SORCE Science Meeting
29 January 2014

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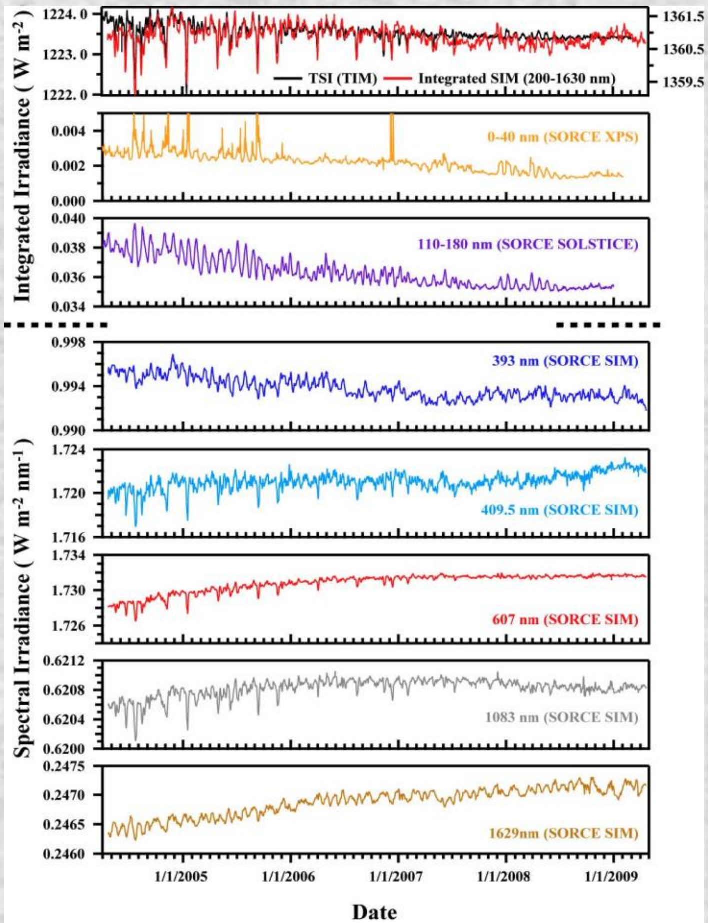
~~Radiometric Solar Telescope (RaST)~~

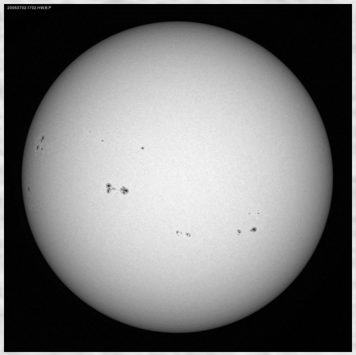
The case for a Radiometric Solar Imager,

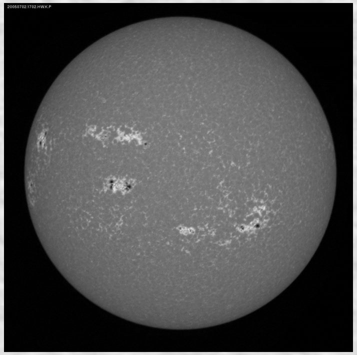
and how one might build one



Harder et al. 2009

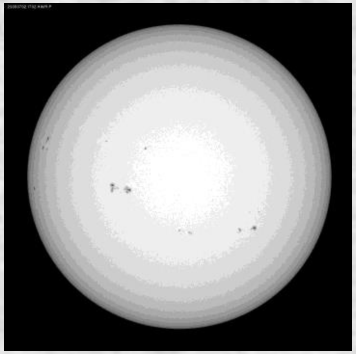
409.4nm





393.4nm

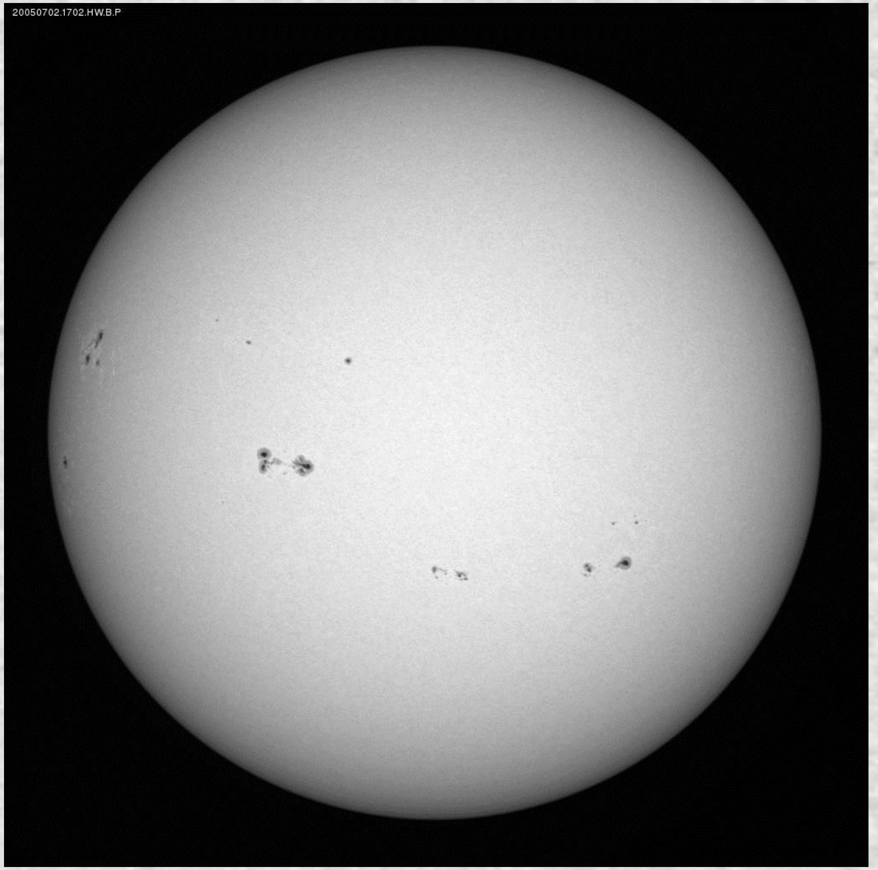
607.1nm

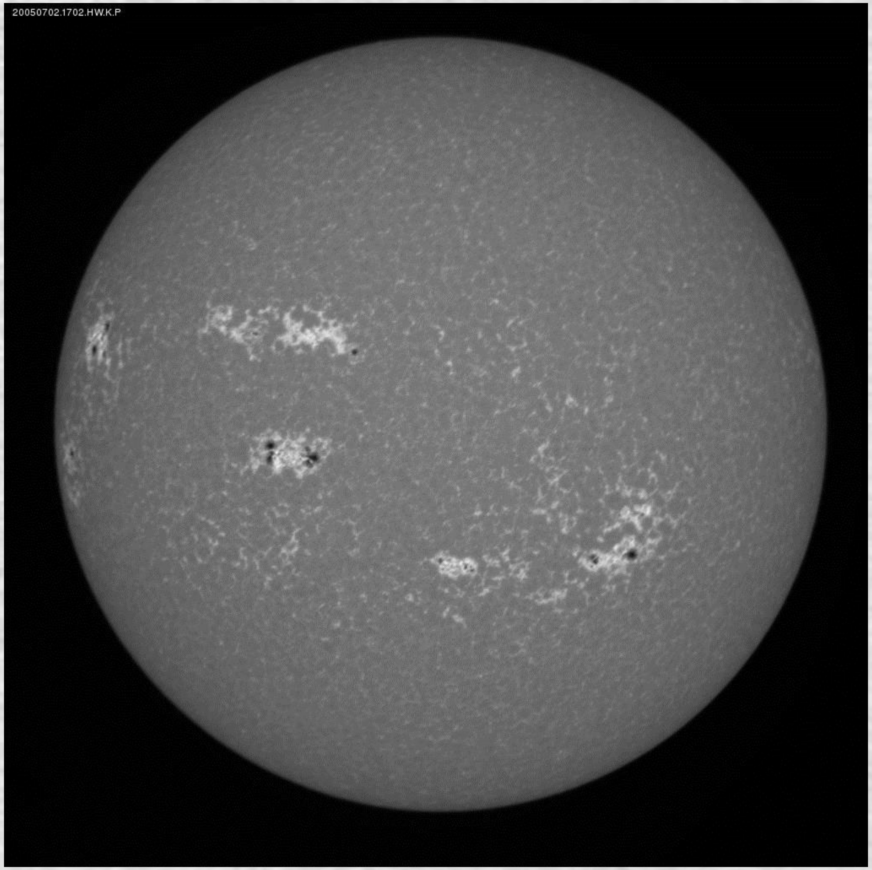


Modeling challenges:

