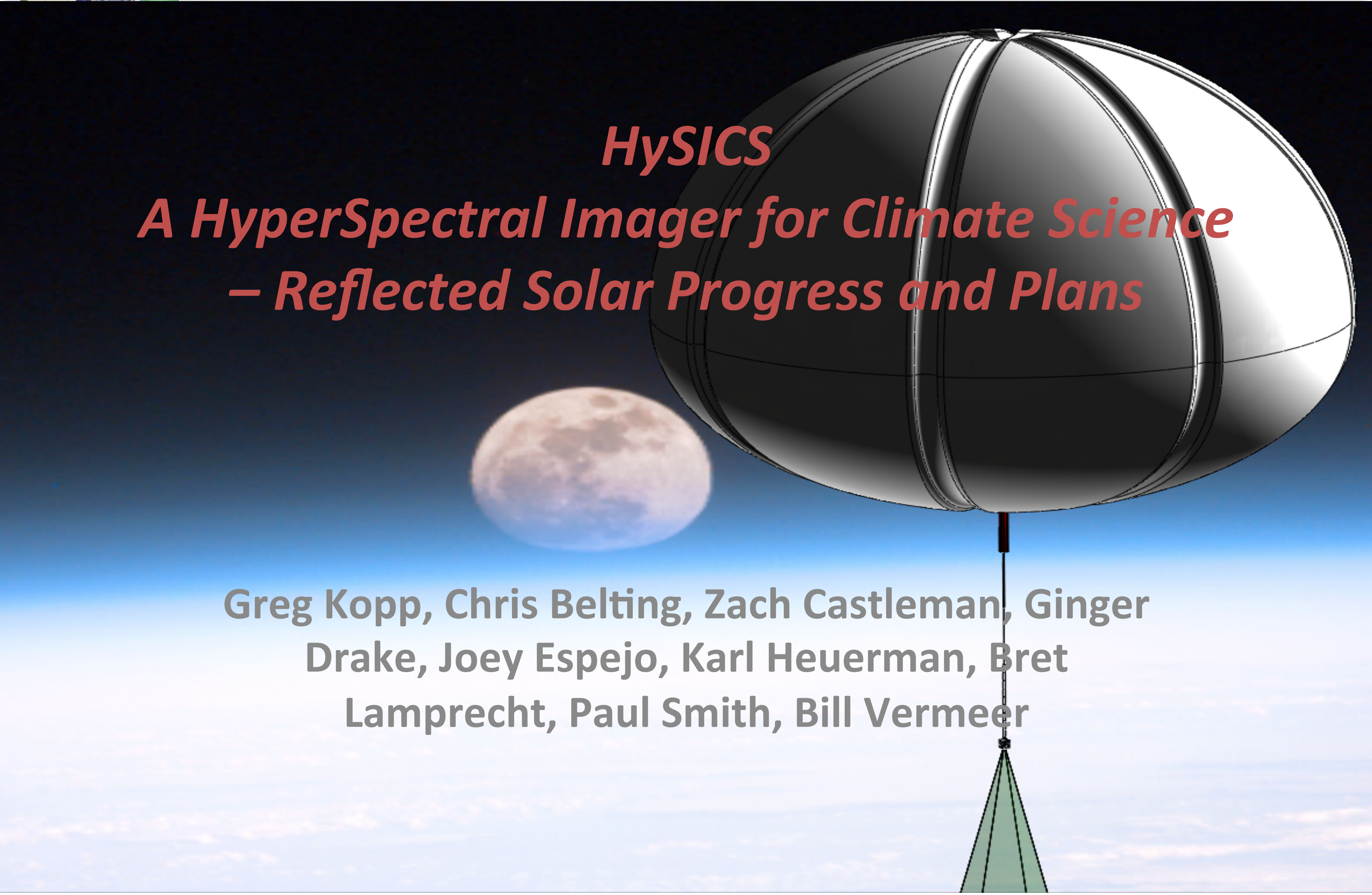
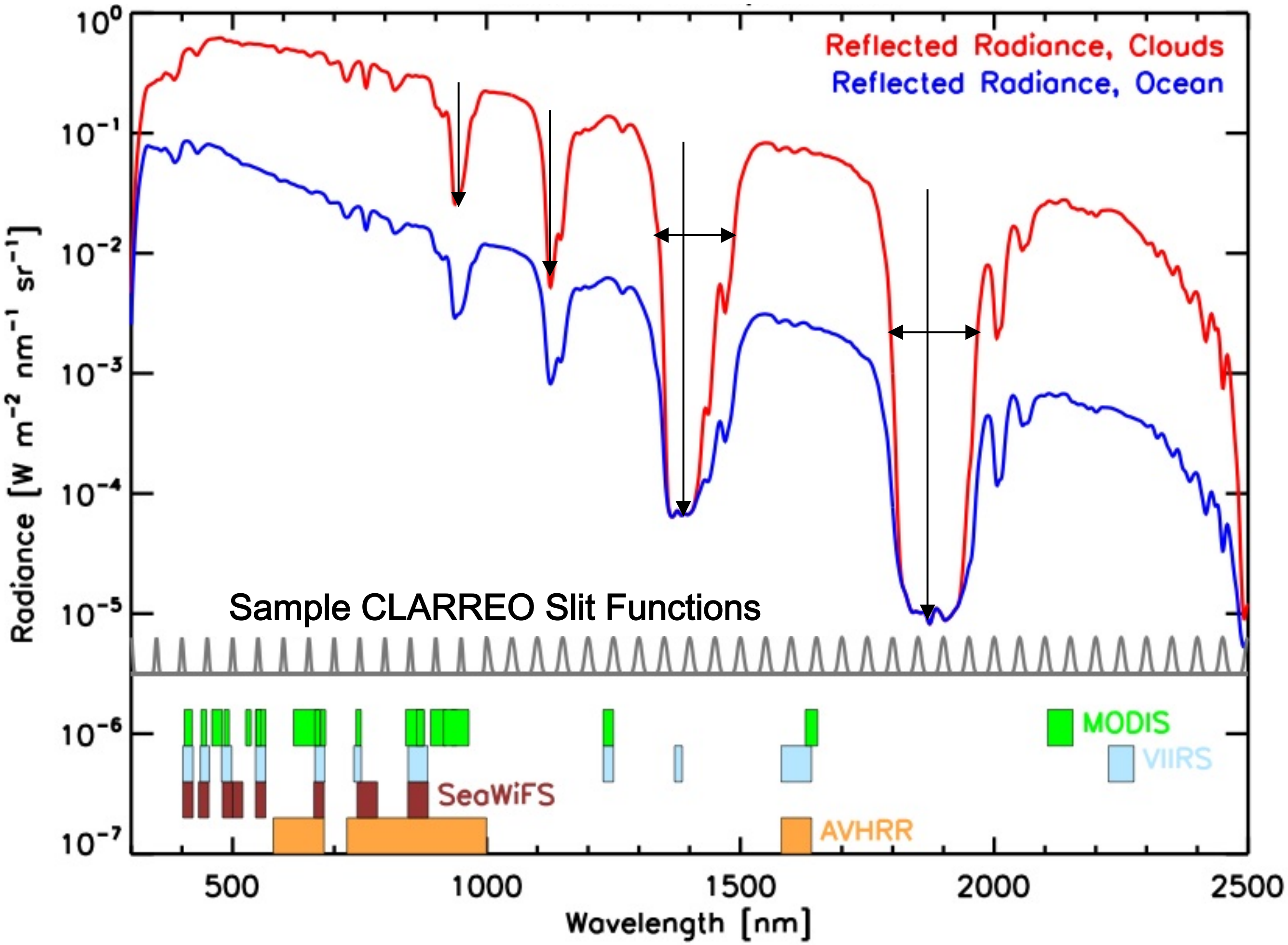


HySICS
A HyperSpectral Imager for Climate Science – Reflected Solar Progress and Plans

Greg Kopp, Chris Belting, Zach Castleman, Ginger Drake, Joey Espejo, Karl Heuerman, Bret Lamprecht, Paul Smith, Bill Vermeer

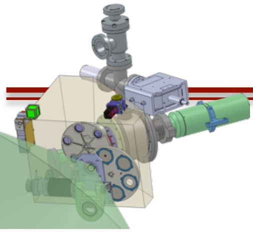
Requirements: from Water Vapor Trend



MODTRAN simulations used to predict changes in outgoing spectral radiance due to 0.4 kg/m^2 per decade trend

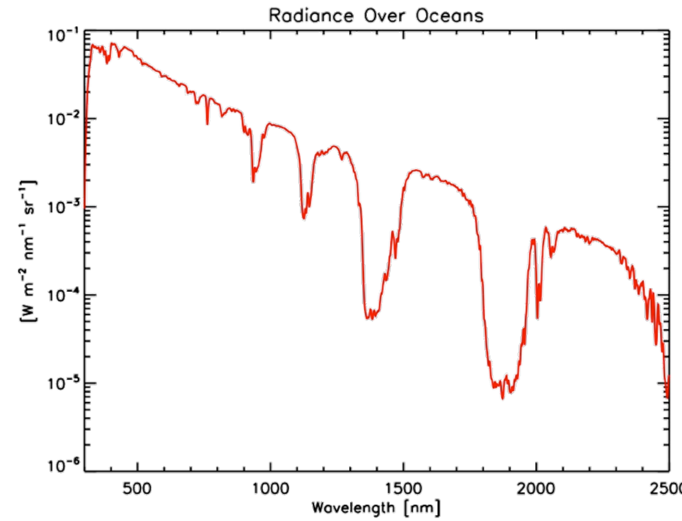
Define accuracy/stability requirements needed to detect trend

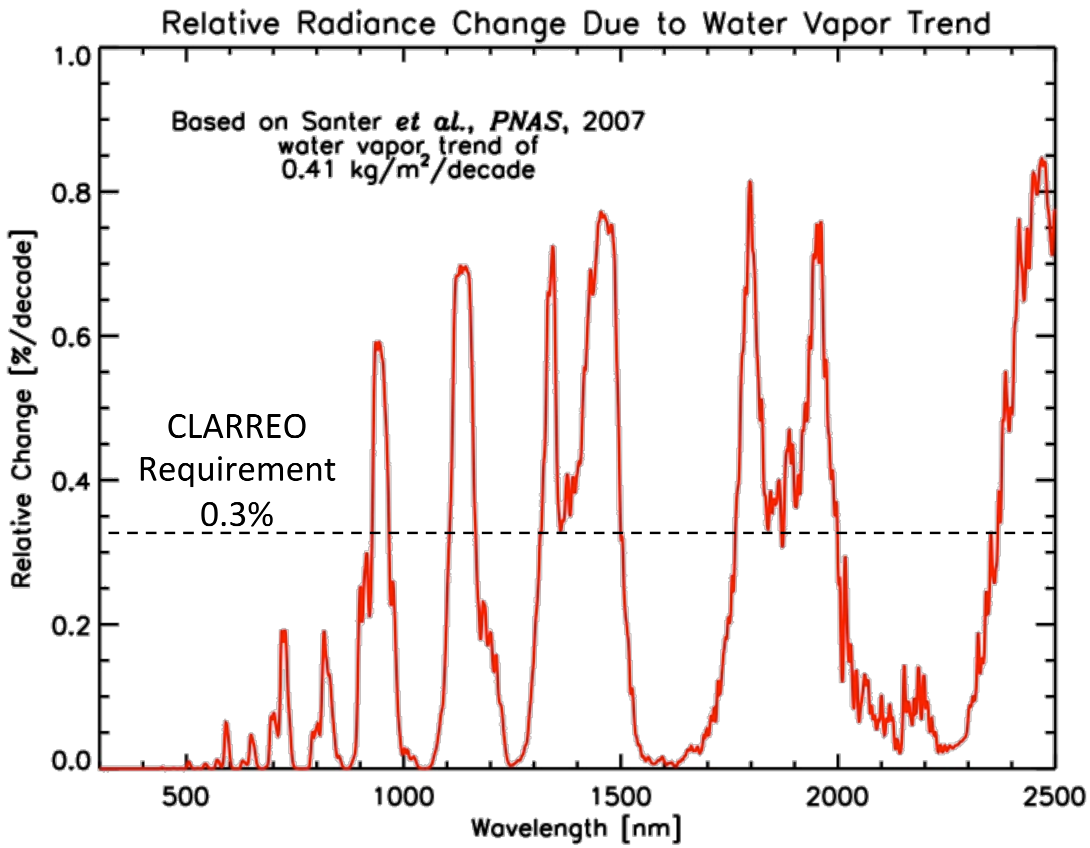
- Requires broad spectral coverage with moderate resolution
- Averages for climate require broad spatial sampling

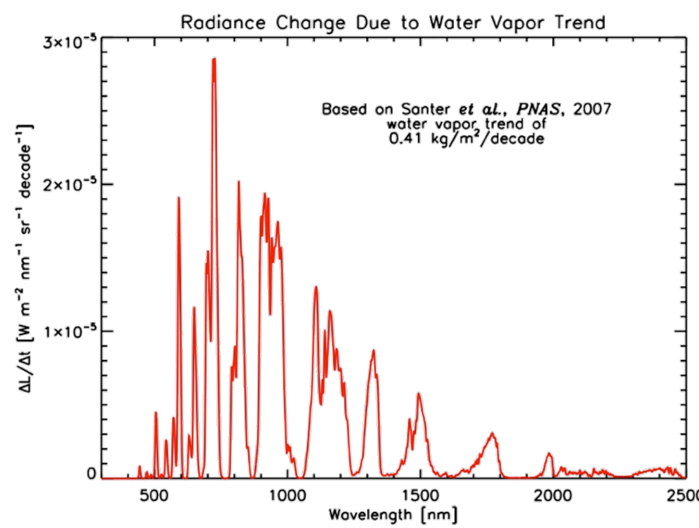


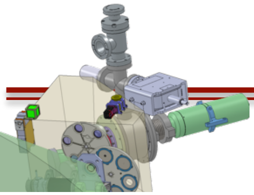
Requirements: Water Vapor Radiance Sensitivity

Largest absolute changes (below right) occur in the sub-saturated VNIR water bands; largest relative changes (below left) in the wings of the strong SWIR bands

