SCD
Optical Design Document

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INTRODUCTION

1.1 PROJECT OVERVIEW

The High Altitude Observatory (HAO) of the National Center for Atmospheric Research (NCAR) is building a Solar Chromospheric Detector (SCD) instrument to be operated on one of the 20 cm Zeiss coronagraphs at the Lomnický Štít Observatory. The SCD instrument will be capable of observing the solar disk and prominences above the limb in a variety of absorption and emission lines ranging in wavelength from 588 nm to 1083 nm. It will enable measurements of the complete polarization state across these solar lines providing information on the velocity field and vector magnetic field in the solar chromosphere.

1.2 DOCUMENT SCOPE

This document briefly describes the optical layout of the SCD instrument. This includes details of the optical layout, prefilter and calibration optical inventories, Lyot Filter and full-system expected performance, as well as information on focusing.

1.3 RELEVANT DOCUMENTS

1.3.1 HAO Documents

- Zemax Optical Design (7/7/2014)
- 5653-RQ-6000 (Instrument Science Requirements Document)
- 5653-OD-6003 (Flux Budget)
- Proposal

1.3.2 External Documents

- Andor Neo Spec Sheet

1.4 ACRONYM LIST

CONOPS	Concept of Operations
ISRD	Instrument Science Requirements Document
NCAR	National Center for Atmospheric Research
FOV	Field of View
HAO	High Altitude Observatory
UCAR	University Corporation for Atmospheric Research

Table 1 - Table of acronyms

2   ZEISS OBJECTIVE SINGLET DESIGN

2.1   REQUIREMENTS SUMMARY

This is a sublist of relevant requirements from the ISRD. See the referenced document for a full list of requirements.

Parameter	Unit	Requirement	Design Value	Compliance Section
Wavelength Range	nm	585-1083	585-1083	2.10, 2.11.2, 2.11.3, 2.11.4, 2.11.5
Pre-filter Inventory	nm	557.60 ± 0.02 587.60 ± 0.02 589.60 ± 0.02 630.20 ± 0.02 656.30 ± 0.02 849.80 ± 0.04 854.20 ± 0.04 866.20 ± 0.04 1083.00 ± 0.06	557.60 ± 0.02 587.60 ± 0.02 589.60 ± 0.02 630.20 ± 0.02 656.30 ± 0.02 849.80 ± 0.04 854.20 ± 0.04 866.20 ± 0.04 1083.00 ± 0.06	2.6
Spectral Resolution [at 1083]	$\lambda/\Delta\lambda$	23500	23509 at 1083nm 41477 at 656nm 47817 at 587nm	2.8
Field of View [at 587]	Arcseconds	$835'' \times 692''$	$835'' \times 702''$	2.11.1
Spatial Resolution	arcseconds	0.74 @ 588 nm	Diffraction limited at all wavelengths	2.11.2, 2.11.3
Maximum Length	mm	1100		