The surface distribution of magnetic field is importance to spectral irradiance

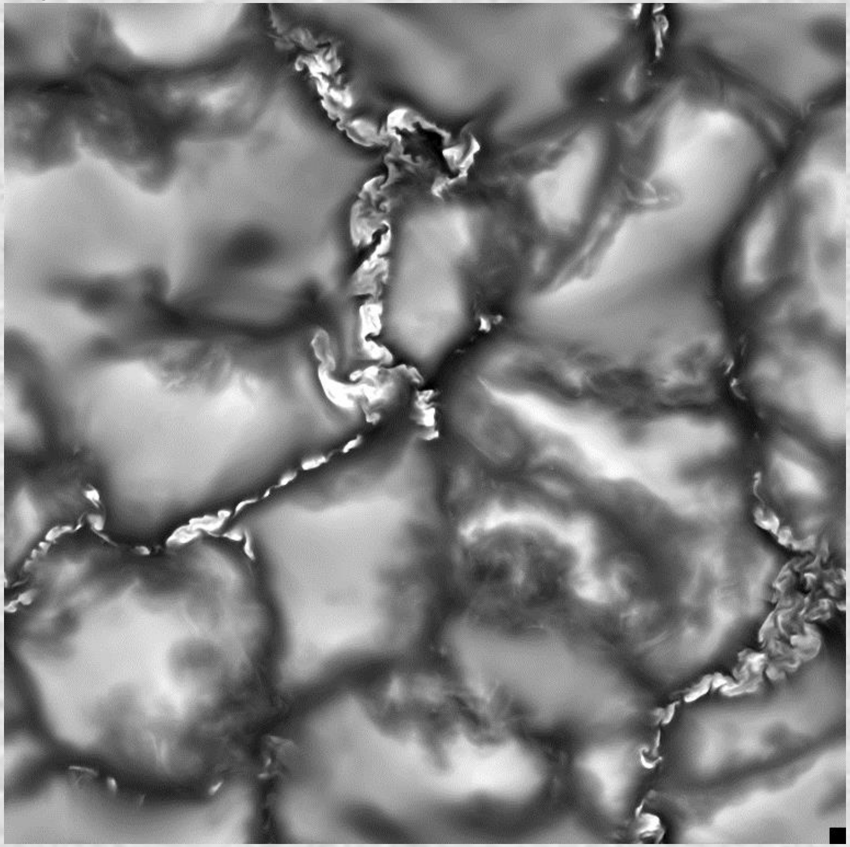
➔ full disk images or models of flux distribution on sphere are required.





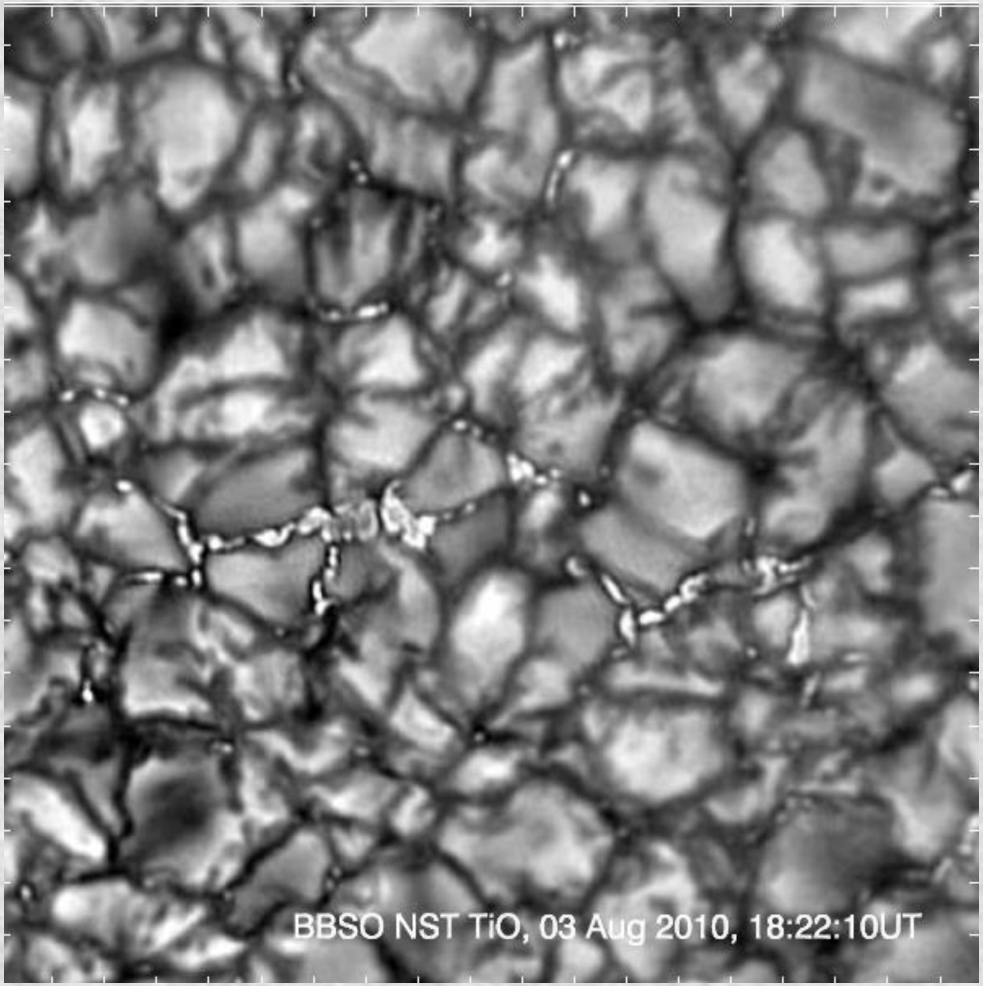
Underlying any one arcsecond pixel in a full disk image or model lies a tremendous amount of unresolved wavelength dependent substructure.

I_c



Radiative magnetohydrodynamic simulations
Courtesy Matthias Rempel
6.144 x 6.144 x 1.44 Mm domain
768 x 768 x 180 (16km resolution)

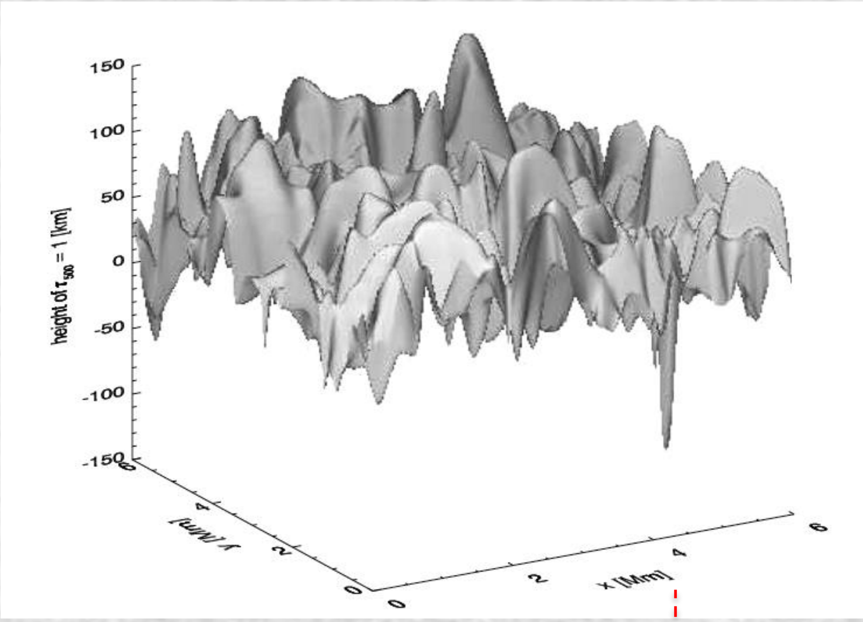
$|\mathbf{B}|$



Abramenko et al. 2010, NST BBSO

1 arcsecond ≈ 725km on Sun

The spectrum of the average atmosphere is not the average spectrum of the atmosphere (Uitenbroek & Criscuoli 2011)



