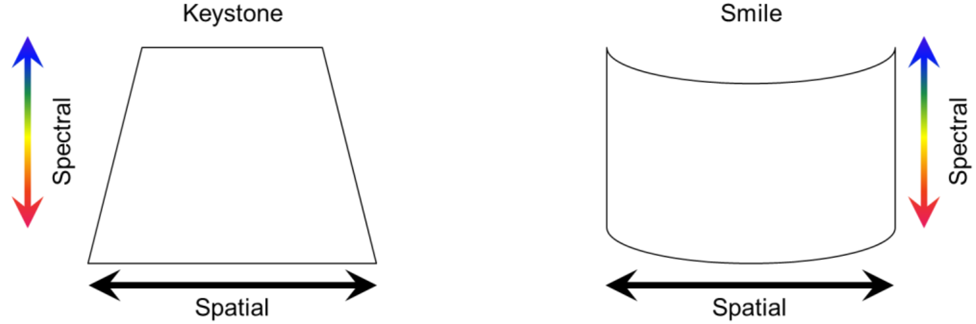
Dyson spectrometers provide for a compact volume with low optical distortions and exceptional image quality at low f-number.

Spectrometer optimized for 64 channels.



# End-to-End Optical Performance: Image Distortion

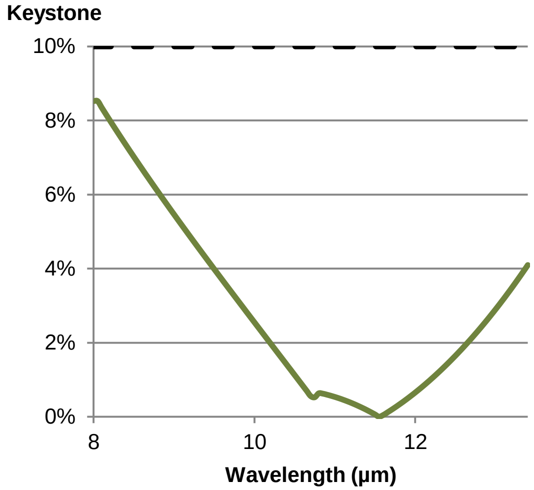
- End-to-end design minimizes spectral image distortion.
- Spectral smile and keystone drive spectro-meter requirements.

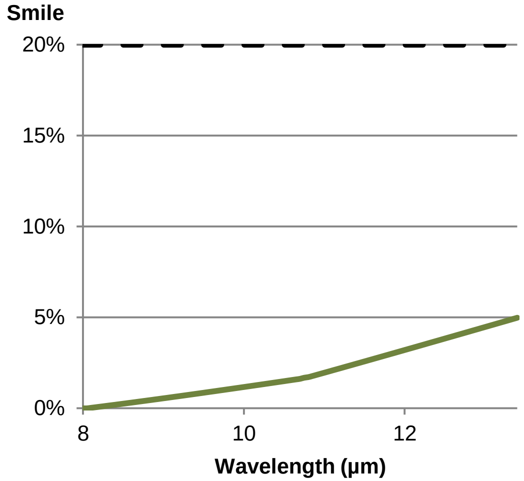



Keystone <0.09 pixel

Smile <0.05 pixel

| | Requirement | Prediction |
|---|---|---|
| Keystone | 0.10 pixel | 0.09 pixel |
| Smile | 0.20 pixel | 0.05 pixel |