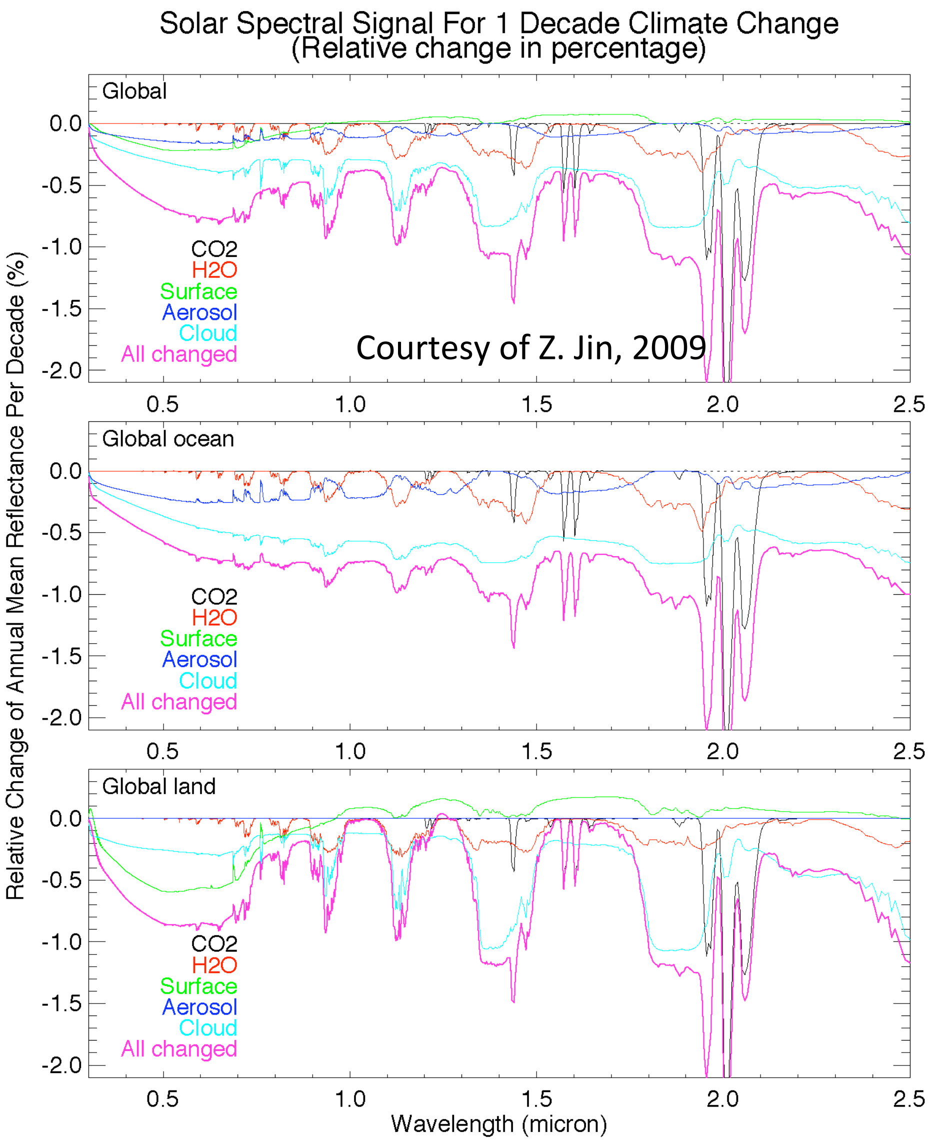


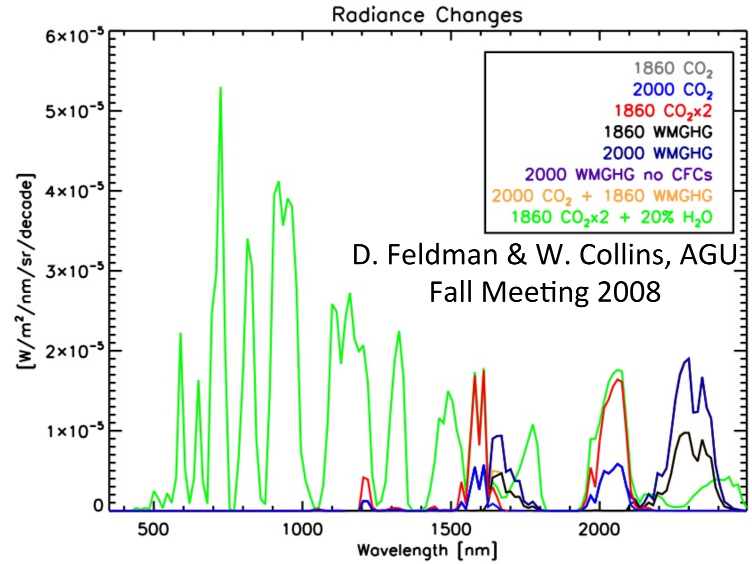


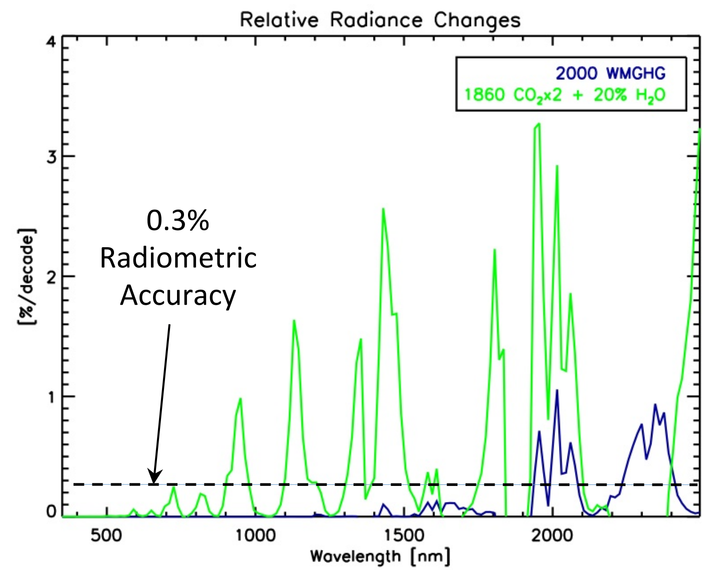




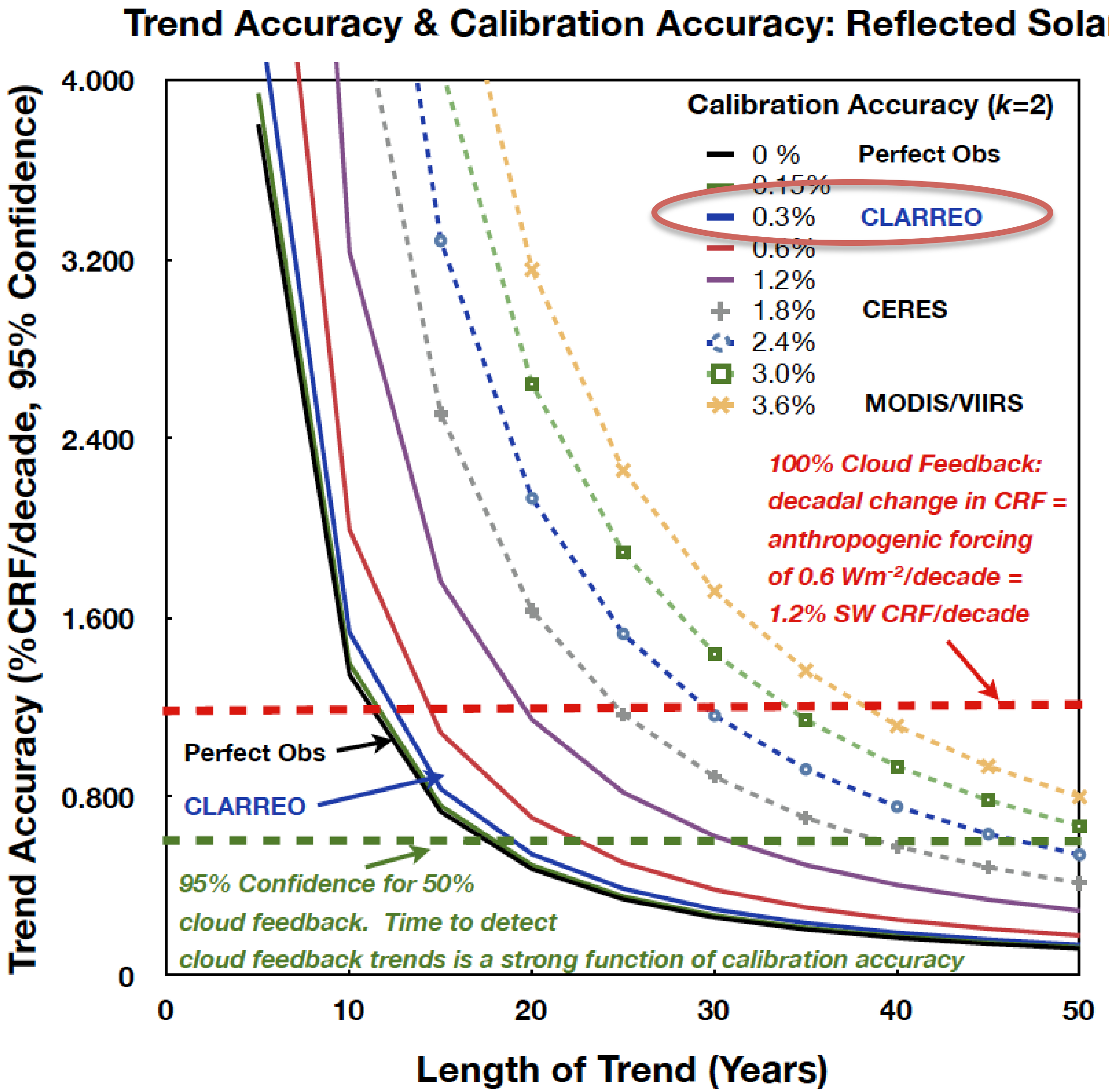
Requirements: from Modeled Climate Signatures