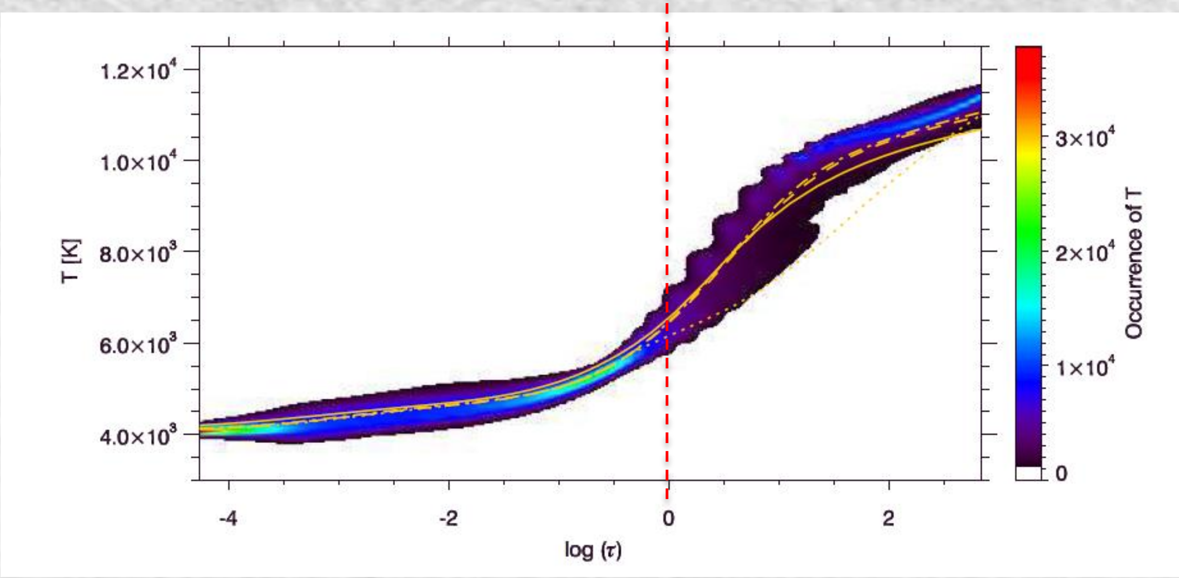
LTE: $\langle I_\lambda \rangle = \langle B_\lambda(T) \rangle_{\tau_\lambda = 1}$

Compare with one dimensional model: $B_\lambda(\bar{T})$

$$T = \bar{T} + \Delta T \quad T' = \Delta T / \bar{T} \ll 1 \quad \langle T' \rangle = 0$$

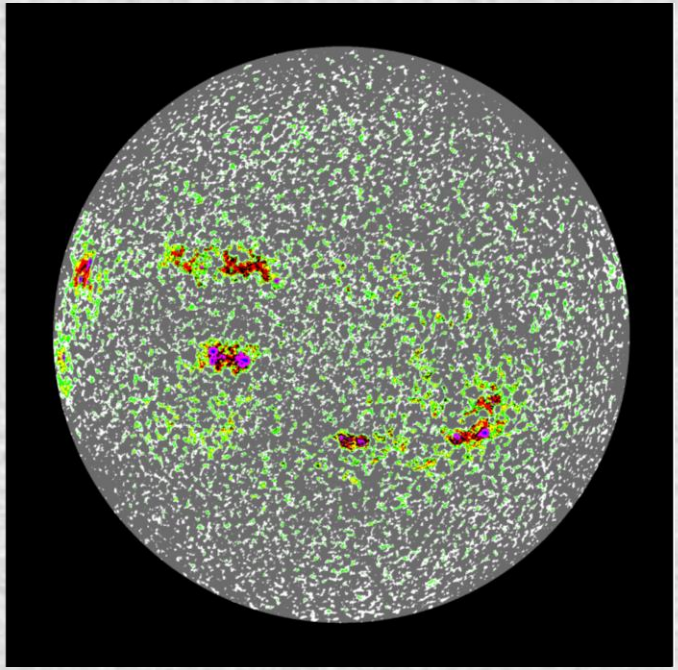
$$\langle \Delta B_\lambda \rangle = \frac{1}{2} \langle (T')^2 \rangle \left. \frac{d^2 B_\lambda(T')}{d(T')^2} \right|_{T'=0} + O(\langle (T')^3 \rangle)$$

Second derivative of Planck function positive



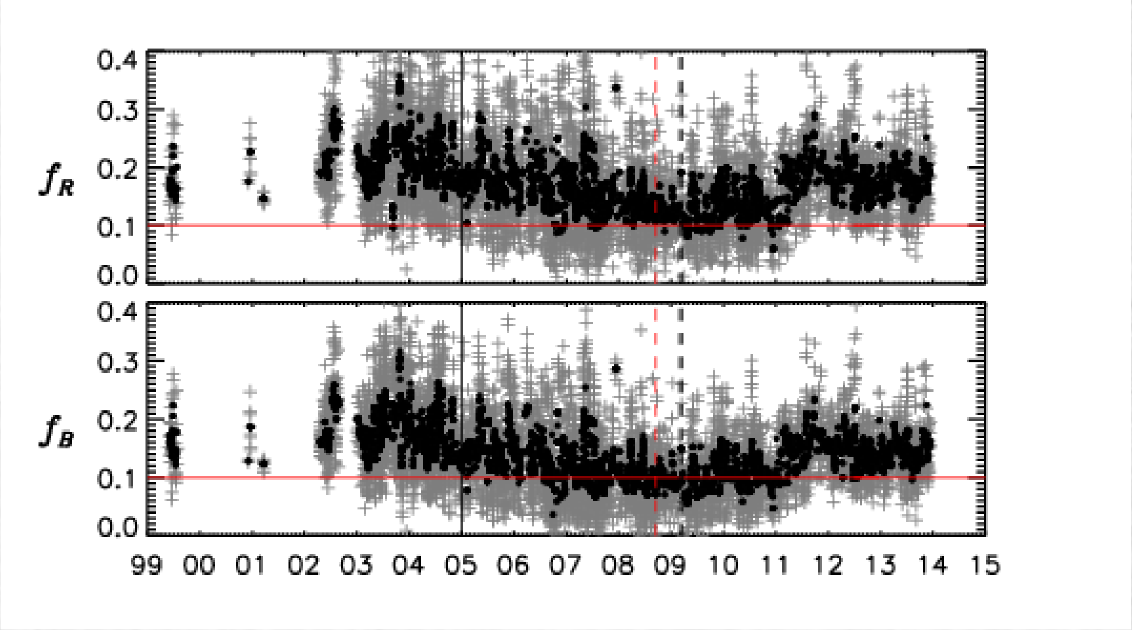
Radiation from inhomogeneous atmosphere always greater that of homogeneous atmosphere of the mean temperature

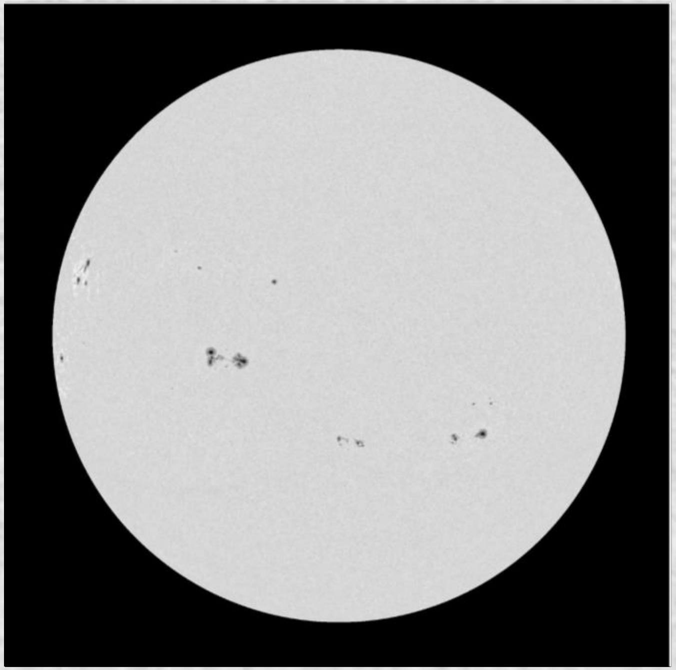
Correction at one disk position or wavelength won't work at others