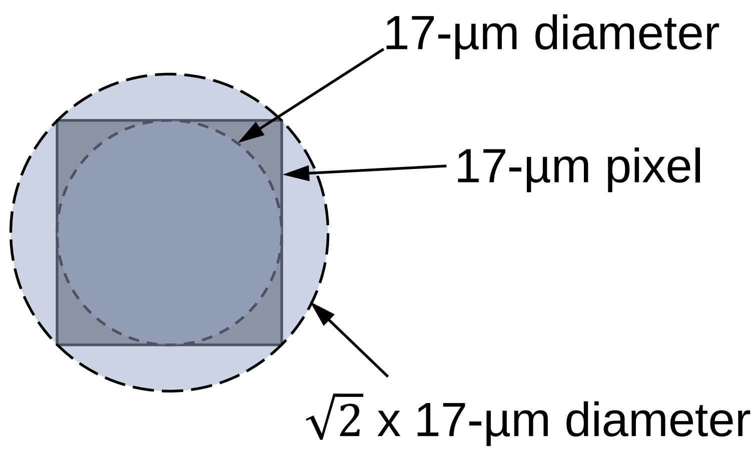



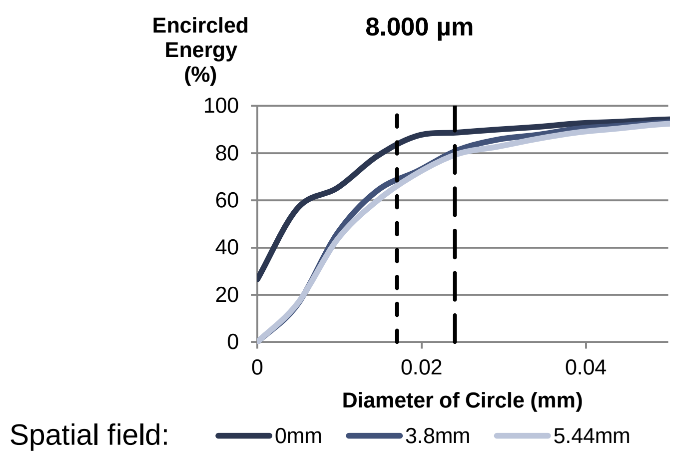

Optical design provides low distortion and thus accurate spectral positioning, minimizing the need for extensive spectral and geospatial calibration.

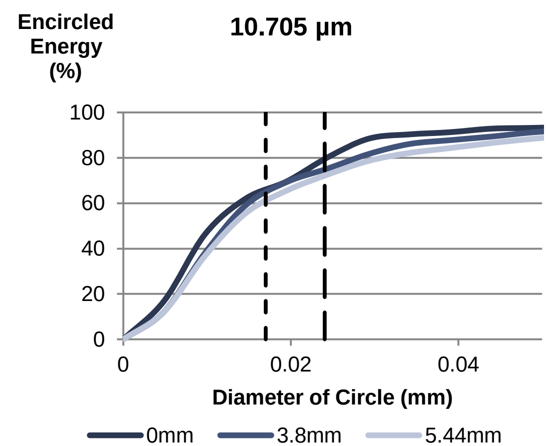
# End-to-End Optical Performance: Encircled Energy

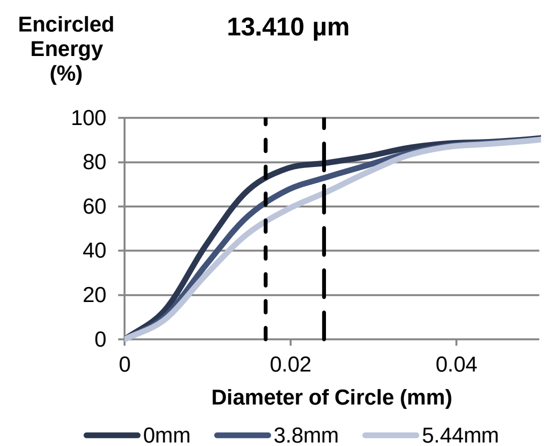
- Encircled energy provides measure of energy on detector.

All fields and wavelengths have >50% energy on detector.