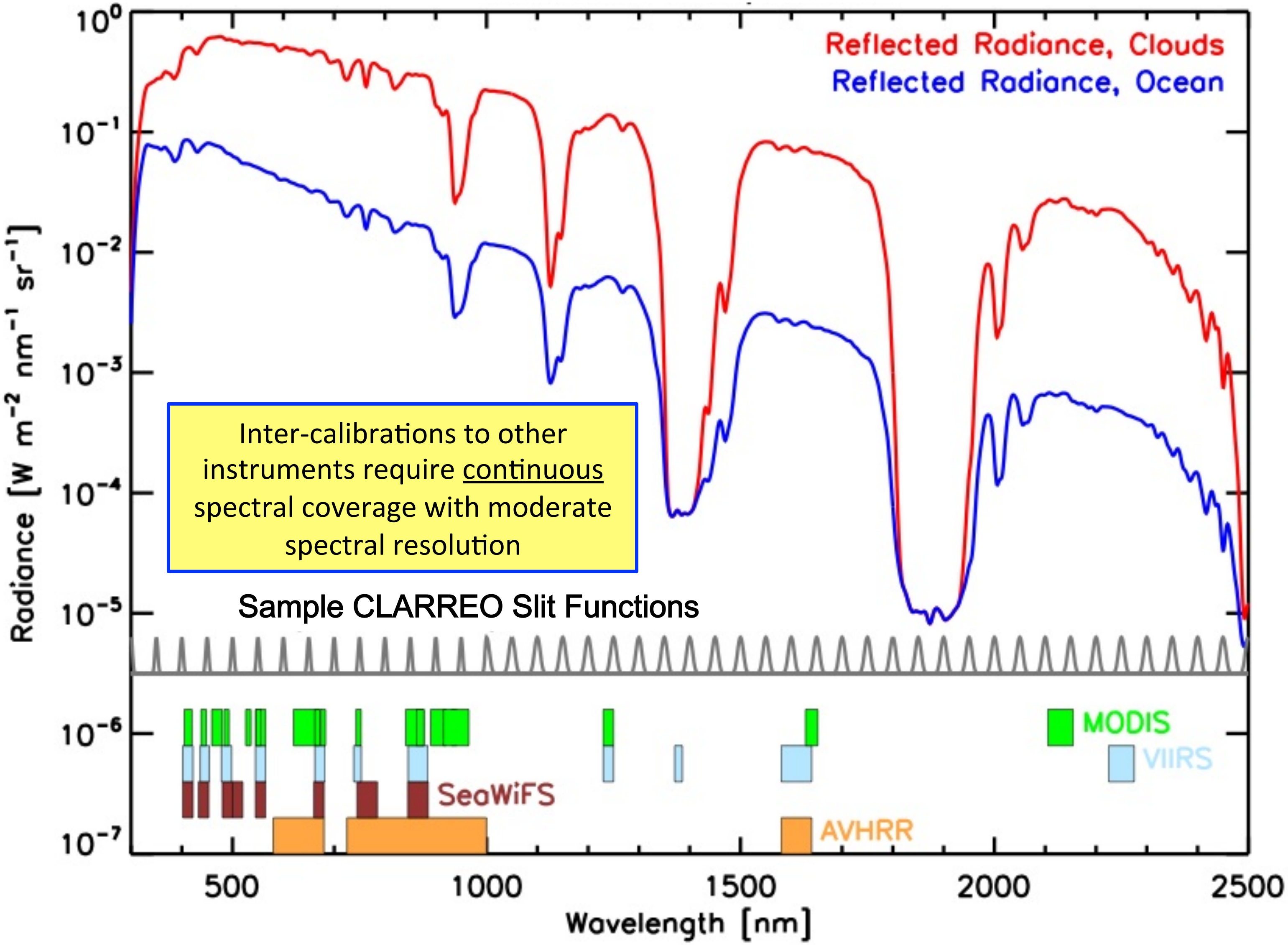


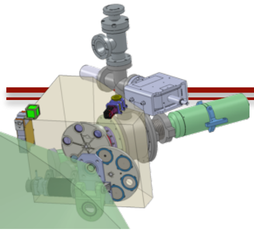


Requirements: from Cloud Radiative Feedback

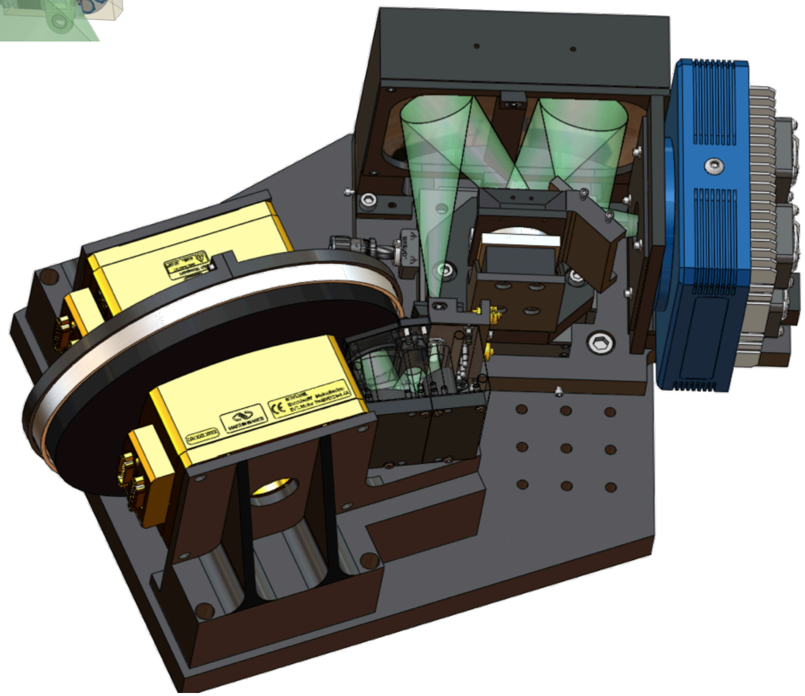


Requirements: from Inter-Calibrations





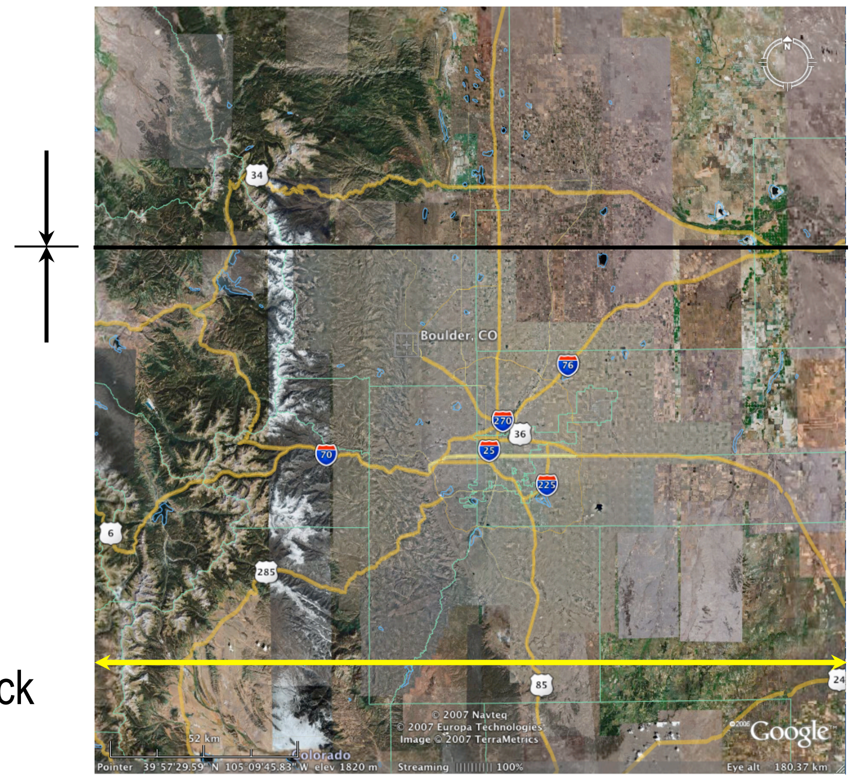
Earth-Viewing Shortwave Goals for 2007 IIP



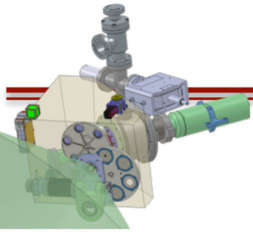
Hyperspectral Imager Requirements

Parameter	Value	Units
Spatial Resolution	0.5	km
Spatial Range (cross-track)	200	km
Wavelength (min)	300	nm
Wavelength (max)	2400	nm
Spectral Resolution	10	nm
Relative Std Uncertainty	0.2	%

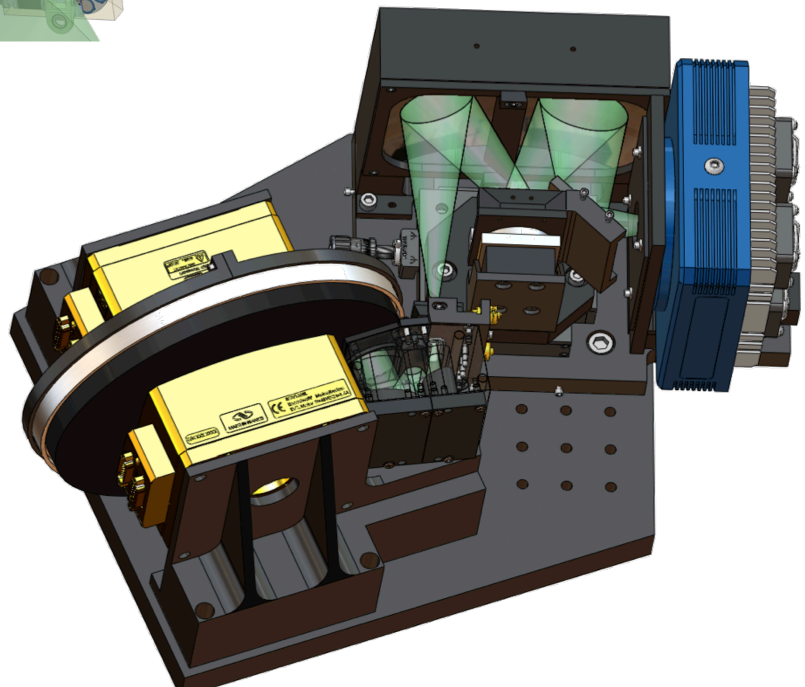
0.5 km (2.5 arcmin) IFOV



15° (180 km) (~370 pixels) Earth cross-track



Solar Cross-Calibration Gives Radiometric Accuracy



Ratio of solar incoming to outgoing radiances benchmarks climate in shortwave

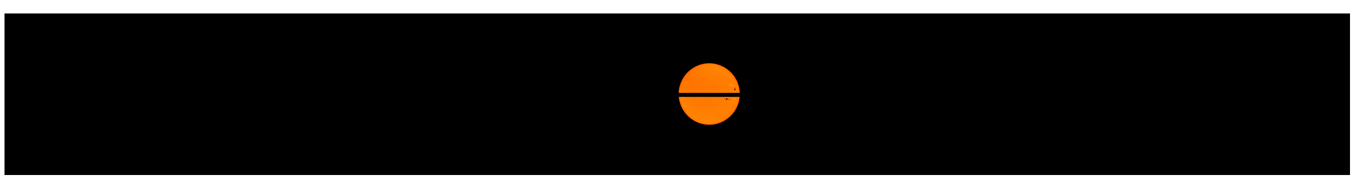
Ratio of reflected (outgoing) to incoming solar radiation measured to <0.2% (1-σ).

Hyperspectral Imager Requirements

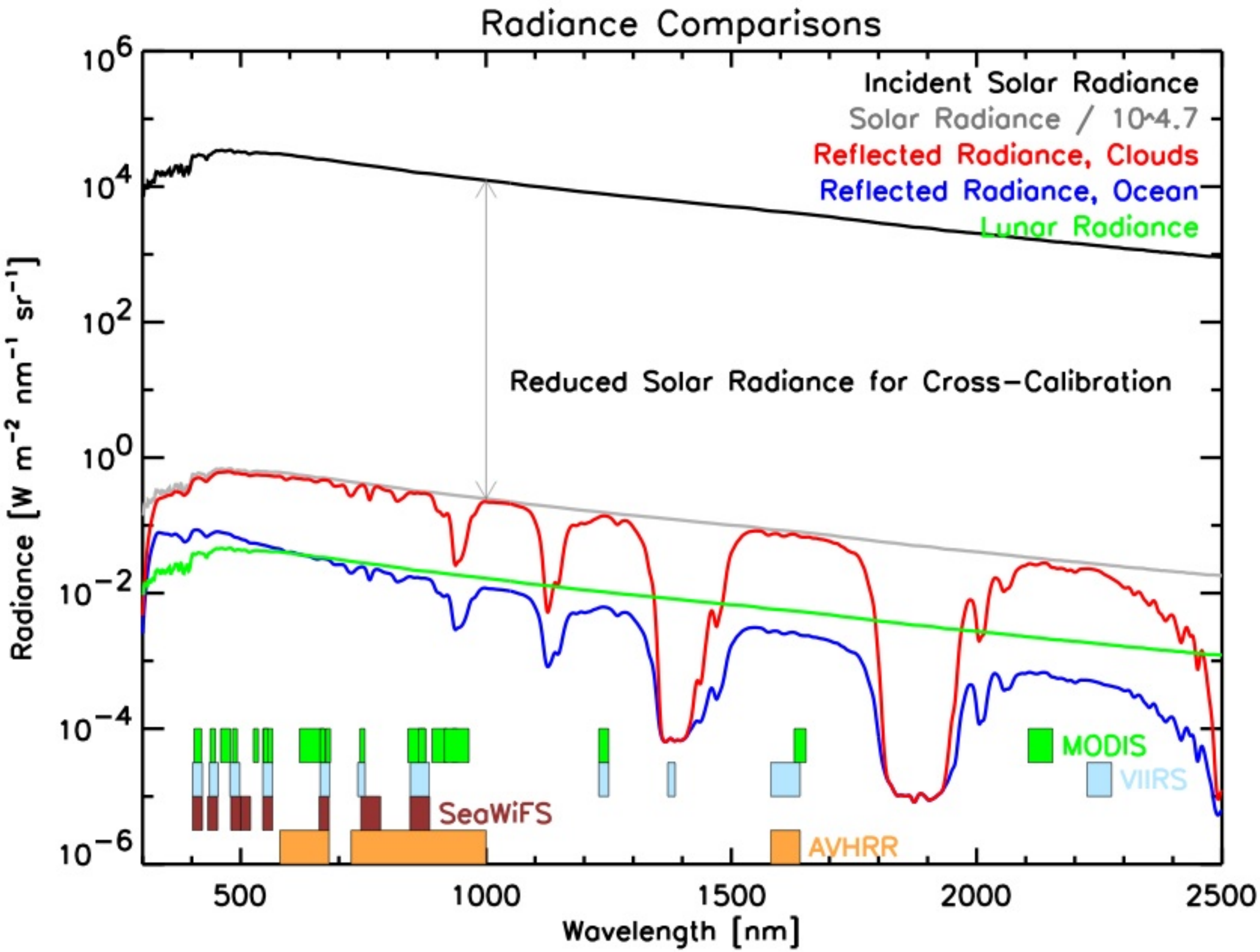
Parameter	Value	Units
Spatial Resolution	0.5	km
Spatial Range (cross-track)	200	km
Wavelength (min)	300	nm
Wavelength (max)	2400	nm
Spectral Resolution	10	nm
Relative Std Uncertainty	0.2	%

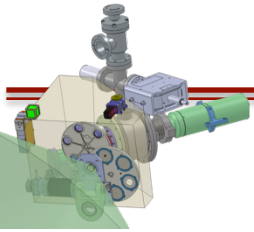
Cross-calibration accuracy from incident solar 0.2% (1-σ)

One or two spatial/spectral imagers cover 300-1000 and 1000-2400 nm.
Small (~2-cm) telescope optics image the Earth onto spectrographs.
Radiance attenuation methods reduce intensity an accurately known amount, allowing cross-calibrations with Sun.



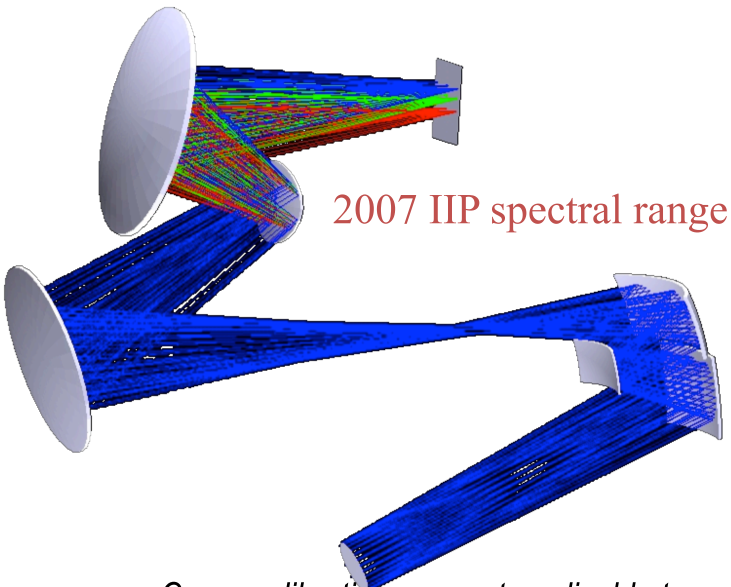
Solar Cross-Calibrations Require ~10^{-5} Attenuation