Not all faculae are created equal

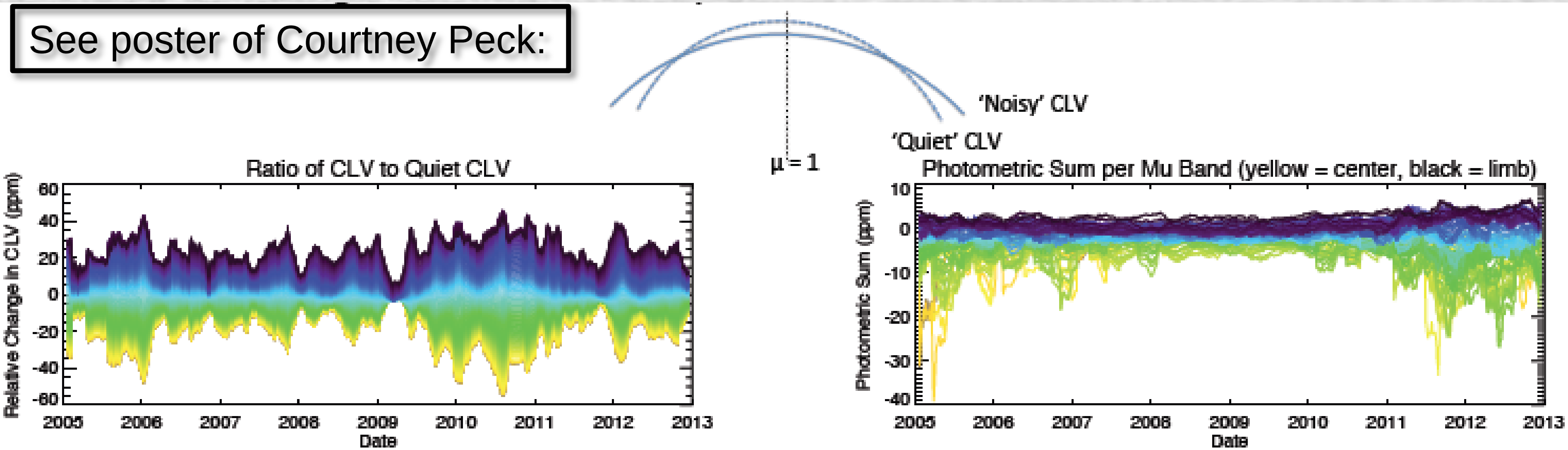
- Some faculae and plage have negative contrast at red continuum wavelengths
- The position of dark faculae on the disk is not a simple function of heliocentric angle
- The fraction of dark faculae decreases into the last minimum





Is the time dependance because the faculae (or unresolved underlying flux distributions) are changing, or because the CLV against which their contrast is measured is changing?

See poster of Courtney Peck:



Ground based instrumentation can only measure photometric contrast compared to some definitions of the background "quiet-sun."

- we do not know the center-to-limb variation of the "quiet-sun," against which these contrasts are measured
- we do not know whether the structures, or the background against which they are measured, or both, are changing with solar cycle
- these difference are important in our interpretation of the solar spectral irradiance

The Radiometric Solar Imager (RSI):

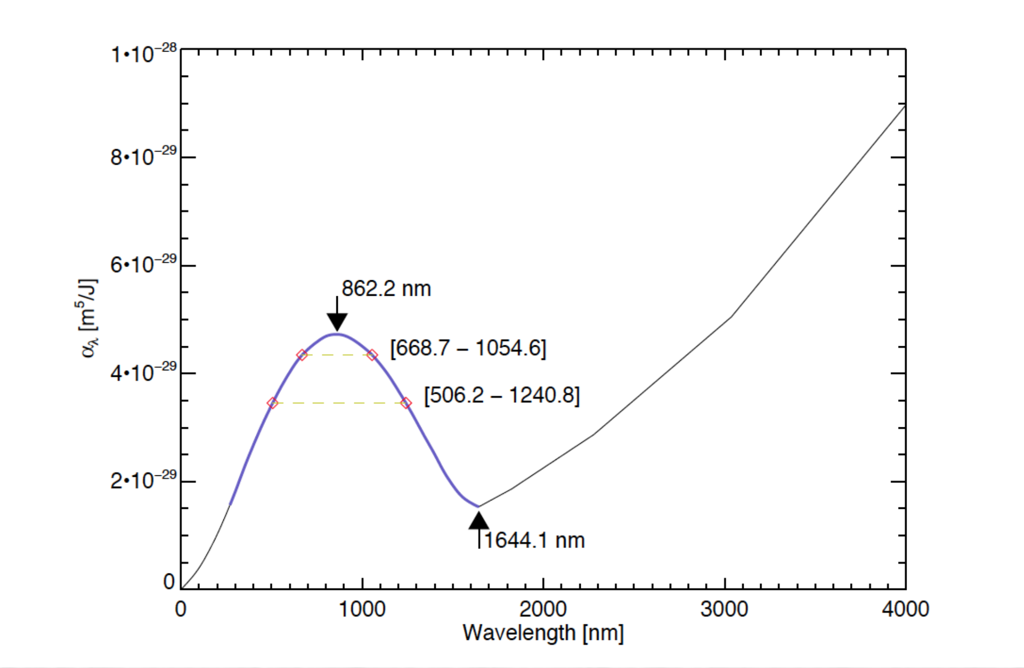
Jerry Harder
Ginger Drake
Dave Harber
Joel Rutkowski
Han Uitenbroek
Serena Criscuoli

GOAL: *radiometrically calibrated, absolute intensity, full disk solar images at wavelengths critical to determining the role of magnetic fields in solar spectral output, the temperature gradient of the solar photosphere, and the absolute variation in radiative intensity across the solar disk*

RSI Filters:

Primary:

Red (R) = 607.1nm
Ca II K (K) = 393.48nm
Opacity Conjugate (CA) = 668.7nm
Opacity Conjugate (CB) = 1054.6nm
Opacity Conjugate (CC) = 506.25nm
H minus max (Hmm) = 864.2nm



Avoid having to calibrate monitor the degradation along the full optical path and imaging detector by

Combining three instruments: Telescope, Radiometer, Spectrometer

Two possible instrument designs:

I. Spectral integration approach: most accurate, assuming challenges can be met

- Photometric images of full disk with relative pixel-to-pixel precision of 1 part in 10^3
- Photometric monitoring of the filter pass band shapes
- Radiometric spectra of the pass bands at high-spectral resolution

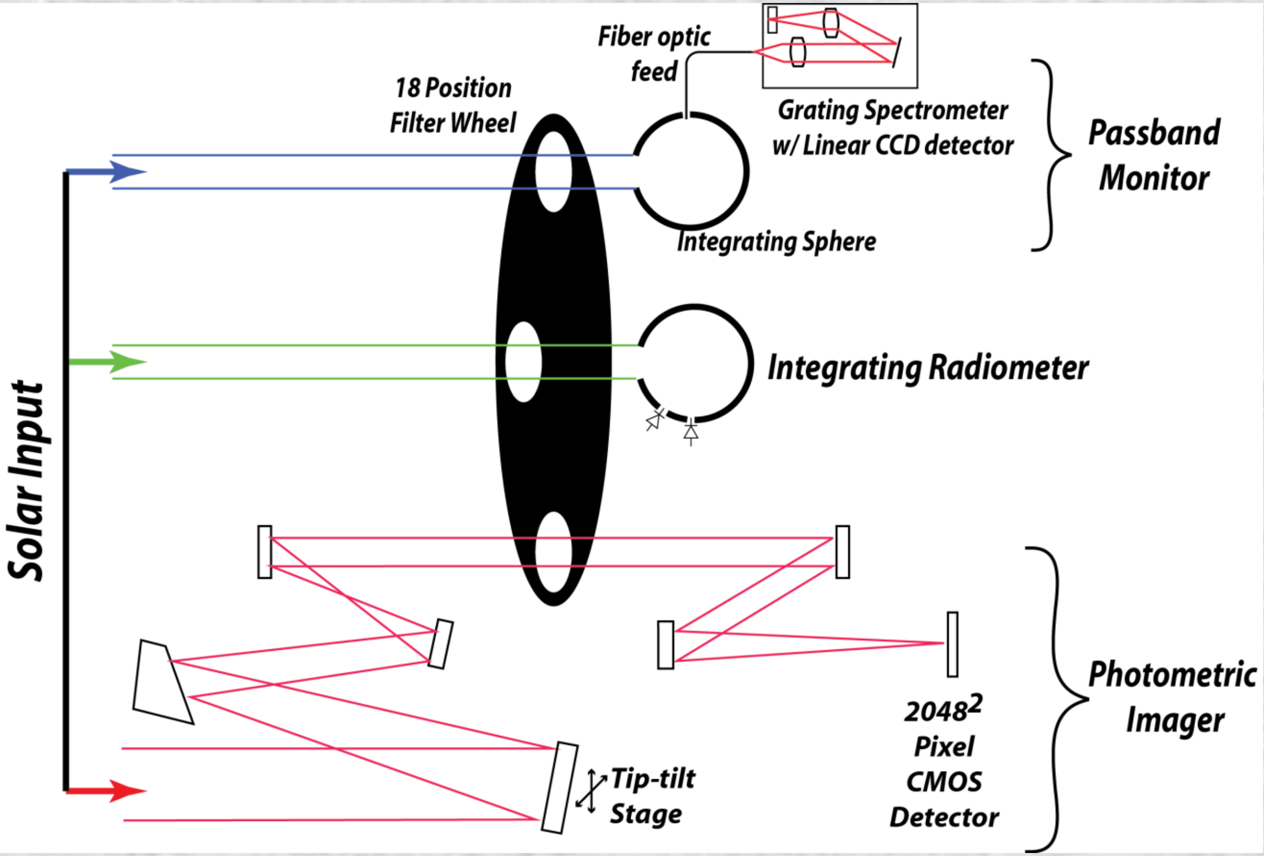
Calibration of the images by integration of the filter pass band over the radiometric spectra.