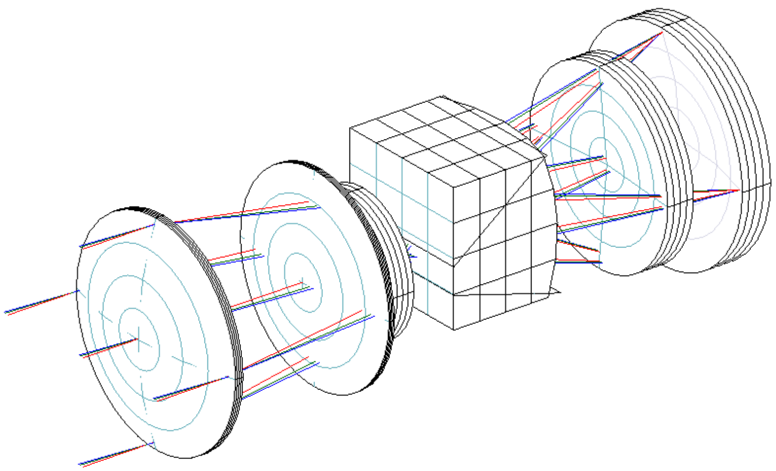



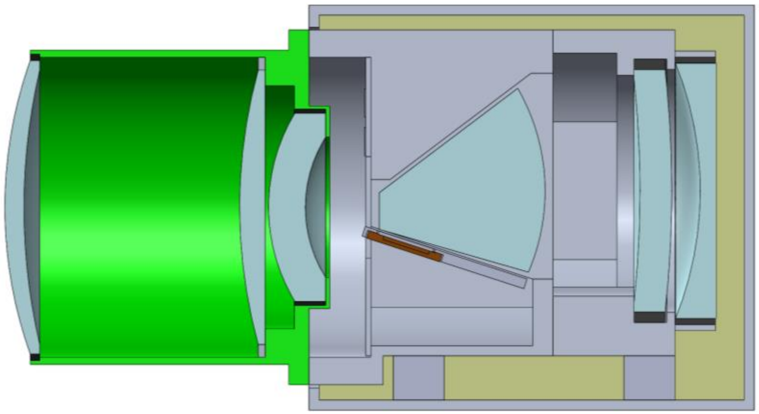



# System CAD Model

*Opto-mechanical modeling in progress*



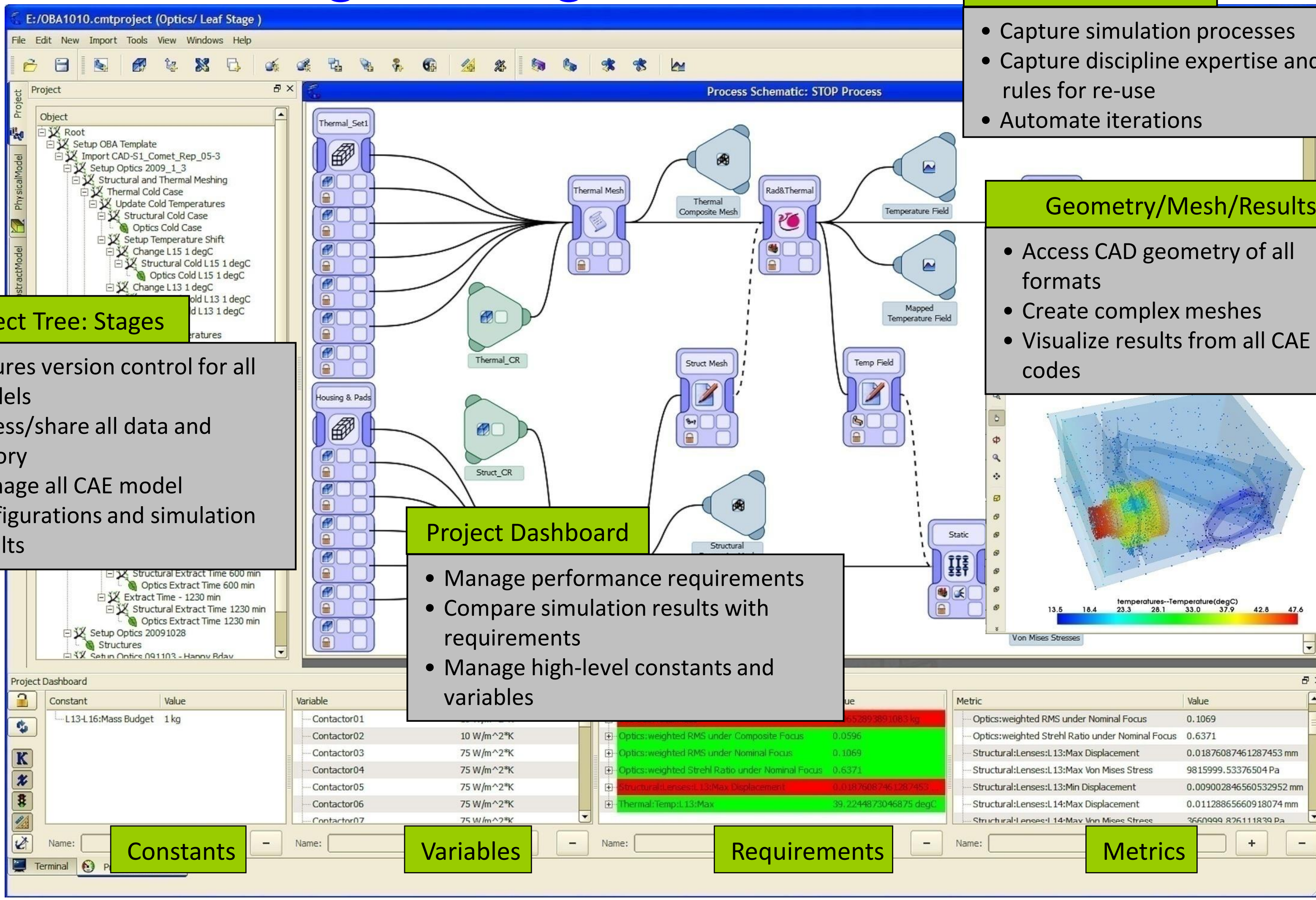


- Optical elements are bonded
- Entire system is <23 cm in length
- Spectrometer housing is 12 cm x 13 cm
  - *Future work could include packaging this spectrometer into a CubeSat form factor*