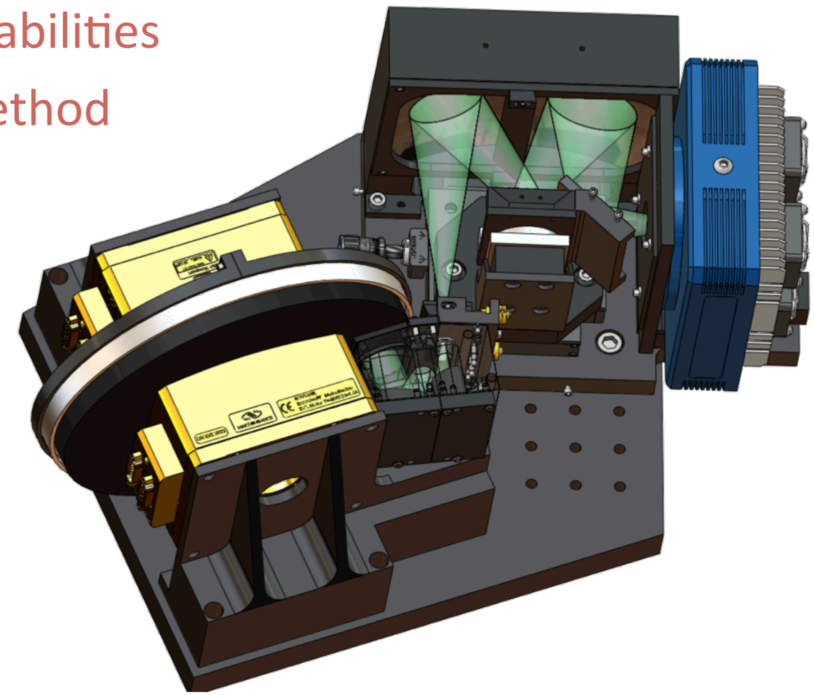


2007 IIP Demonstrated LASP's Novel Solar Cross-Calibration Approach

- **Intent** is to demonstrate cross-calibration capability from spectral solar irradiance to desired accuracies
- **Method** is to prototype a visible (Si-based) hyperspectral spectrometer with integrated attenuation methods and
  - Demonstrate accurate attenuation capabilities
  - Show a solar irradiance observation method



2007 IIP spectral range 300-1050 nm

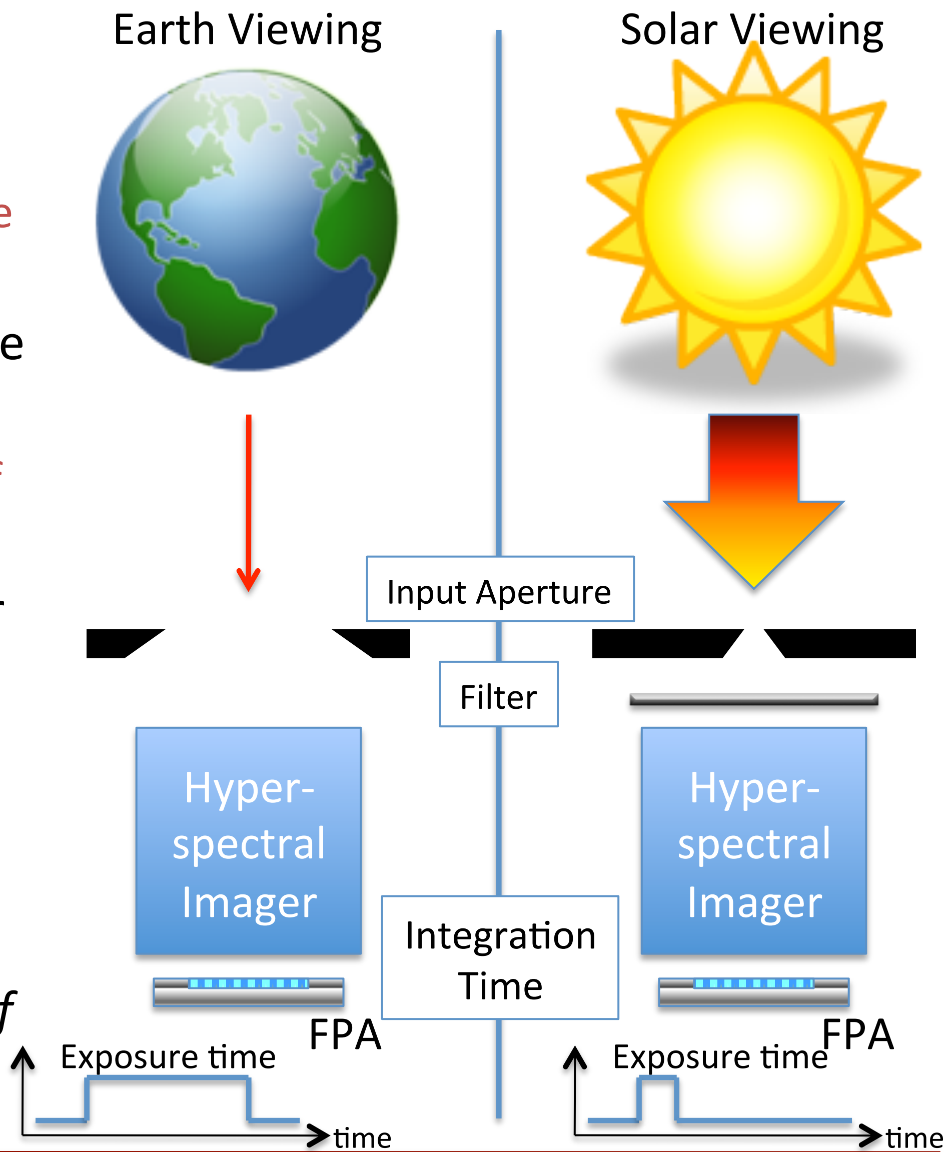


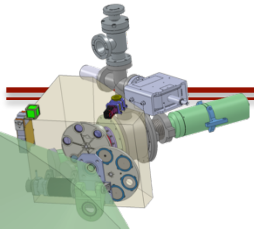
Cross-calibration concept applicable to many instruments; demonstrated in IIP using a hyperspectral imager.

Attenuation Methods Demonstrated

- Reduction of input aperture area (aperture attenuation)
  – Can achieve over 3 orders of magnitude of attenuation (limited by diffraction)
- Reduction of detector integration time (integration time attenuation)
  – Can achieve 1.7 orders of magnitude of attenuation (limited by electronics)
- Attenuation filters with on-orbit lunar calibrations
  – Can achieve 1 order of magnitude of attenuation (limited by S/N)

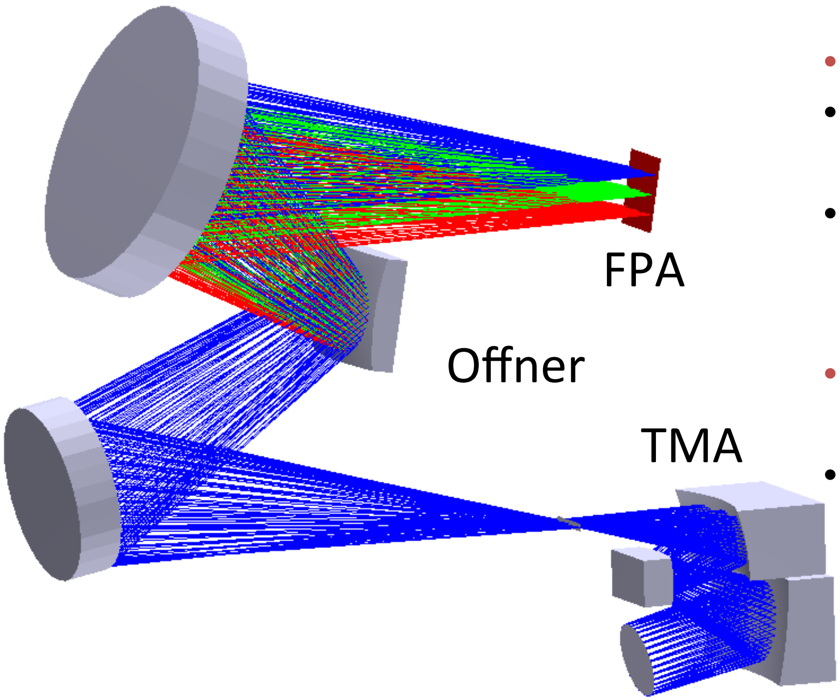
All attenuation methods are relative measurements; direct measurements of solar or Earth irradiances not required.





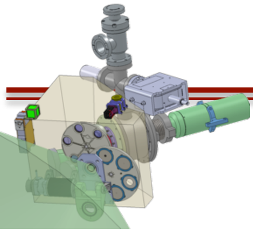
Overview of the Optical Design (2007 IIP)

- **CMOS FPA** provides fast readout (to test integration time attenuations) and electronic shuttering (to eliminate image smear for accurate radiometry)



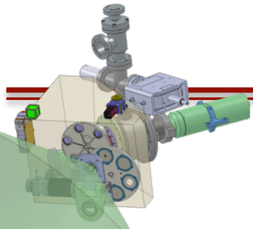
- **Offner spectrometer** provides spectral dispersion
- Designed around commercially available components for IIP proof-of-concept
- Imaging errors (aberration, smile, keystone) are <20% the effective pixel size.

- **Three mirror anastigmat (TMA)** images scene onto spectrometer slit
- Diamond turned optics/mounts simplified assembly & alignment



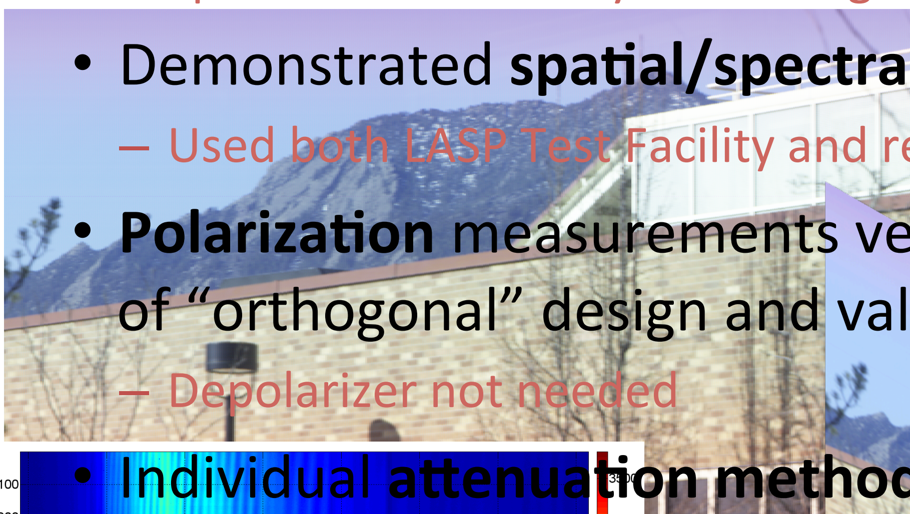
2007 IIP Accomplishments Chart

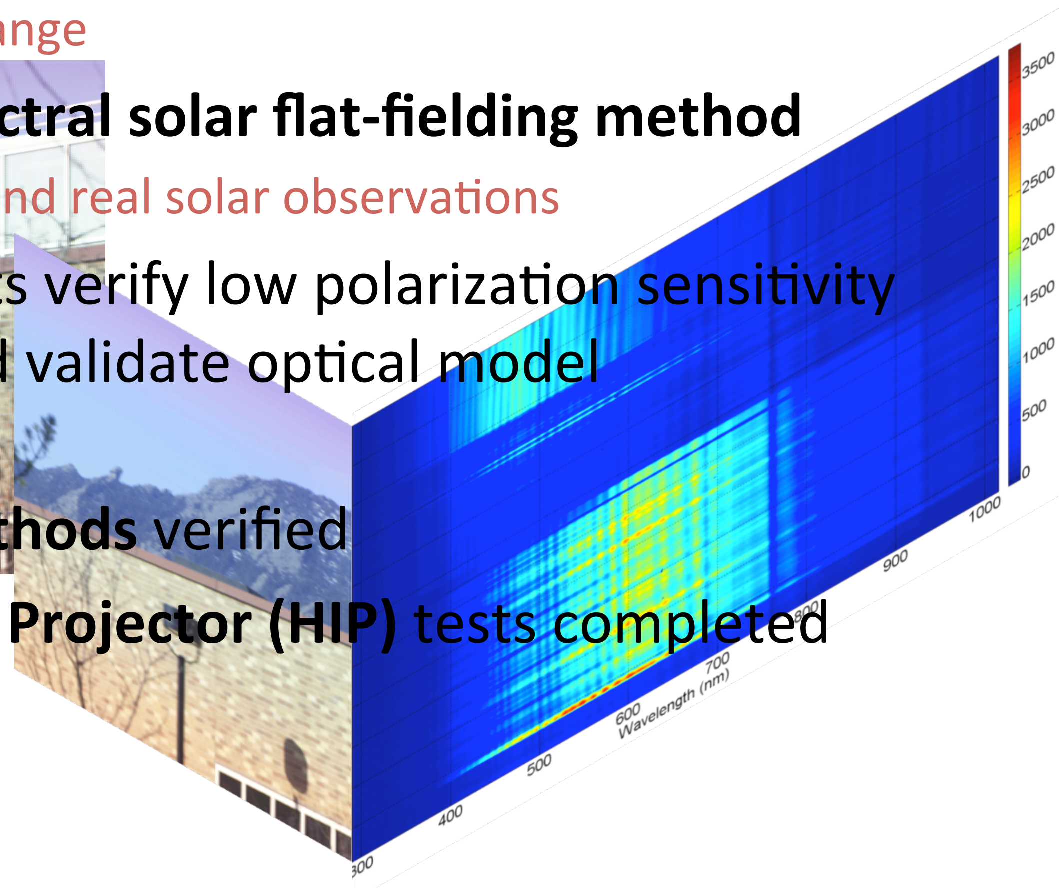
System	Accomplishment	Completed
Attenuation System	Methods tested; uncertainties quantified	•
Hyperspectral Imager	Designed and built; used as test instrument for attenuation studies	•
Test Facility	Designed and built; used for attenuation studies	•
End-to-End Testing	Outdoor scenes (Sun, Earth, Moon); heliostat; NIST/HIP	•
Environmental Testing	Built Engineering Model and tested for vibe, thermal/vacuum, lifetime	•

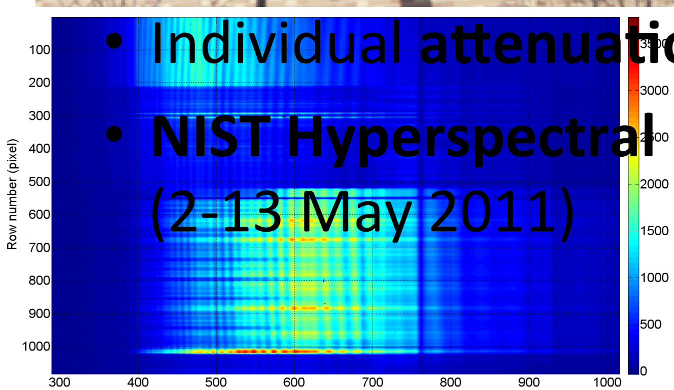


Hyperspectral Imager Testing (2010-2011)