Advantages: 1. image radiometry achieved without monitoring imager degradation
2. radiometric component is independent – a high resolution SIM over narrow passbands
3. two independently valuable data sets which combine to produce radiometric images

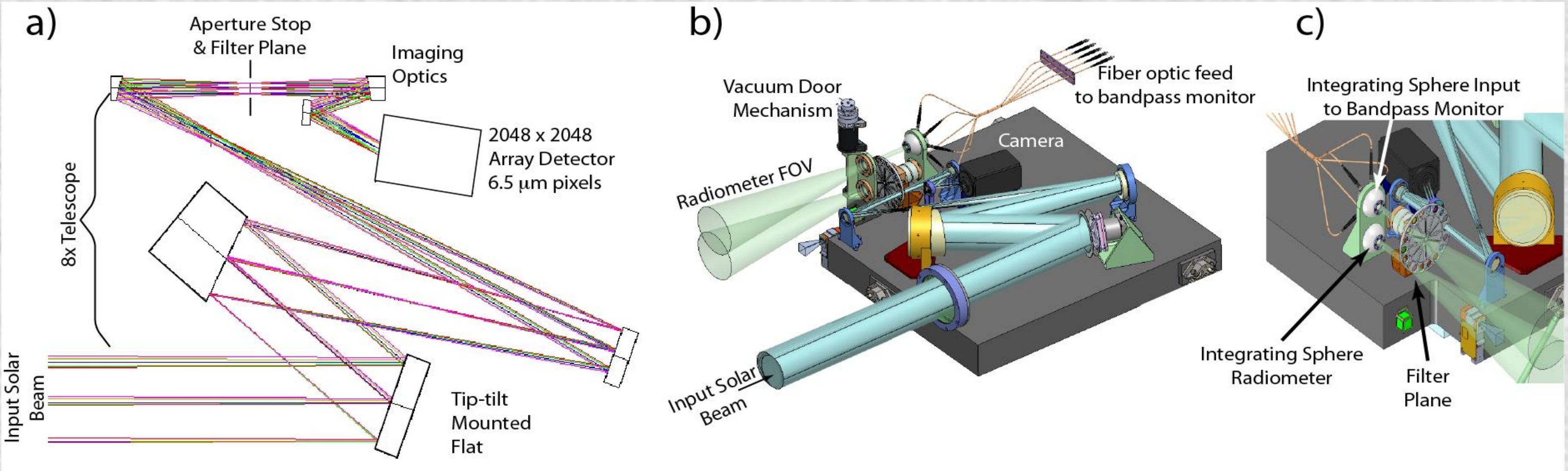
II. Filter transmission measurement approach: less challenging

- Photometric images of full disk with relative pixel-to-pixel precision of 1 part in 10^3
- Separate radiometer which shares imager filter wheel and precision aperture (though illumination of filter differs) determines throughput of filter
- Independent spectrometer – to monitor filter pass band

Advantage: 1. spectrometer does not require absolute calibration and
2. can be of lower spectral resolution



The idea is to normalize the an image that has good pixel to pixel relative photometry using the absolute integrated intensity of the light that *should* have come through the filter.



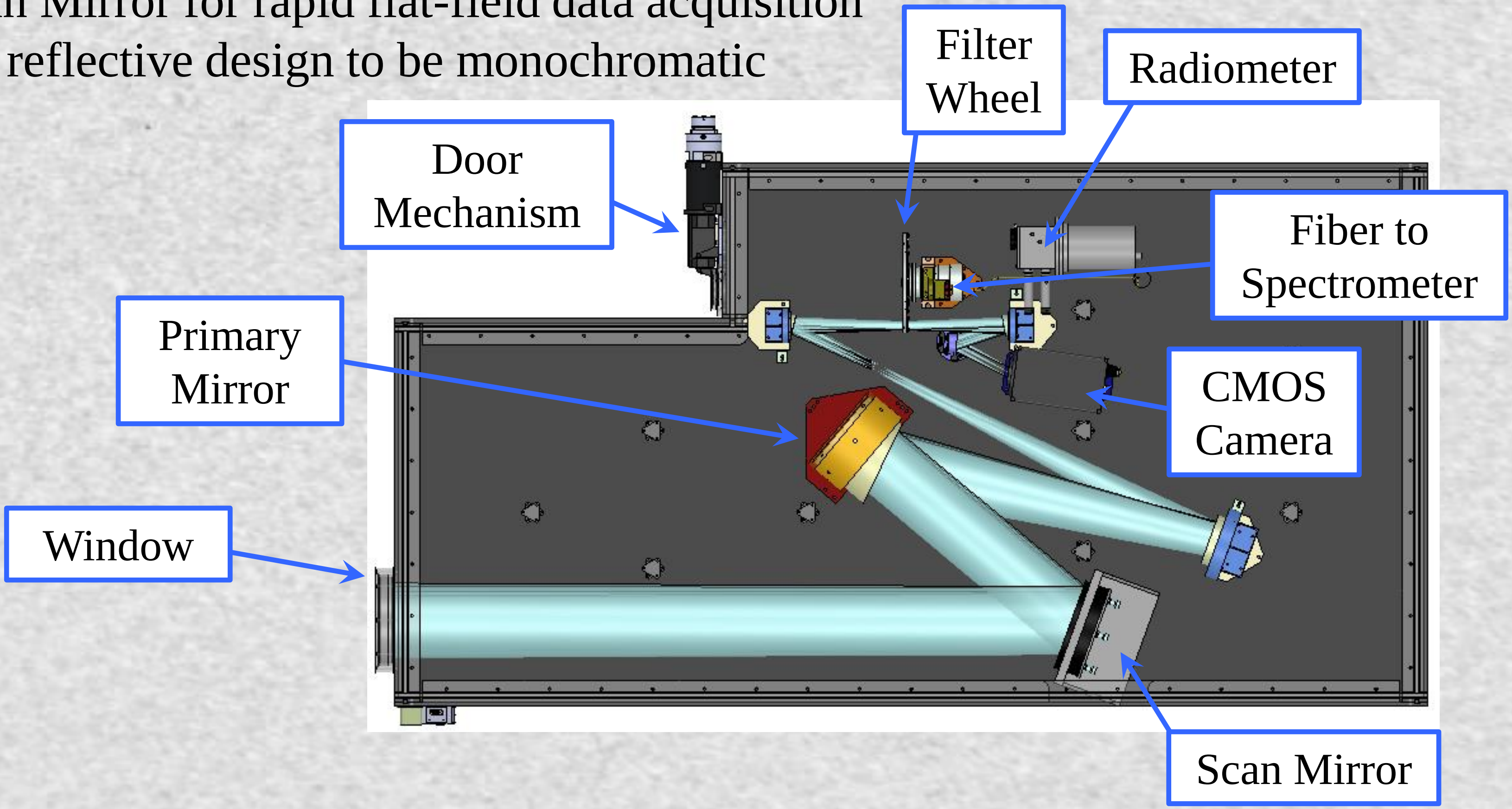
- 100mm diameter entrance pupil and a 12.5mm aperture stop where the filters are positioned