2.2   OVERVIEW

3D Layout

SCD Instrument - Design Phase
7/17/2014

SCD_7_7_2014.ZMX
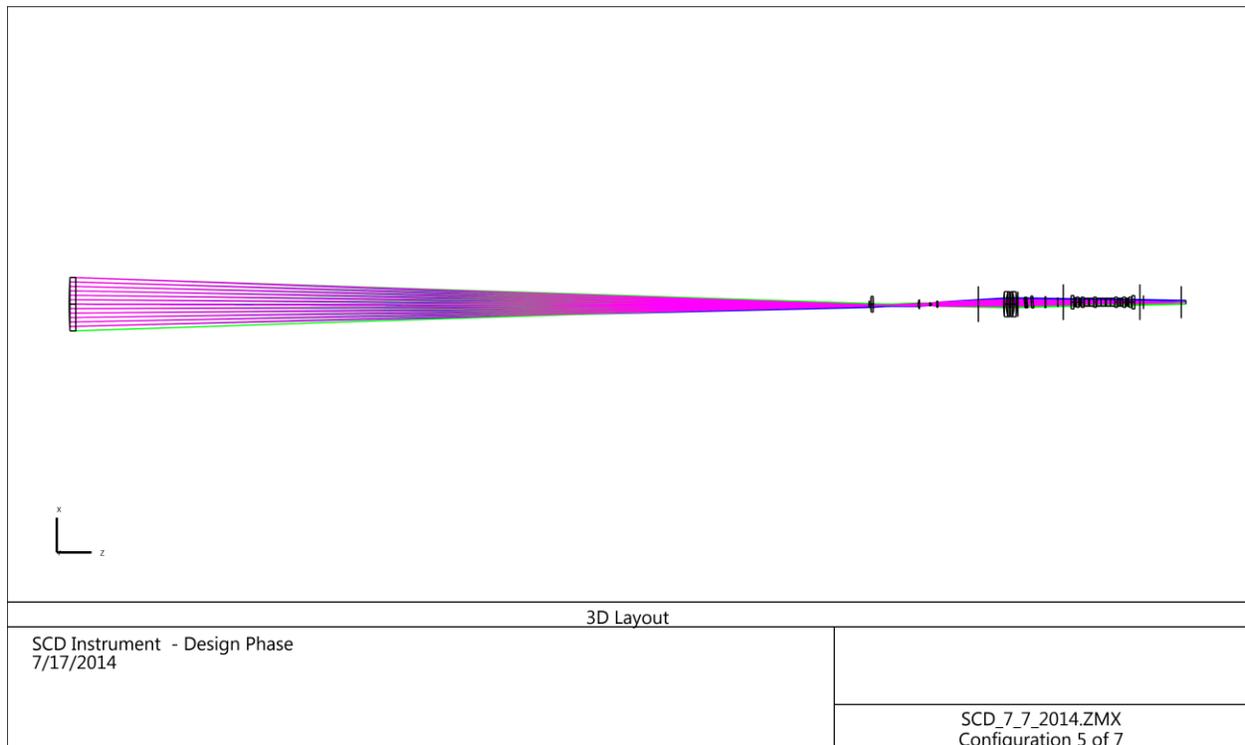Configuration 5 of 7

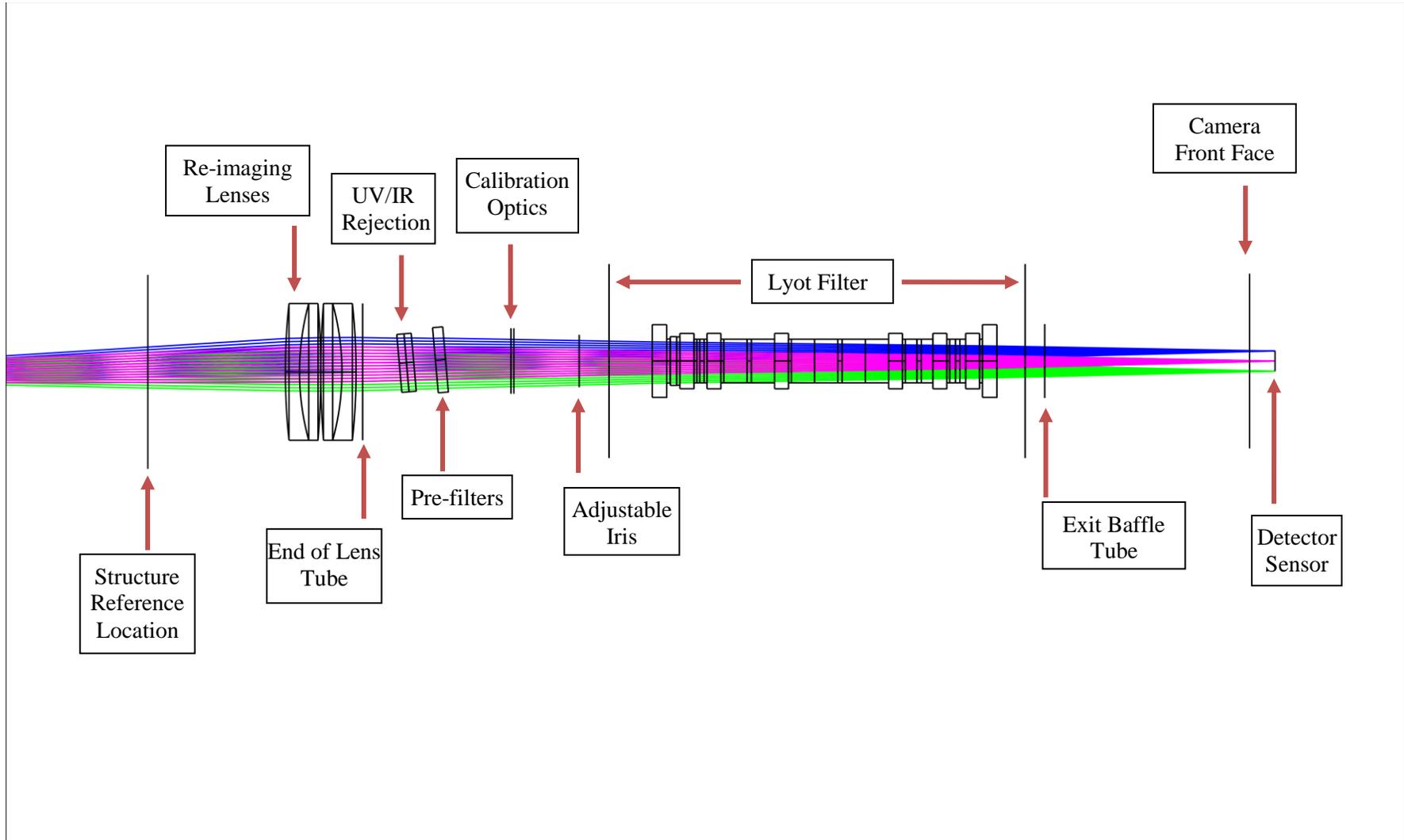**Figure 1 - Overview