- **Outdoor Tests** provide spatial/spectral scans of Sun, atmosphere, water, sky, clouds, vegetation, and buildings
  - Provides realistic spectral profiles for demonstrating capabilities
  - Spans much of 10^5 dynamic range
- Demonstrated **spatial/spectral solar flat-fielding method**
  - Used both LASP Test Facility and real solar observations
- **Polarization** measurements verify low polarization sensitivity of "orthogonal" design and validate optical model
  - Depolarizer not needed
- Individual **attenuation methods** verified
- **NIST Hyperspectral Image Projector (HIP)** tests completed (2-13 May 2011)

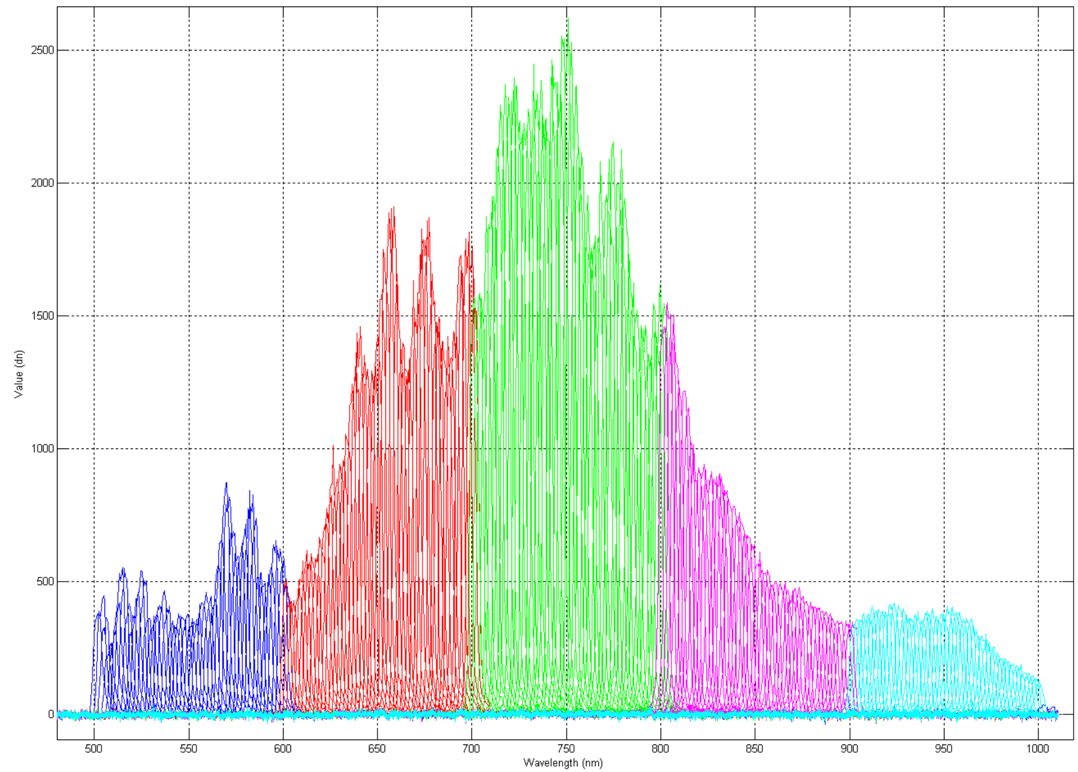


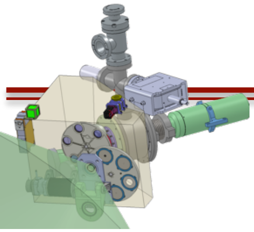




NIST HIP Tests Performed (2011)

- "Sun" scans with solar spectrum
- "MTF" patterns test optical performance and stray light
- Simulated ground track motions of real scene
- Digital attenuation studies validate linearity and attenuations
- Spectral reference comparison provides QE and calibrations
- Radiometric calibrations

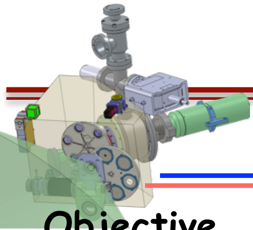




Recommended Future Work at End of 2007 IIP

- Attenuation methods
  - Integration times exceed expected capabilities; successful
  - Filter calibration method proven; successful
  - Aperture ratio difficult but close
    - Improve optics and test scene (Test Facility or solar viewing)
- Include and characterize flight-qualified FPA for full spectrum
- Spectrometer
  - Utilize demonstrated TMA-type optics
  - Reduce slit scatter
- Test Facility is more difficult than applying attenuations
  - Benefit from more realistic solar scenes (high altitude flights)

Implement via 2010 IIP "HySICS"



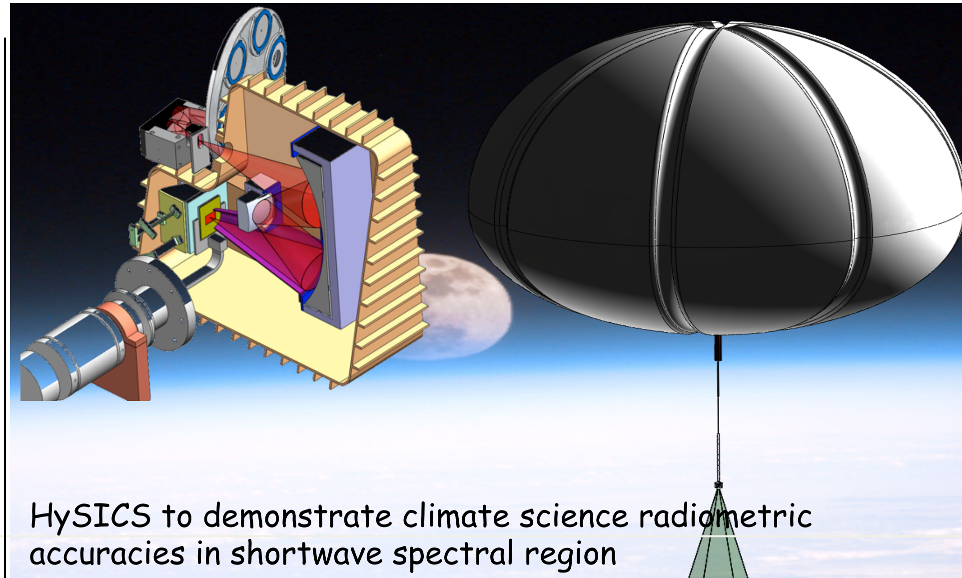
HyperSpectral Imager for Climate Science

Objective

Build and flight test a hyperspectral imager with improved radiometric accuracies for climate science

- 350-2300 nm with single FPA to reduce cost & mass
- <0.2% (k=1) radiometric accuracy
- <8 nm spectral resolution
- 0.5 km (from LEO) IFOV and >100 km FOV
- <0.13% (k=1) instrumental polarization sensitivity

Perform two high-altitude balloon flights to demonstrate solar cross-calibration approach and to acquire sample Earth and lunar radiances



Approach

Single HgCdTe FPA covers full shortwave spectral range with reduced mass, cost, volume, and complexity

Incorporate solar cross-calibration approaches demonstrated on prior IIP to provide on-orbit radiometric accuracy and stability tracking

Orthogonal configuration reduces polarization sensitivity

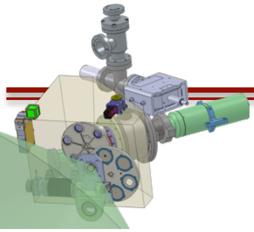
No-cost balloon flights from experienced team at NASA WFF demonstrate on-orbit capabilities

CoIs: Co-I – Peter Pilewskie / LASP
Balloon Flight Manager – David Stuchlik / WFF

Key Milestones

• Instrument Design Complete	12/11
• Balloon Gondola and Interface Design Complete	08/12
• Gondola Assembly Complete	11/12
• Long Lead FPA, Grating, & Filter Procured	12/12
• FPA Characterizations Complete	02/13
• Instrument Assembly Complete	02/13
• Instrument Calibrations Complete	07/13
• Environmental Tests Complete	08/13
• Balloon Flight #1 Complete	10/13
• Balloon Flight #2 Complete	05/14

$TRL_{in} = 3$

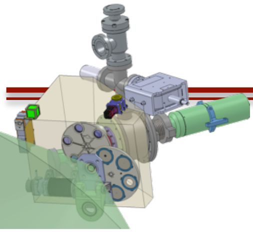


HySICS Optical Design Requirements

Parameter	Design Requirement
Spatial Resolution	2.5 arcmin
Field of View (cross track)	10°
Wavelength Range	350-2300 nm
Wavelength Resolution	6 nm, constant, Nyquist
Aperture	20 mm

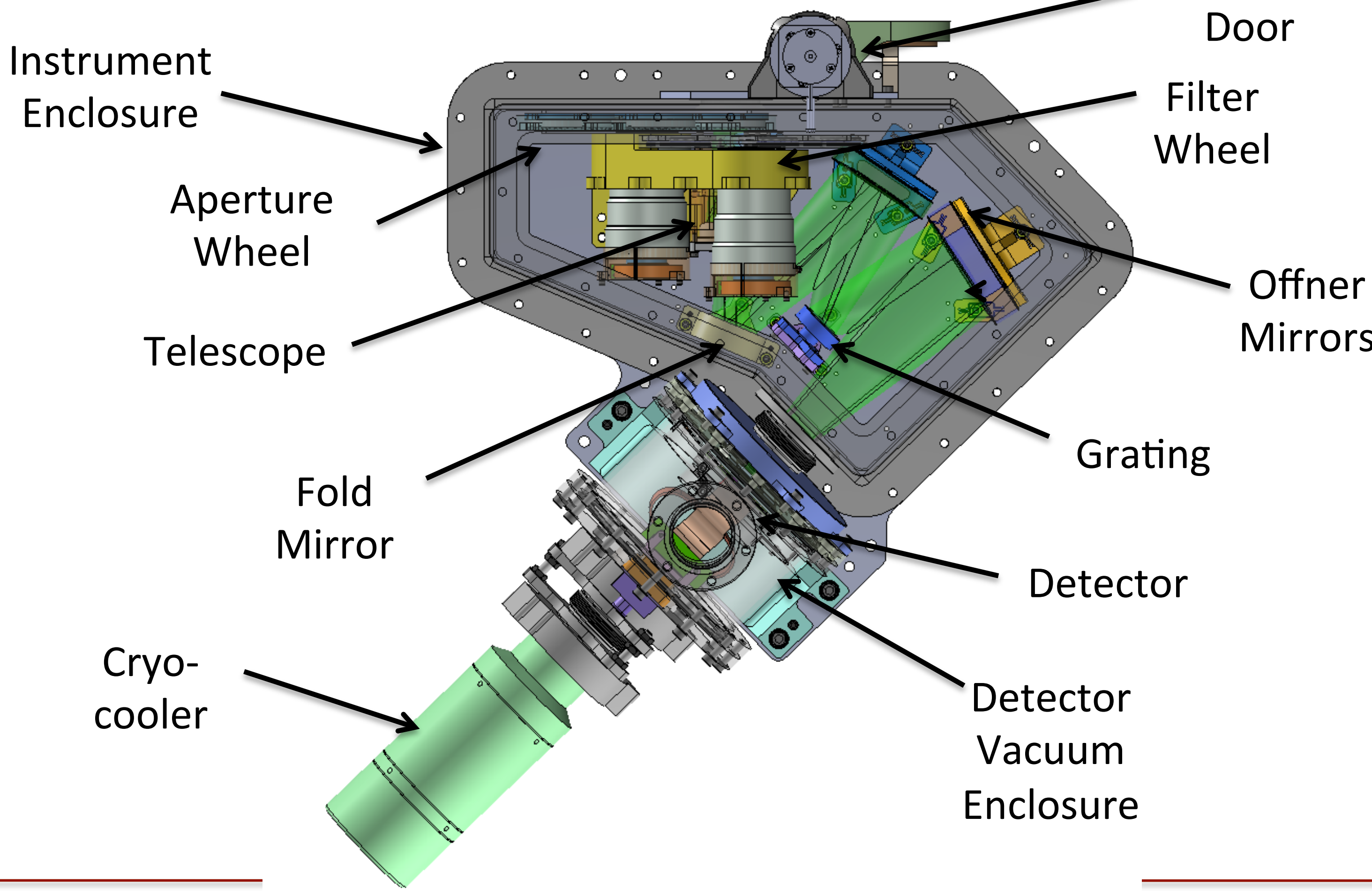
Other items guiding the optical design:

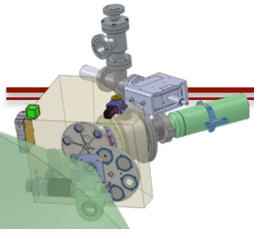
- High altitude balloon flight environment
- Pushbroom imaging spectrometer
- Precision aperture stop in front of the telescope
- FPA operates at 150 K
- Low polarization sensitivity



HySICS Is a Spatial/Spectral Spectrometer for Imaging Earth Scenes Using Sun as Radiometric Reference

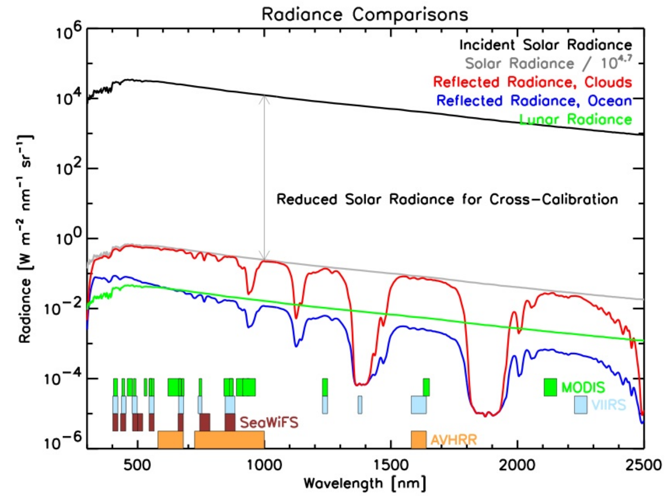
- Telescope images scenes through Offner spectrometer onto broadband detector