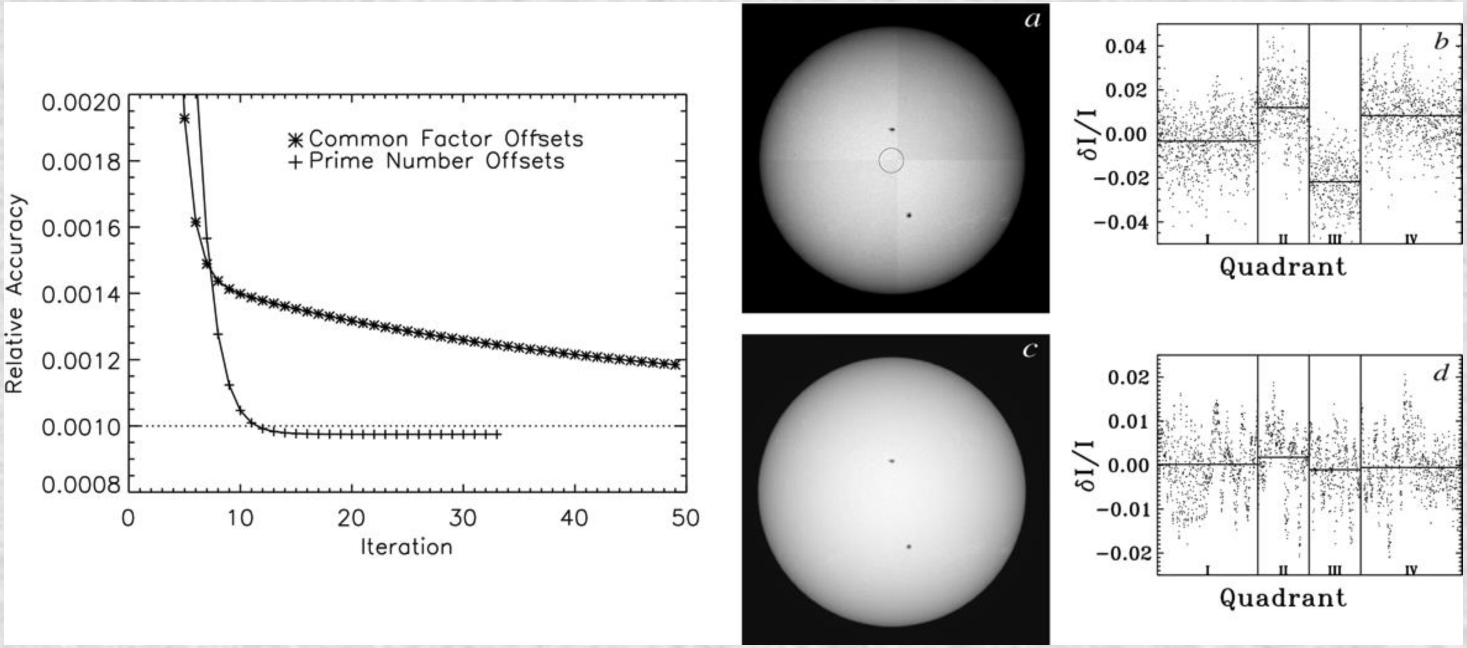
- Placing the filters at the aperture stop significantly reduces the spatial uniformity requirements for the filters compared to placing them just before the focal plane array, and make them much smaller than placing them at the entrance

- Light path (ray angles) through filters is however slightly different in telescope than into radiometer

RSI Design: Telescope & Radiometer

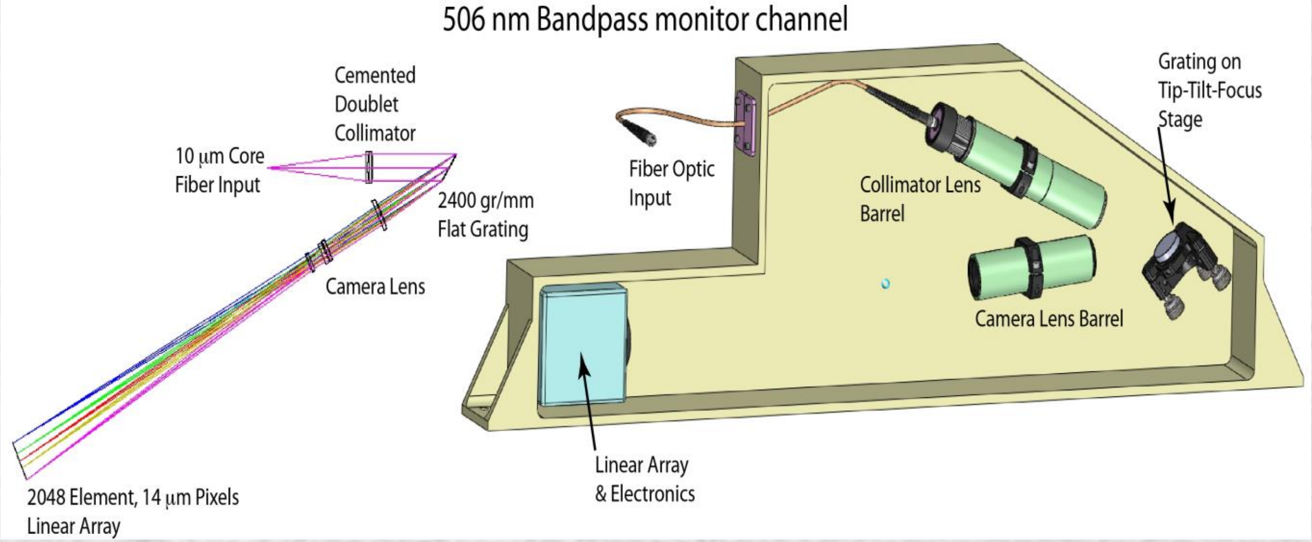
- ~1 arc-second resolution
- 100 mm Entrance pupil to achieve resolution
- 12.5 mm Aperture Stop to accommodate filter wheel & radiometer
- Scan Mirror for rapid flat-field data acquisition
- All reflective design to be monochromatic





- In order to achieve the radiometric images of 0.1% accuracy after normalization by the integrated radiometric intensity, the Photometric Imager must achieve relative precision of better than 0.1%

- We will accomplish this using a version of the algorithm of Kuhn et al. (1991) applied to offset images of the Sun acquired in rapid succession using the tip-tilt mounted steering mirror



Fiber fed spectrometers:

- Fed by 10-micron core fiber optics that are in turn fed by an 50 mm diameter integrating sphere
- Using an integrating sphere ensures that light from the entire spatial extent of the Sun and illuminated portion of the filter is coupled into the fiber and fed to the spectrometer
- Transmission profile measured by filter-in filter-out comparison
- Each optimized for a narrow spectral range around the filter passbands. Example: a 10 nm spectral range around the 506.25nm band-center with 0.005nm sampling using 2400 lines/mm grating

Integrating Radiometer:

- Based on a NIST integrating sphere design (Eppeldauer et al. 2009) with a photodiode detector
- For increased stability against degradation, this could be replaced with an Electrical Substitution Radiometer (ESR).
- Precision aperture occupies an unvignetted position behind the filter wheel that allows the filter to rotate in front of it
- Same size as the aperture stop in the imager, and aligned so that the same portion of the filter illuminated in the telescope falls in the radiometer light path
- Absolute calibration of the radiometer to be established in the LASP SRF facility (Richard et al. 2011)
- Area of the precision aperture to be measured at the NIST aperture area facility (Fowler & Litorja 2003).

Global irradiance changes over cycle time scales may depend on contributions at the smallest scales, yet

Full disk imagery (or models) will always be required – disk position critical because of CLV

This :

1. What is the real $I_\lambda(\mu)$ as a function of $\mathbf{B}$ and filling factor (magnetic structure type)?

   ➔ Radiometric Imager

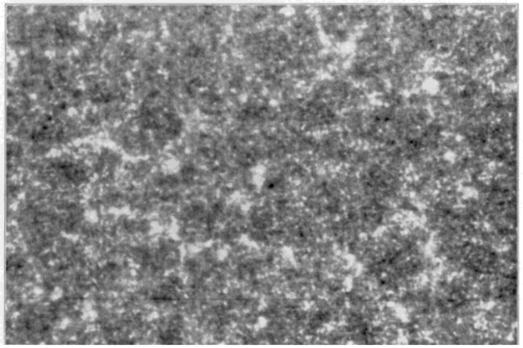
1. Sub-arcsecond field distribution governs variance in irradiance contributions of "structures."