of the SCD optical layout.**
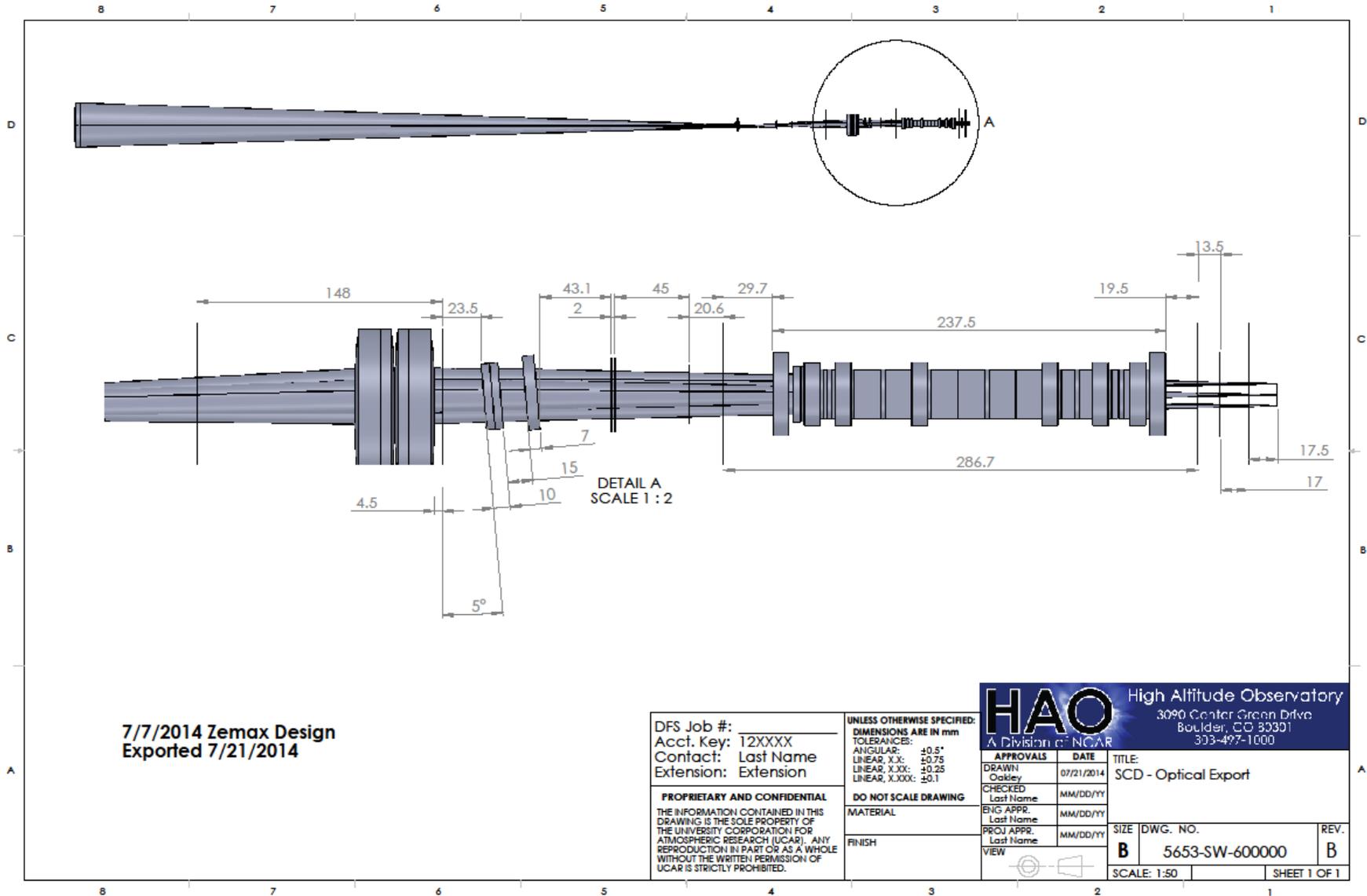
Figure 2 - Rear optics for SCD.