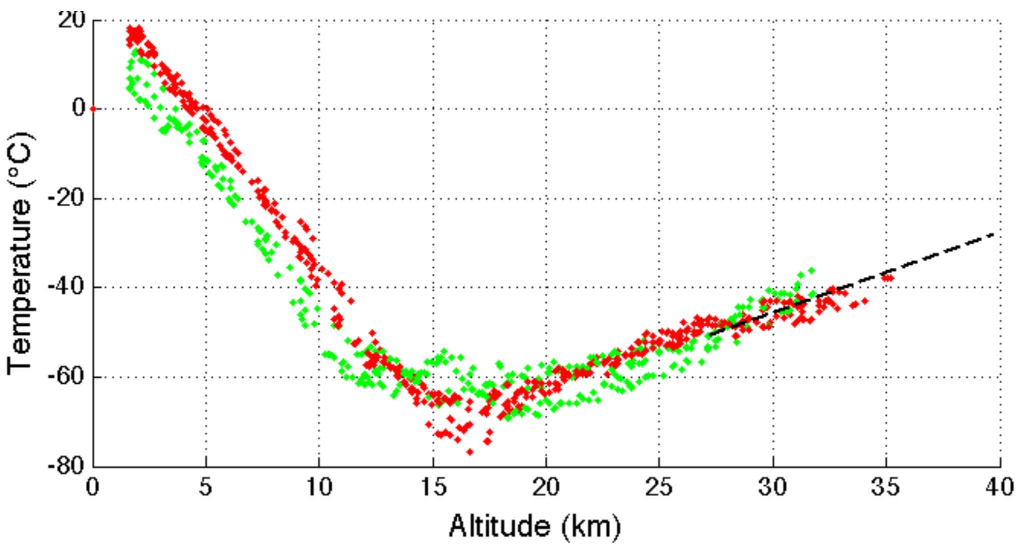


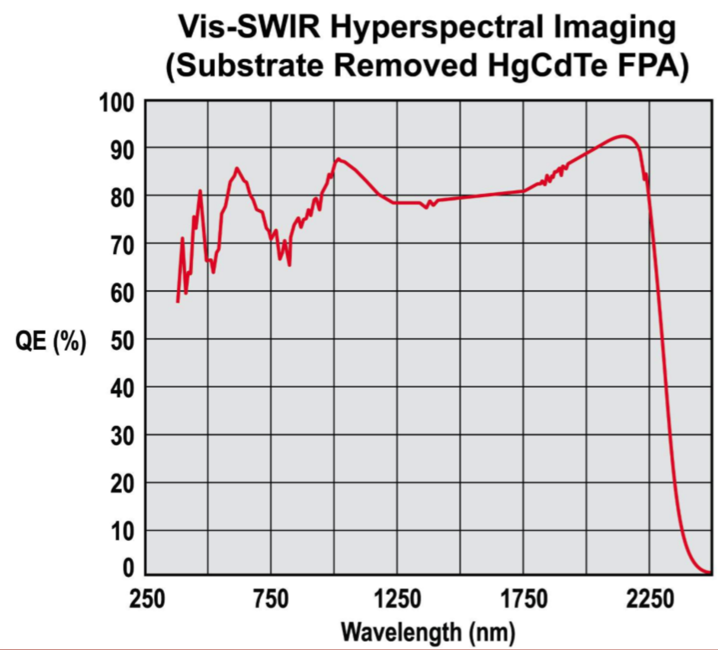


HySICS Instrument Changes from 2007 IIP

- Full spectral range (350 - 2300 nm)
  - HgCdTe FPA allowing short integration times
  - Order-sorting filter
- Thermal and environmental conditions

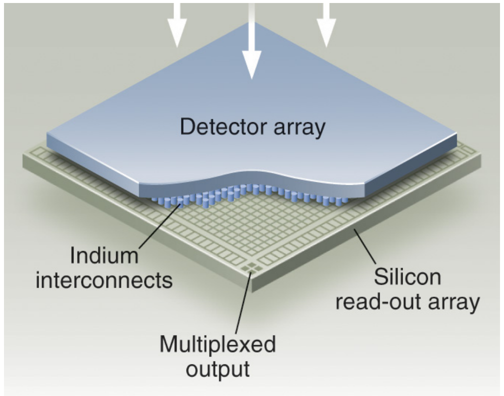


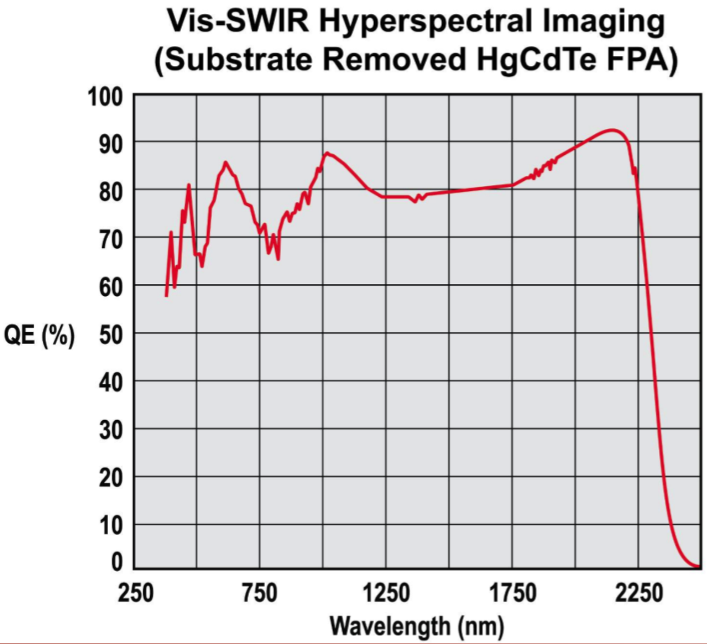


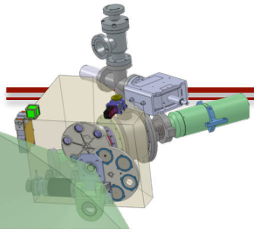


Single Spectrometer Spans Spectral Range

- Broadband array allows single spectrometer to span range
  - Reduces mass, volume, cost, power, optical complexity
- FPA is substrate-removed HgCdTe array
  - 350-2300 nm sensitivity
- Must operate at 150 K to meet noise requirements
- Delivery imminent



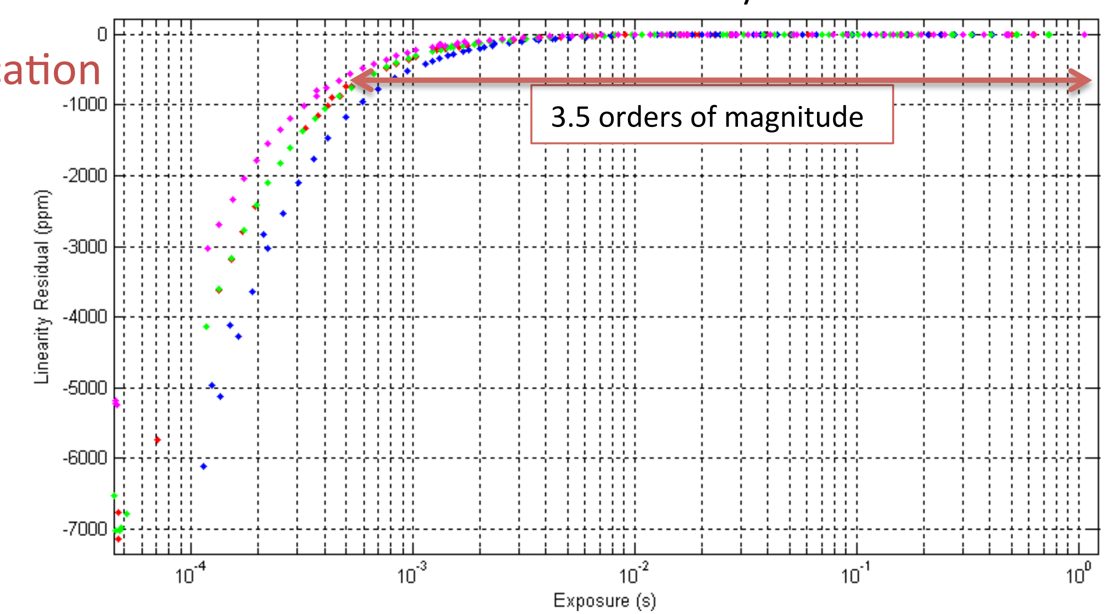




Detector Calibration and Test Plans

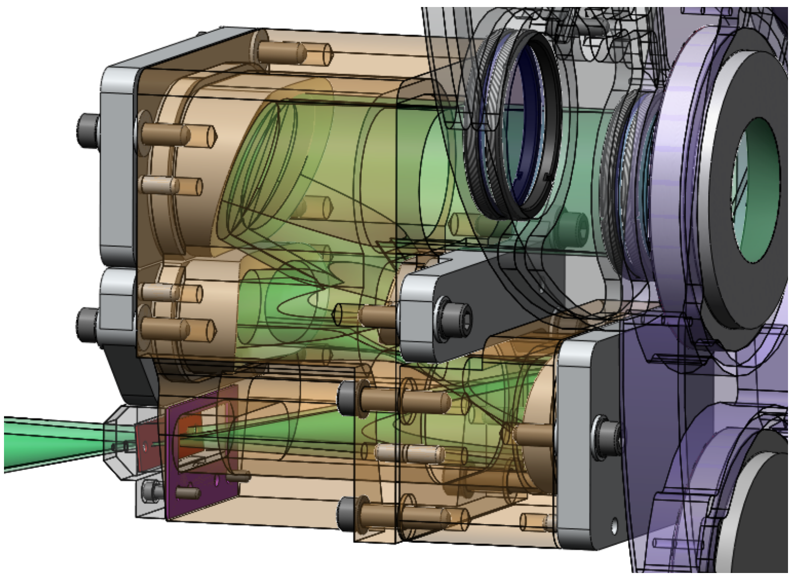
- The detector test plan will verify operation of FPA
  - Linearity test over 3 orders of magnitude
    - Measure integration time attenuation and associated uncertainty
  - Sensor gain using photon transfer curve
    - Read noise
    - ADC max gain setting (or full well)
  - Dark current
    - Temperature stability verification
  - Global shutter extinction
  - Flat field
  - UV degradation testing

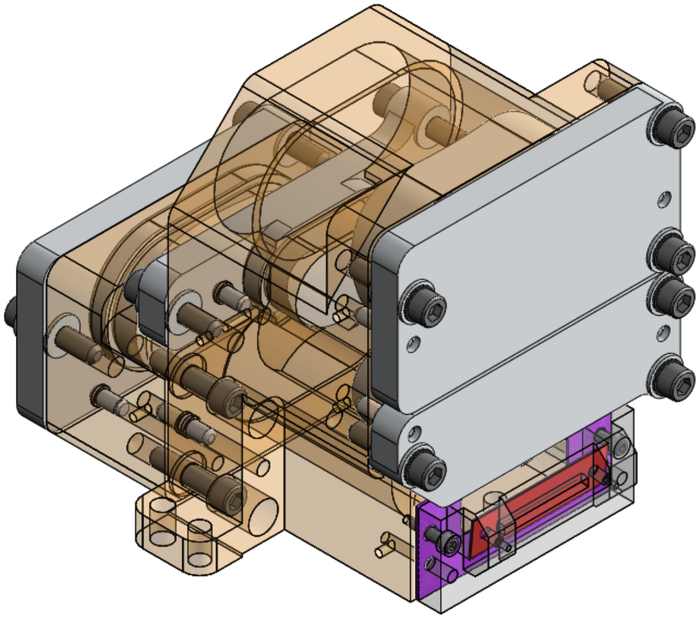
Photon Focus Linearity Residual

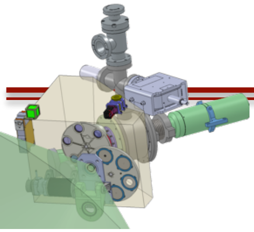


Optical Improvements

- Telescope redesign has lower scatter and better packaging
  - Re-packaging reduces glint from front of instrument
- Optimized non-conventional Offner design implementation that provides low polarization sensitivity
  - Validated optical model from 2007 IIP guides design tuning

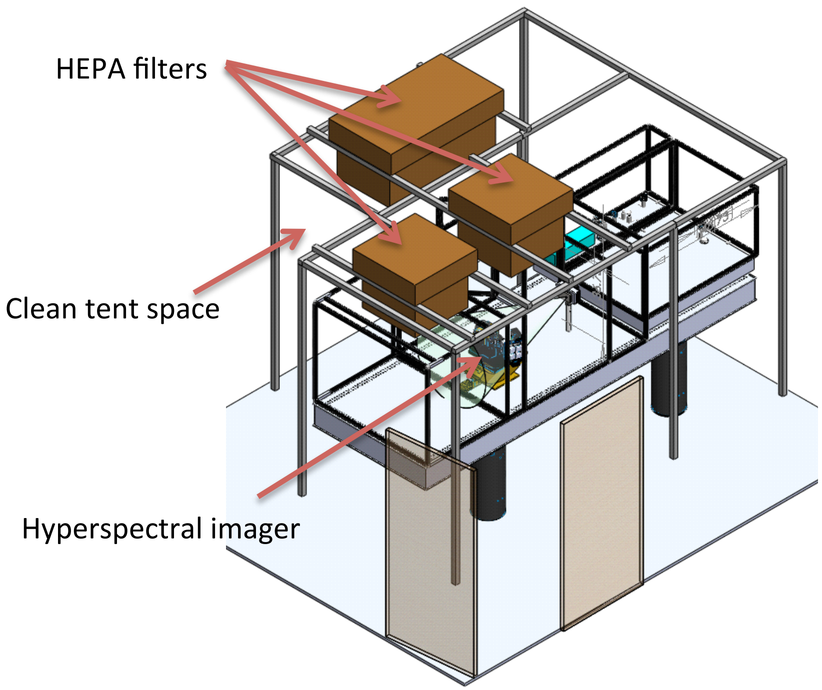


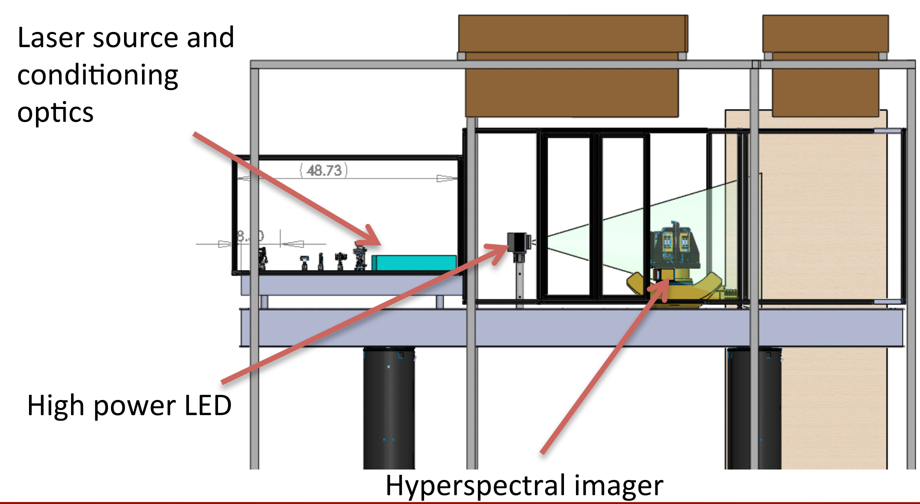


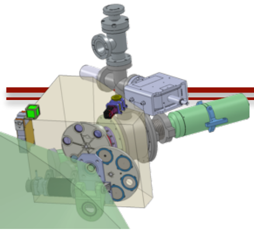


Test Facility Improved

- Power stability and beam uniformity of solar intensity beam improved
  - – High power laser adjusts intensity over >5 orders of magnitude
    - Monitored with trap detector calibrated by NIST over 7 orders of magnitude
  - – Uniform and stable white light source provides broadband calibrations