   ➔ High resolution imaging and 3D RMHD modeling

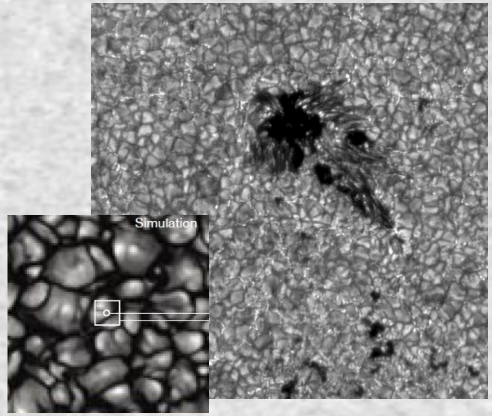
1. Introduce the variance due to unresolved substructure into full disk spectral irradiance models:

   ➔ Monte Carlo sampling of distributions

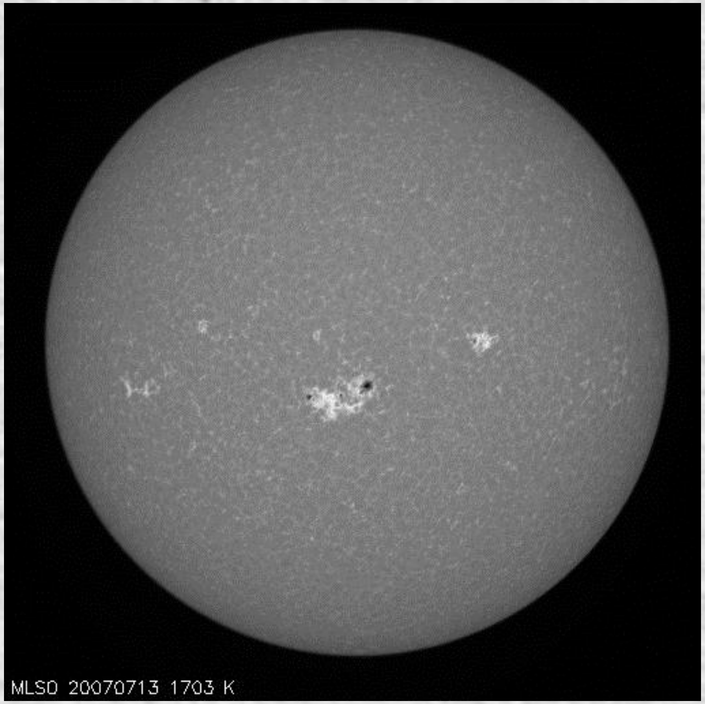
High resolution observations and RMHD models



Minute Structure of the Calcium Flocculi at H_2 Level. 1903, September 22.
(Scale: Sun's Diameter = 0.890 Meter.)