# Structural/Thermal/Optical (STOP) Analysis

- A key component of this study is a STOP analysis of the system optical performance to validate the sensor resilience to launch loads and the GEO operating environment
- Concurrent engineering sessions review status of each discipline and interactions between them to identify design/modeling deficiencies and requirement conflicts
  - ***More efficient turn around*** *due to automated propagation of changes in unified system model*
- Engineering data and models are shared across disciplines using integrated concurrent engineering software tool, Comet™
  - ***Modifications occur real-time*** *across disciplines*
  - ***Maintains consistency*** *among discipline design models at each stage in design*
  - ***Enables parallel design*** *modifications, increasing efficiency*

# Concurrent Engineering Environment




**Simulation Process**

- Capture simulation processes
- Capture discipline expertise and rules for re-use
- Automate iterations

**Geometry/Mesh/Results**

- Access CAD geometry of all formats
- Create complex meshes
- Visualize results from all CAE codes

**Project Tree: Stages**

- Ensures version control for all models
- Access/share all data and history
- Manage all CAE model configurations and simulation results

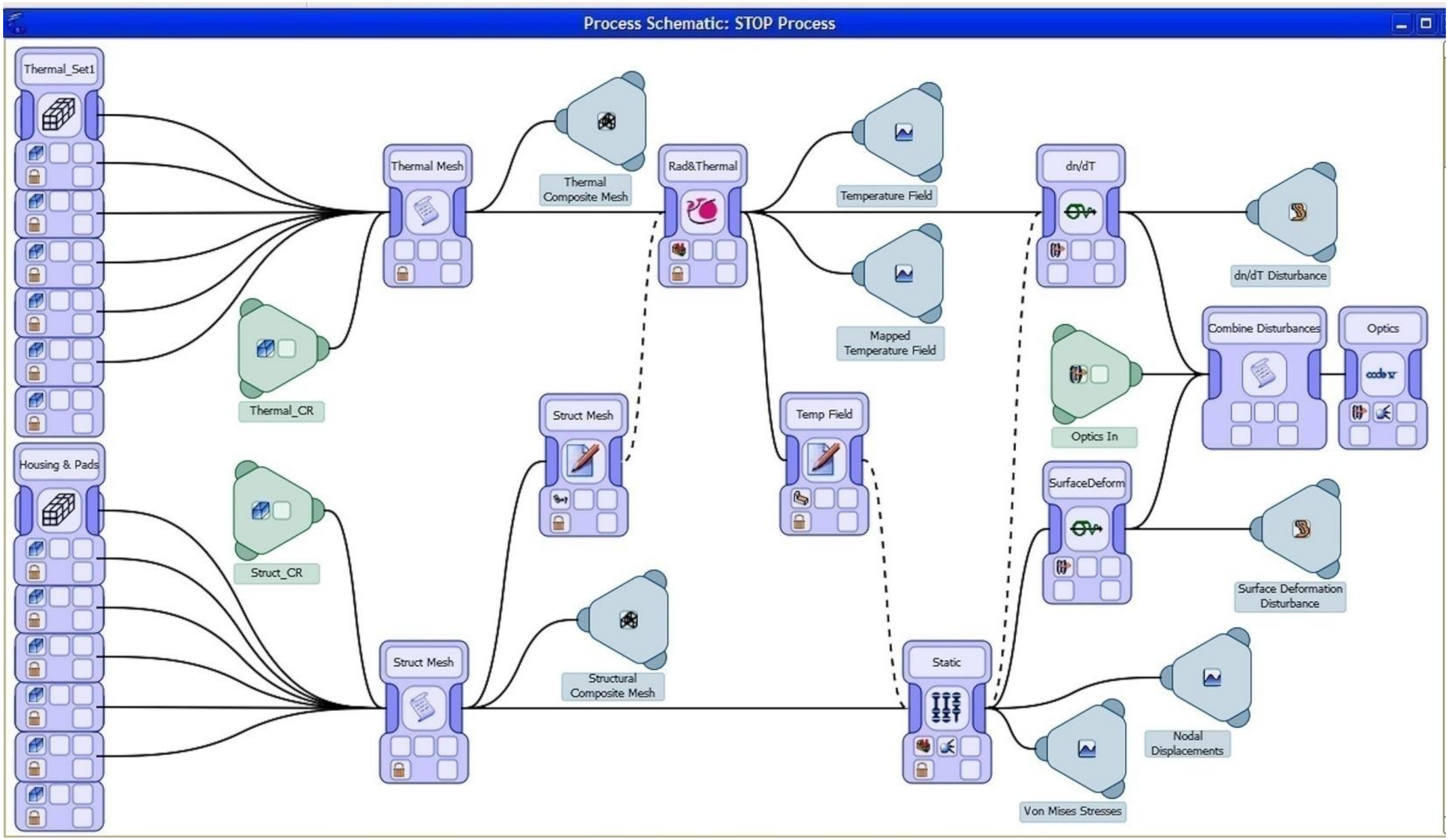
**Project Dashboard**

- Manage performance requirements
- Compare simulation results with requirements
- Manage high-level constants and variables

**Constants** **Variables** **Requirements** **Metrics**

***Comet™ enables multi-disciplinary approach to EO sensor design***

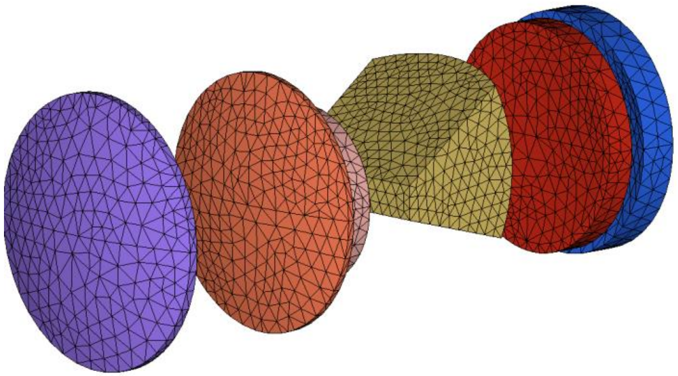
# STOP Analysis Process

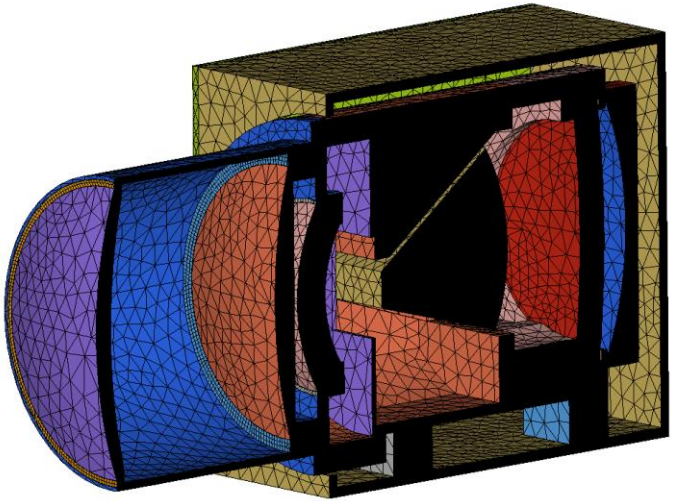


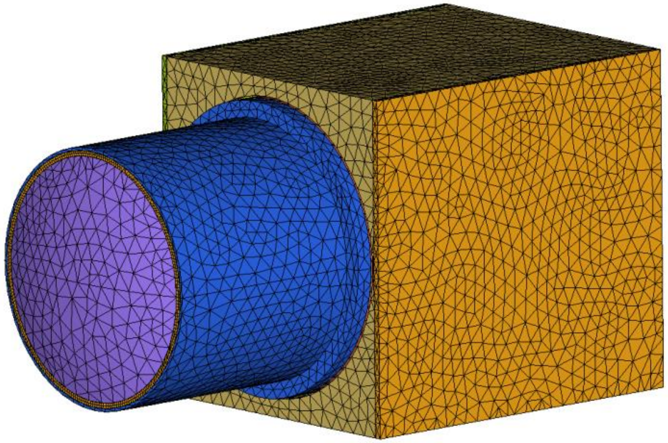
# Finite Element Model (FEM) Development

*Meshing tasks in progress*

- Parts are meshed for structural and thermal analysis
  - *Mesh can be refined at critical interfaces*
- Mesh studies are underway to determine appropriate level of detail







# Summary

- The end goal of this study is to validate emergent TIR spectral imaging technology solutions for deployment in Earth orbit.
  - *Persistent high-accuracy monitoring of Earth's outgoing longwave radiation (OLR) spectrum.*
- The low-SWAP design is compatible with SmallSat platforms or as a hosted payload.
- Next steps include verification of the optomechanical design through Structural/Thermal/Optical (STOP) analysis.
- The final output from the study will include a standard mission risk matrix.