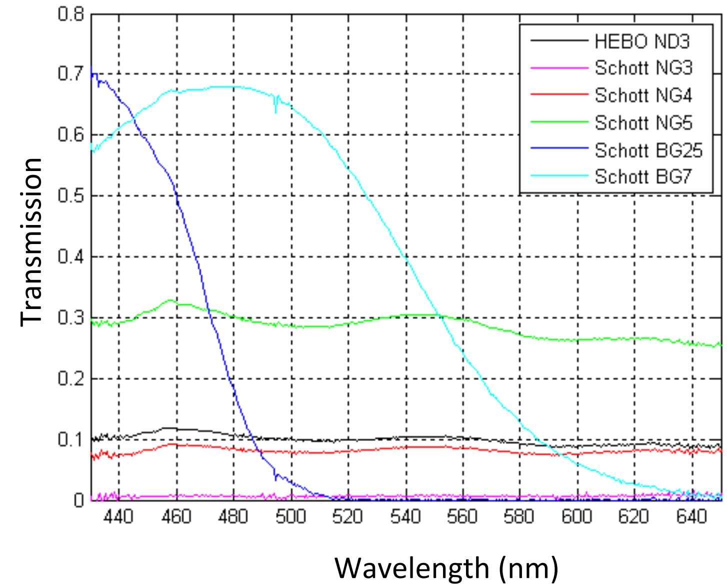




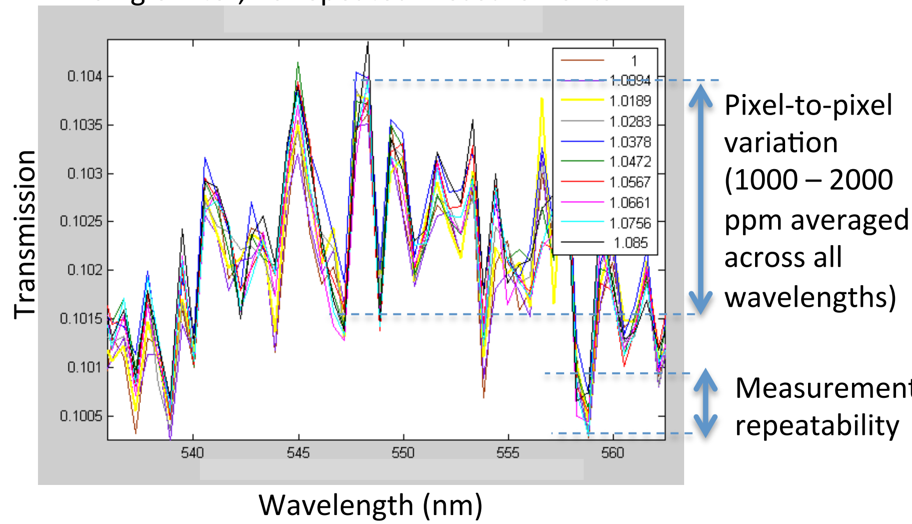


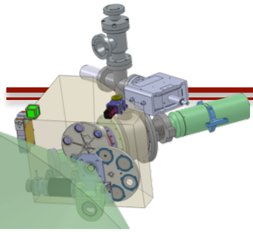
Filter Calibration Method Demonstrated

- Filters tested using 2007 IIP instrument
  - Relative measurement between power spectra with filter in and filter out
  - Validates test plan for HySICS filter calibration
- Multiple measurements span several days
  - *Repeatability exceeds pixel-to-pixel variations*
- The test procedure will be repeated with HgCdTe FPA
  - Should have better uniformity

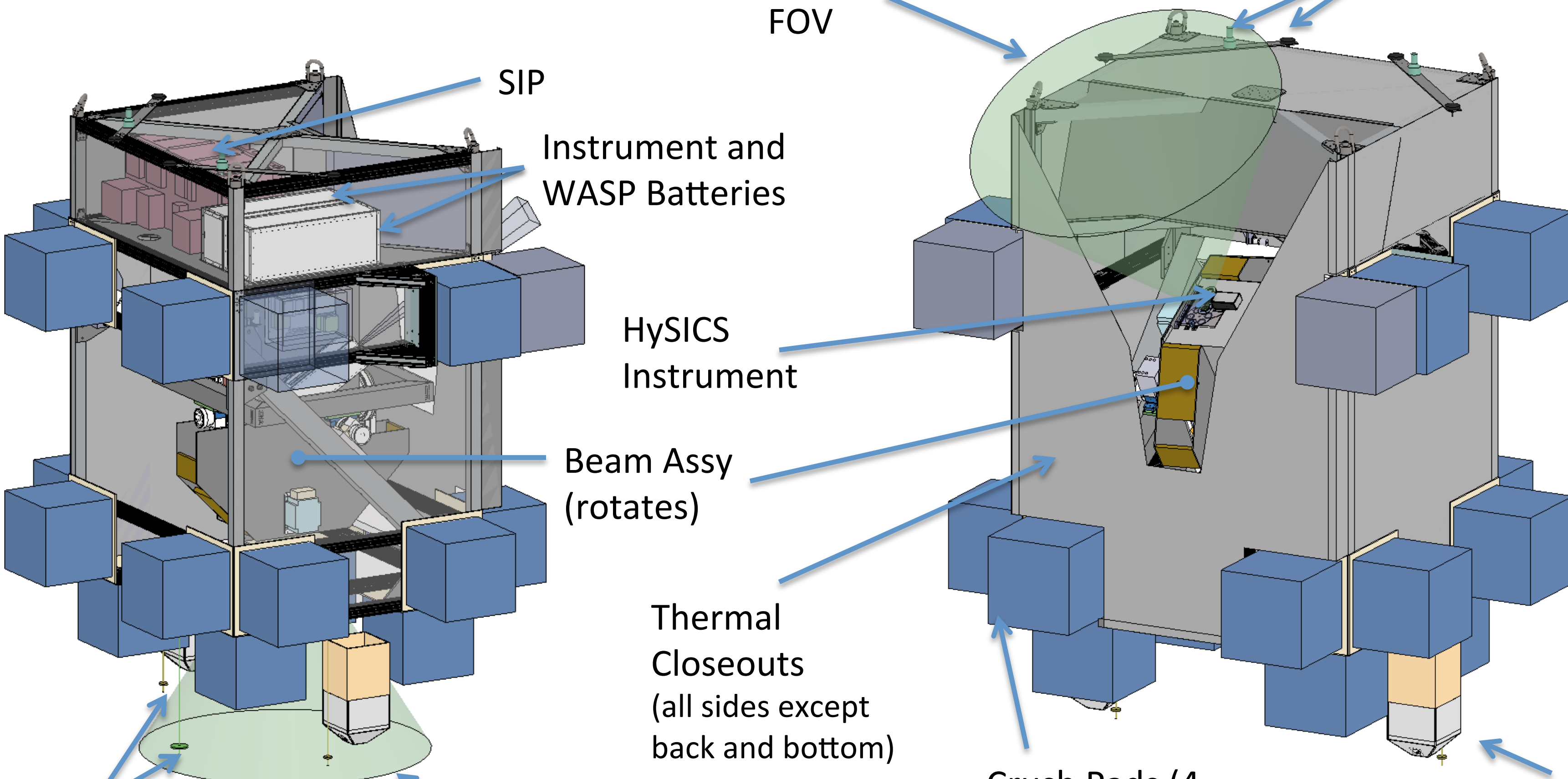


Single filter, 10 repeated measurements



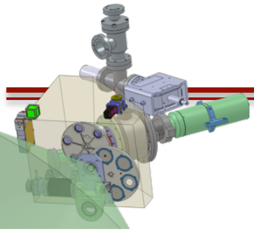


Gondola Allows Solar, Lunar, and Earth Viewing

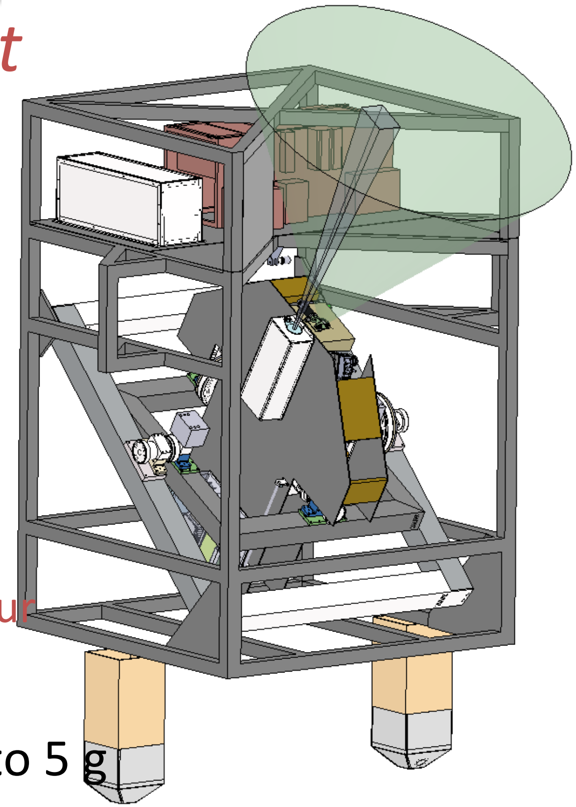


Nadir Pointing

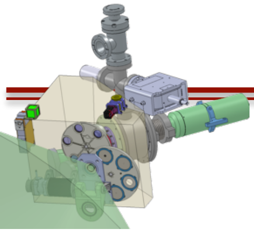
Sun/Moon Pointing



Balloon Environment

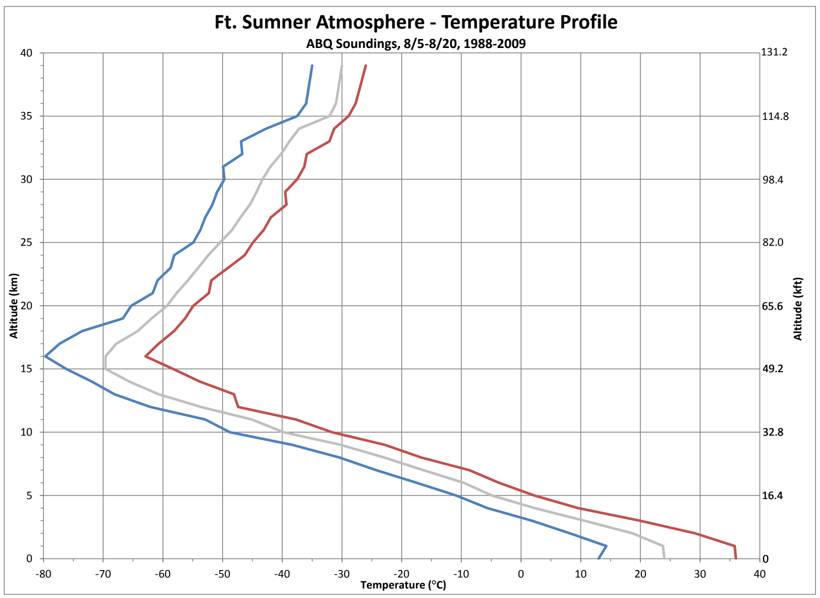


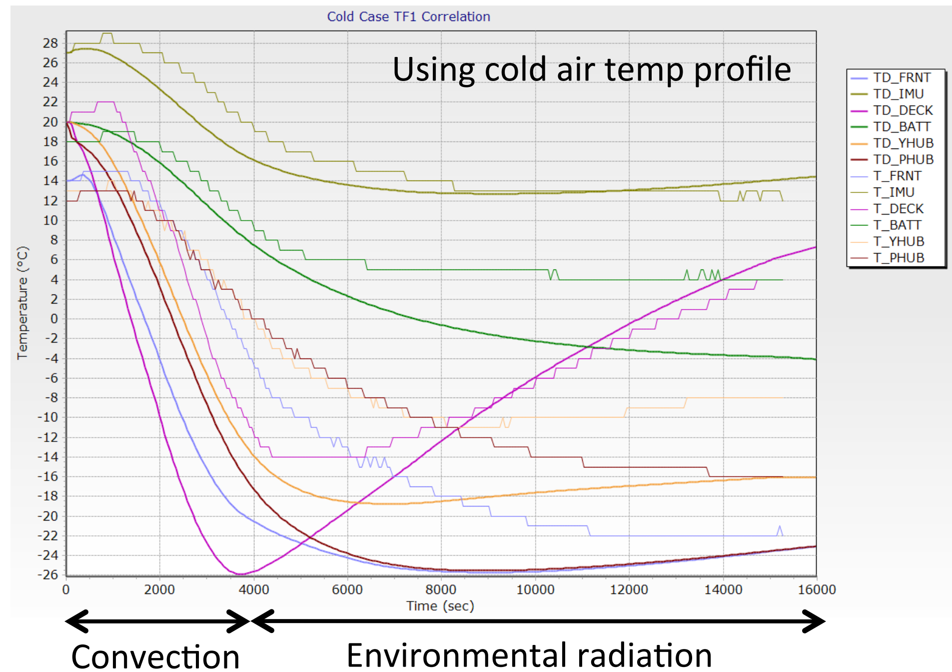
- 2 high-altitude balloon flights from Ft. Sumner, NM
  - Expected flight durations ~12 hours each
  - 125,000 ft altitude
  - 2.5-3.0 hours to get to altitude
- Temperature range
  - ~+60°C common above launch pad
  - -60°C can be experienced from 40k-70k ft for up to an hour
- Typical pressure at altitude 3-4 Torr
- Termination loads of up to 10 g with side loads of up to 5 g
- Relatively few weight limitations (balloons can carry 4000 lbs)
- Pointing system - WASP (Wallops Arc Second Pointer) will be provided by Wallops
  - Supplemented by LASP Fine Sun Sensor (10 arcsec)
- Two balloon "seasons" - Fall (Sept-Oct) and Spring (April-May)
  - Flights planned for Sept 2013 and Spring 2014