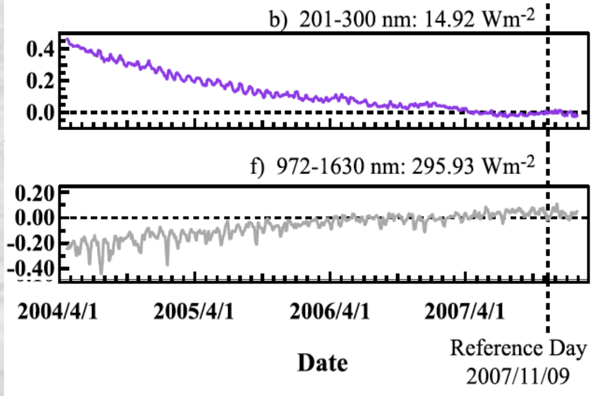


Statistical models of unresolved contributions



Full-disk radiometric and synoptic photometric imaging

Ensemble of solar atmosphere and transfer models

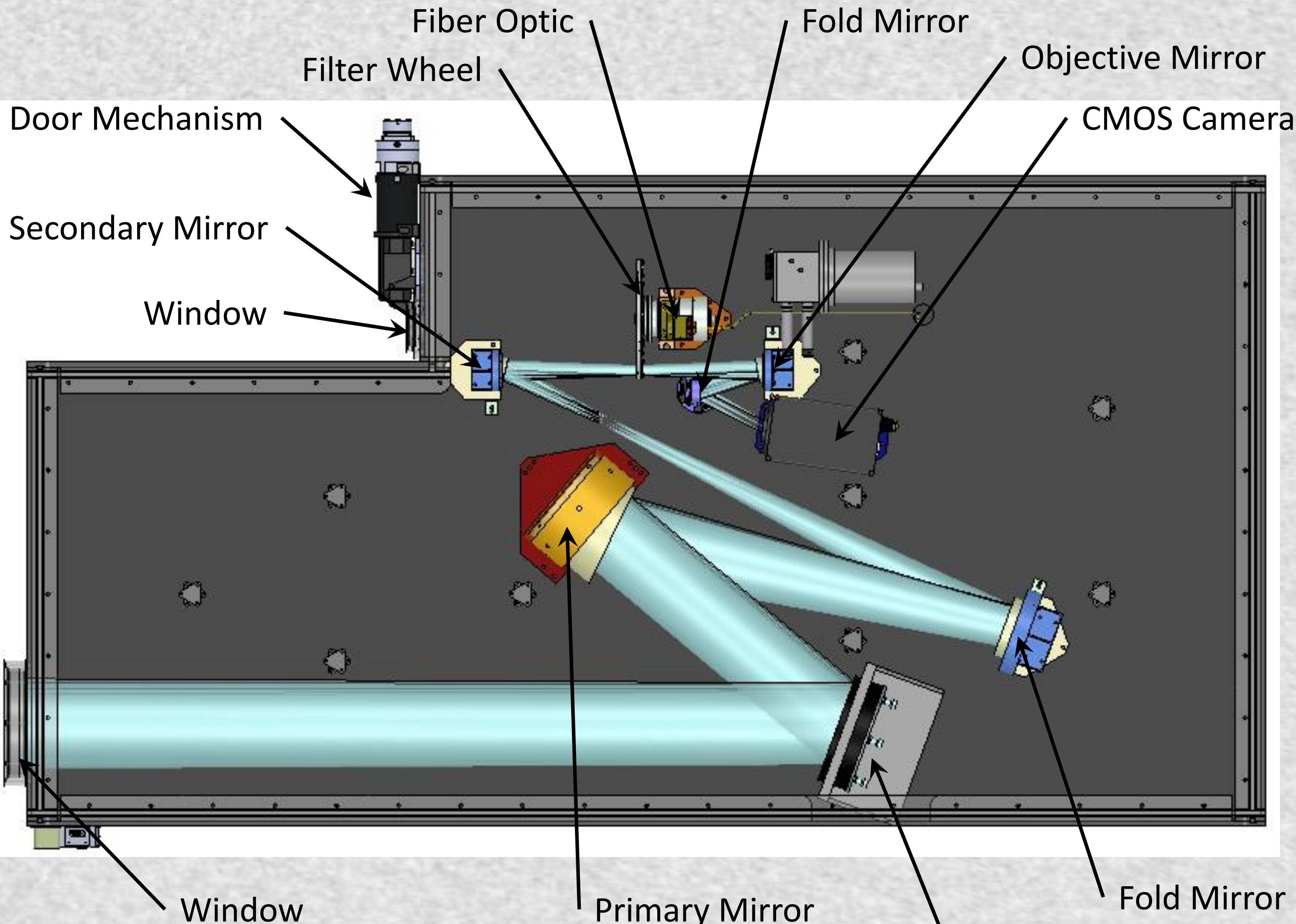


Spectral irradiance monitoring

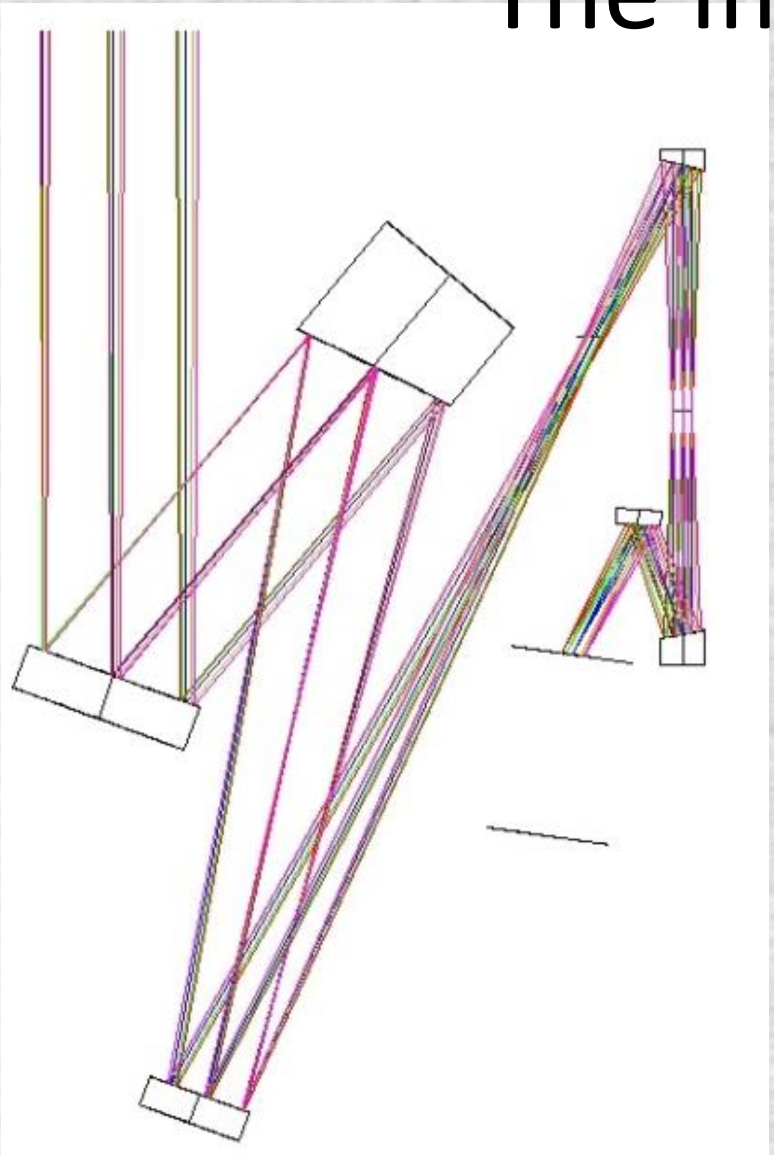
The RSI will:

- Elucidate the underlying causes of solar spectral variability by making first radiometric measurements of the resolved solar disk
- First radiometric determination of center-to limb profiles of the quiet-sun and solar magnetic elements as a function of solar cycle
- First determine of the photospheric temperature gradient both within and outside of magnetic flux structures using opacity conjugate wavelengths
- Determine the veracity and cause of spectral irradiance trends for terrestrial climate modeling

Wavelength	ID	Motivation
393.4nm	Ca II K	Historic record, magnetic structure identification, core-to-wing ratio
506.1nm, 1241nm	Pair 1	Opacity-conjugate wavelengths (Uitenbroek & Criscuoli 2012)
668.4nm, 1055nm	Pair 2	Opacity-conjugate wavelengths (Uitenbroek & Criscuoli 2012)
607.1nm	PSPT Red	Continuum sample of anti-TSI trend
857nm	Near IR	Continuum sample of TSI-like trend
1083nm	He II	Chromospheric dynamics, CLV for scattering polarization
1644nm	Opacity minimum	Opacity minimum, deep photosphere


Fiber Optic
Fold Mirror
Filter Wheel
Objective Mirror
Door Mechanism
CMOS Camera
Secondary Mirror
Window
Window
Primary Mirror
Fold Mirror
Steering/Scan Mirror

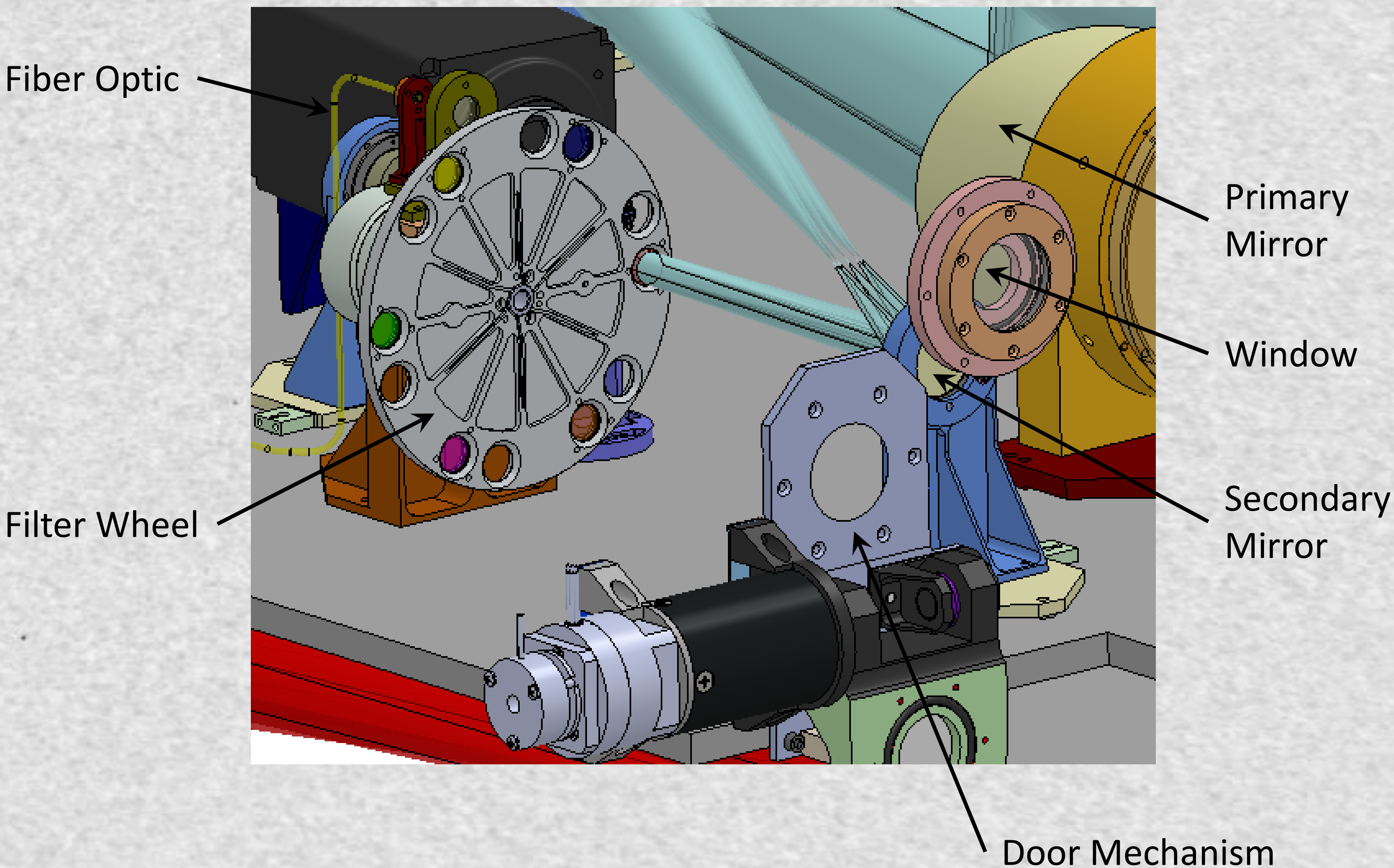
The Imager



- 100mm Entrance pupil to achieve resolution
- 12.5mm Aperture Stop to accommodate filter wheel & radiometer
- Scan Mirror for rapid flat-field data acquisition
- All reflective design to be monochromatic

Spectrometer Specifications

- Grating Ruling: 40 lines/mm
- Blaze Angle: ArcTan(2) = 63.4 degrees
- Spectral Coverage: 380nm to 1060nm
- Number of Orders: 75 orders
- Dispersion: 0.00056 nm/arcsec @ 393nm
- Spectral Sampling: 0.002nm @ 393nm
- Angular Spread: 4.468 degrees @ order 42
- Pixel FOV: ~8 arcsec
- Fiber: 0.050mm, 0.22 NA, mulitmode
- Collimator Focal Length: 1000mm
- Prism Material: N-BK7


Fiber Optic
Filter Wheel
Primary Mirror
Window
Secondary Mirror
Door Mechanism