Figure 3 - Dimensioned assembly drawing

2.3 OBJECTIVE LENS

The telescope objective lens currently has the capability of moving along the optical axis with respect to the instrument. However it would be advantageous to leave this lens stationary, and only adjust the cameras to accomplish focusing. The position of the objective lens is driven by three main constraints:

1) The field lens must not be located at the focal plane of the objective lens for any spectral line of interest. Should the field lens be dusty, this could cause severe flat-fielding issues if the field lens is on the O1 focal plane at the spectral line of interest. The ray-traced spots should be approximately an order of magnitude larger than the dust size expected on the lens.
2) The entire bandpass must be observable by the instrument without the need for adding lenses. This prevents the field lens from being placed after the objective lens focal plane.
3) The instrument performs better when the field lens is more distant from the objective lens.

To satisfy these design criteria, the rear surface of the objective lens is positioned 2968 mm from where the occulter would normally be. This puts 528nm into focus at the field lens (or 511nm in focus where the occulter would have been). The objective lens will then remain stationary over the full bandpass. Figure 4 shows the focal point of the O1 for 587nm, and Figure 5 shows the spot size on the field lens. The spots have a ~1 mm diameter geometrically, and ~0.8mm diameter RMS, much larger than the expected dust size.
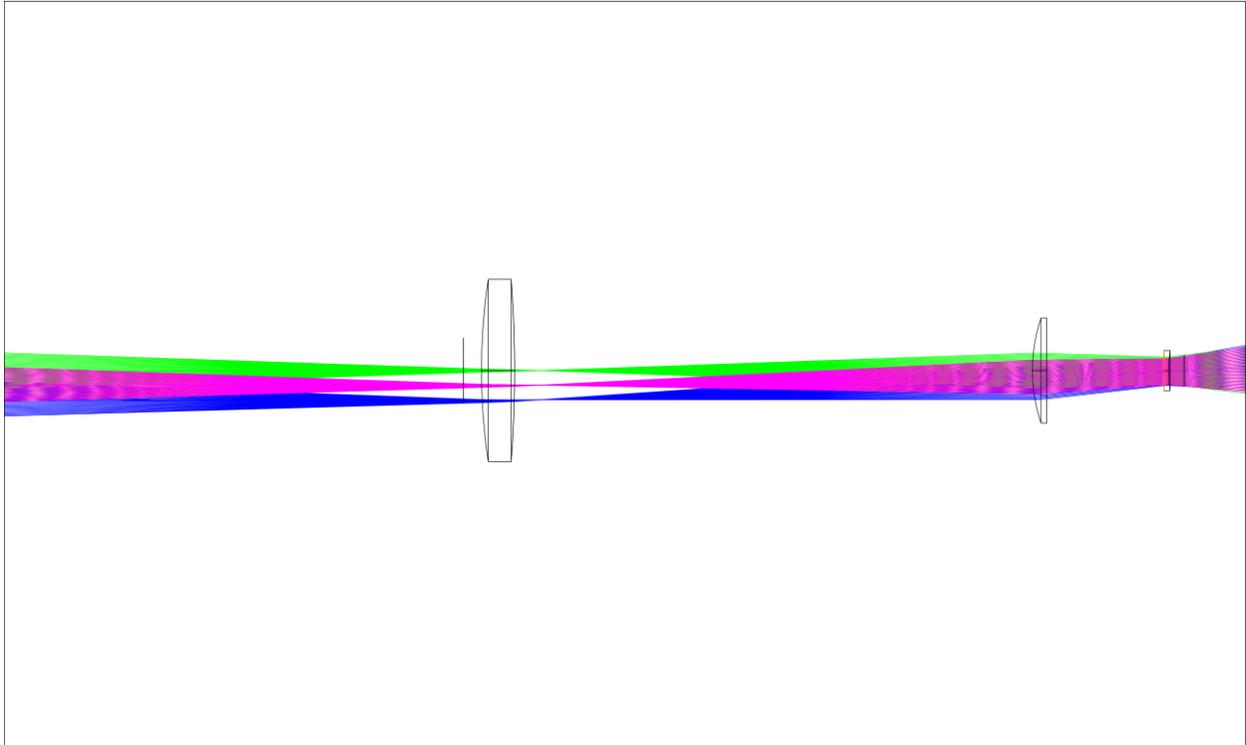

Figure 4 - Raytrace showing the O1 focal point in relation to the field lens.

Figure 5 - Spot diagrams on the field lens for 587nm.

2.4 OCCULTER

The occulter/field lens combination for this telescope will be removed, and an identical field lens without the occulter will be installed.

2.5 HEAT REJECTION FILTERS

Assuming a solar constant of 0.1361 W/cm^2, a geometrical area of 314 cm^2, and a throughput of ~90% at the pre-filter, and a FOV of 0.85 of the solar disk, the pre-filter will see approximately 19.6 Watts of energy, or 1.35 W/cm^2. This is beyond the manufacturer spec of 0.75 W/cm^2. To reduce the heat load on the pre-filters, and to eliminate potentially dangerous UV light from damaging the Lyot Filter, a heat rejection system should be added to the pre-filter stack. This includes a longpass filter to eliminate the UV light, and shortpass filter to eliminate heat. In addition to this the lyot stop should be restricted to allowing 89% of the light to pass through. This requires a lyot stop diameter of 9.36mm. Table 2 details this calculation.