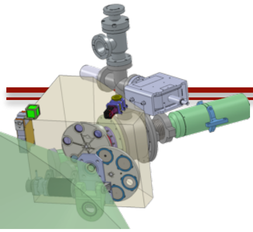


Flight Temperatures Measured and Modeled

- Air temperature and convective coefficient dominate initially
- Solar, Earth albedo, & IR radiation dominate at altitude





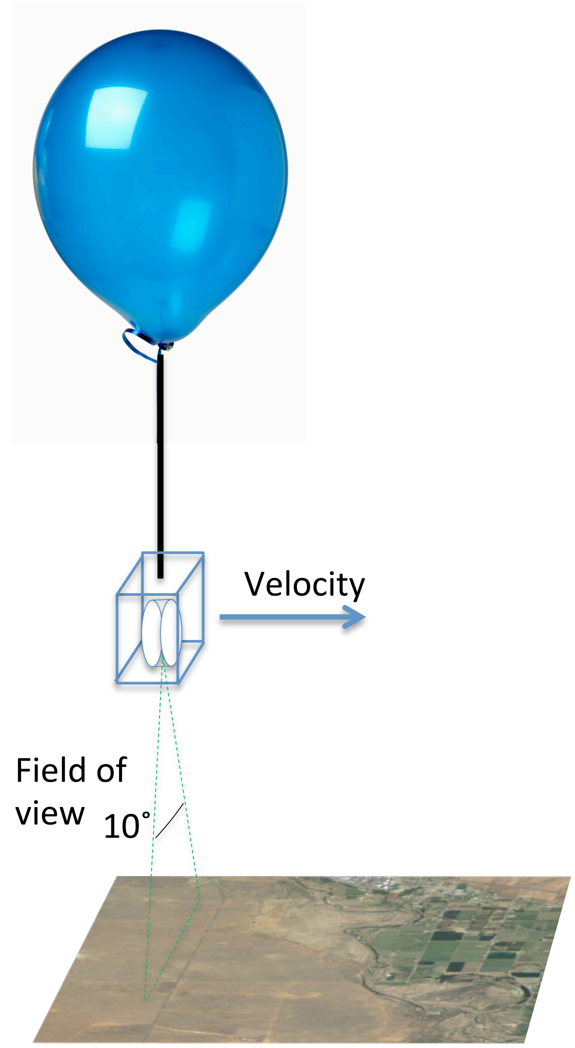


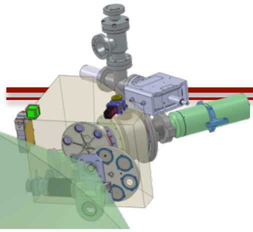
HySICS to Undergo Environmental Testing

- Environmental testing after initial instrument calibrations
- Instrument and electronics box vibration tests
- TVAC
  - 1 survival cycle + 8 hot/cold operational cycles
- Post I&T calibration to confirm instrument performance

HySICS Ground Observations

White Sands and Lake Sumner provide potential calibration sources

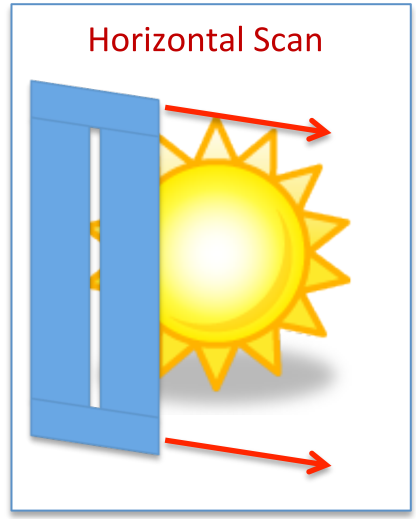


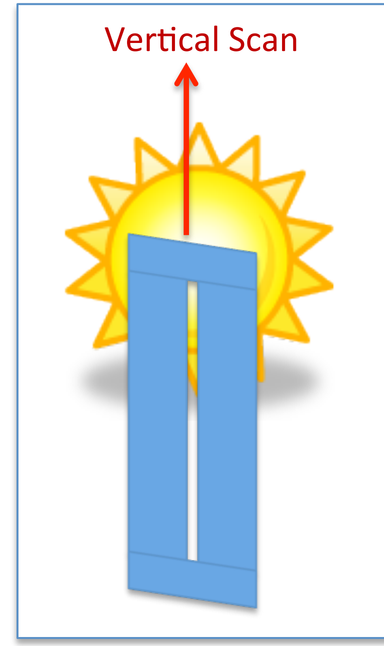


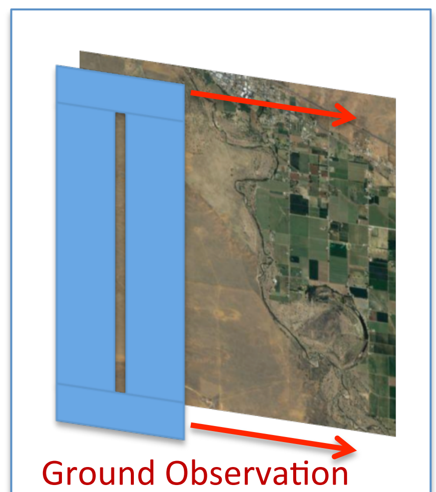
Science and Calibration Observations

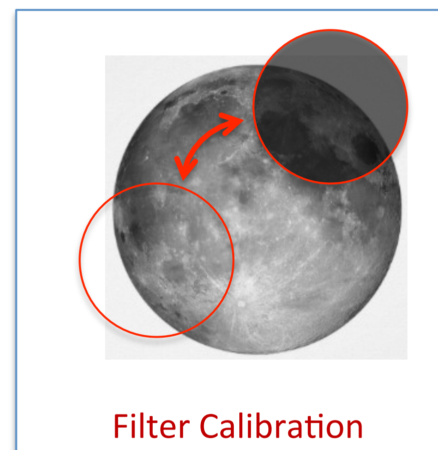
- Ground Observation
  - Acquire hyperspectral data from ground scenes
- Solar Irradiance Measurement (Horizontal Scan)
  - Measure the spectral solar irradiance by integrating images after smooth scan of slit across solar disk
- Flat Field Calibration (Vertical Scan)
  - Scan slit smoothly along diameter of solar disk
  - *Drives pointing requirements to ~15 arcsec*
- Filter Calibrations using Moon
  - Place slit across Moon and acquire measurements with and without filters

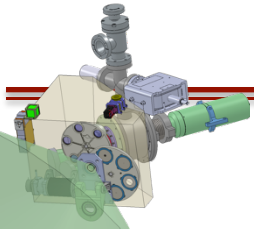
Observations not possible through variable atmosphere, so need >100 kft altitude







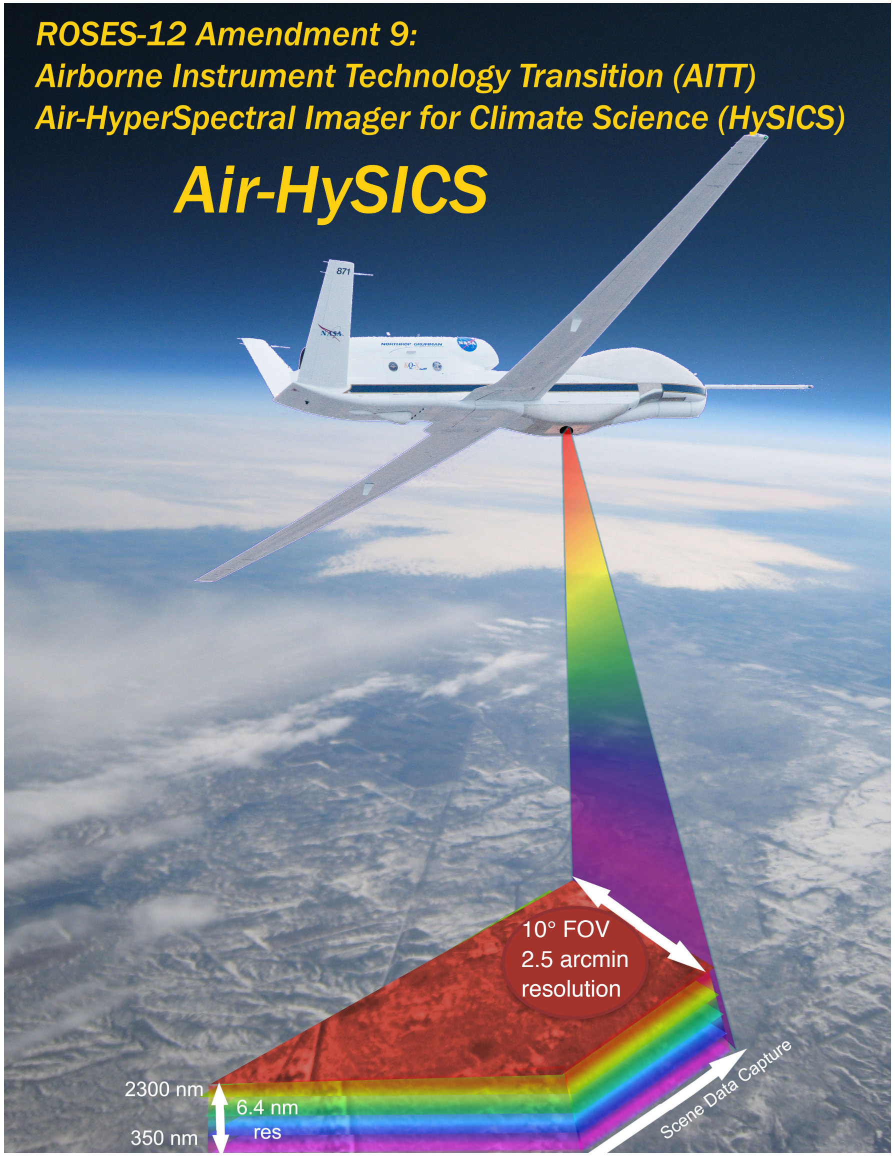


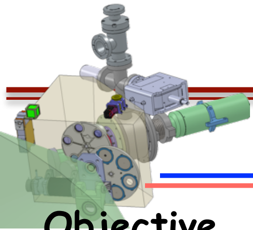


HySICS Has Broad Potential on Proposed Programs

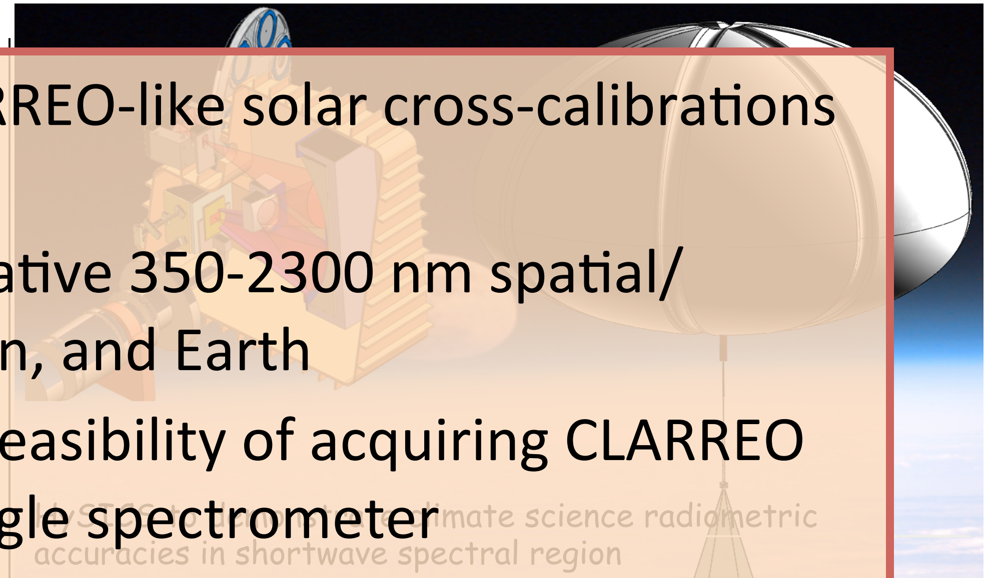
- Earth Venture 1
  - ACCLAIM (airborne)
- Earth Venture 2
  - ECHO (ISS)
- Earth Venture Instrument
  - ECHO (MOO)
- ROSES-12 AIIT
  - Air-HySICS (Global Hawk, ER-2)

<u>And, of course, CLARREO!</u>





HyperSpectral Imager for Climate Science



- HySICS will demonstrate CLARREO-like solar cross-calibrations under realistic conditions
- HySICS will acquire representative 350-2300 nm spatial/ spectral data of the Sun, Moon, and Earth
- HySICS will demonstrate the feasibility of acquiring CLARREO reflected solar data with a single spectrometer
  - Reduces mass, power, volume, cost, risk, and complexity
- HySICS builds on and improves needed ground test equipment
- HySICS demonstrates flight capabilities of RS instrument

Balloon Flight Manager – David Stuchlik / WFF