	Parameter	Value	Resulting Energy Density	Comment
Andover Spec	Andover Safety Recommendation	0.75 W/cm^2	**0.75 W/cm^2**	From email Phil Clark -> Scott
SCD Instrument Expected Values	Solar Constant (Space)	0.1361 W/cm^2	**0.1361 W/cm^2**	Typically quoted value
	Solar Constant (Ground)	0.1100 W/cm^2	**0.1100 W/cm^2**	SMARTS gives 0.0900, but we'll be conservative
	Geometrical area (no aperture stop)	314 cm^2	**34.54 W**	20 cm O1
	Throughput (at pre-filter)	90%	**31.1 W**	O1 is uncoated
	FOV	85%	**26.4 W**	Pre-Filter actually sees the majority of the sun
	Filter Area	19.6 cm^2	**1.35 W/cm^2**	50mm diameter
Dual Heat Rejection Solution	Longpass Filter (525nm)	Cuts off 22%	**1.05 W/cm^2**	From SMARTS analysis see flux budget
	Shortpass Filter (1125nm)	Cuts of 16%	**0.84 W/cm^2**	From SMARTS analysis see flux budget
Dual Heat Rejection Solution with Aperture Stop	Longpass Filter (525nm)	Cuts off 22%	**1.05 W/cm^2**	From SMARTS analysis see flux budget
	Shortpass Filter (1125nm)	Cuts of 16%	**0.84 W/cm^2**	From SMARTS analysis see flux budget
	Lyot Stop or Aperture Stop	Lyot or Aperture stop restricted to 89% of original flux (9.36mm diameter Lyot stop or 189mm diameter Aperture stop)	**0.75 W/cm^2**	Meets Andover spec

Table 2 - Heat analysis at the prefilter

2.6 PRE-FILTERS

The current inventory of pre-filters is listed below in Table 3.

Pre-Filter Number	Central Wavelength [nm]	Bandwidth [nm]
1	557.60 ± 0.02	0.30 ± 0.03
2	587.60 ± 0.02	0.30 ± 0.03
3	589.60 ± 0.02	0.30 ± 0.03
4	630.20 ± 0.02	0.40 ± 0.04
5	656.30 ± 0.02	0.40 ± 0.04
6	849.80 ± 0.04	0.70 ± 0.07
7	854.20 ± 0.04	0.70 ± 0.07
8	866.20 ± 0.04	0.70 ± 0.07
9	1083.00 ± 0.06	1.20 ± 0.12

Table 3 - Filter inventory.

These pre-filters will be tilted by 2 degrees to prevent any internal reflections from re-entering the optical beam. The enclosure for these filters will be thermally controlled to operate at 28° C. The filters will have the following general requirements, taken from 5653-RQ-6004 (Filter Requirements):

Parameter	Value
Size	50±0.5 mm diameter
Clear Aperture	90%
Scratch/Dig	60/40
Wedge	±1.0 arcmin
Operating Angle	2°
Thickness	$7^{+0}_{-0.1}$mm (including mounting ring thickness)
Blocking	X-Ray to FIR
Operating Temperature	28° C
Transmitted Wavefront Distortion (PV)	λ/4
Peak Transmission	Goal >70%
Number of Cavities	3

Table 4 - General filter requirements

2.7 CALIBRATION OPTICS

The calibration optics follow the pre-filters. These must be after the pre-filters to protect them from excessive light, particularly in the UV. The installed calibration optics are detailed in Table 5. These polarizers have different thicknesses, but this is not a focus issue, because these polarizers are only used with a diffuser inserted upstream, and therefore no true image is created.

Slot Number	Optic	Thickness [mm]
1	0° Polarizer	2
2	45° Polarizer	2
3	90° Polarizer	2
4	135° Polarizer	2
5	Left Circular Polarizer	5
6	Right Circular Polarizer	5
7	Dark Slide	5
8	Open	
9	Open	

Table 5 - Preliminary calibration optics inventory

2.8 LYOT FILTER

The LCD Lyot filter is a 5 stage wide field calcite tunable birefringent filter. The thinnest stage is 4mm of calcite (2×2mm elements), while the thickest is 64mm of calcite (4 x 16mm elements). The FLCs will allow state changes to occur quickly. The required spectral resolution of this filter is 0.046nm at 1083 nm. The spectral resolution (FWHM), and free spectral range are shown in Figure 6 and Table 6.

5 Stage Calcite Lyot Filter

d = 4.0 mm

587.00   122.73 mA
656.00   158.16 mA
1083.00   460.67 mA

5 Stage Calcite Lyot Filter

d = 4.0 mm

587.00   0.444 nm
656.00   0.572 nm
1083.00   1.666 nm
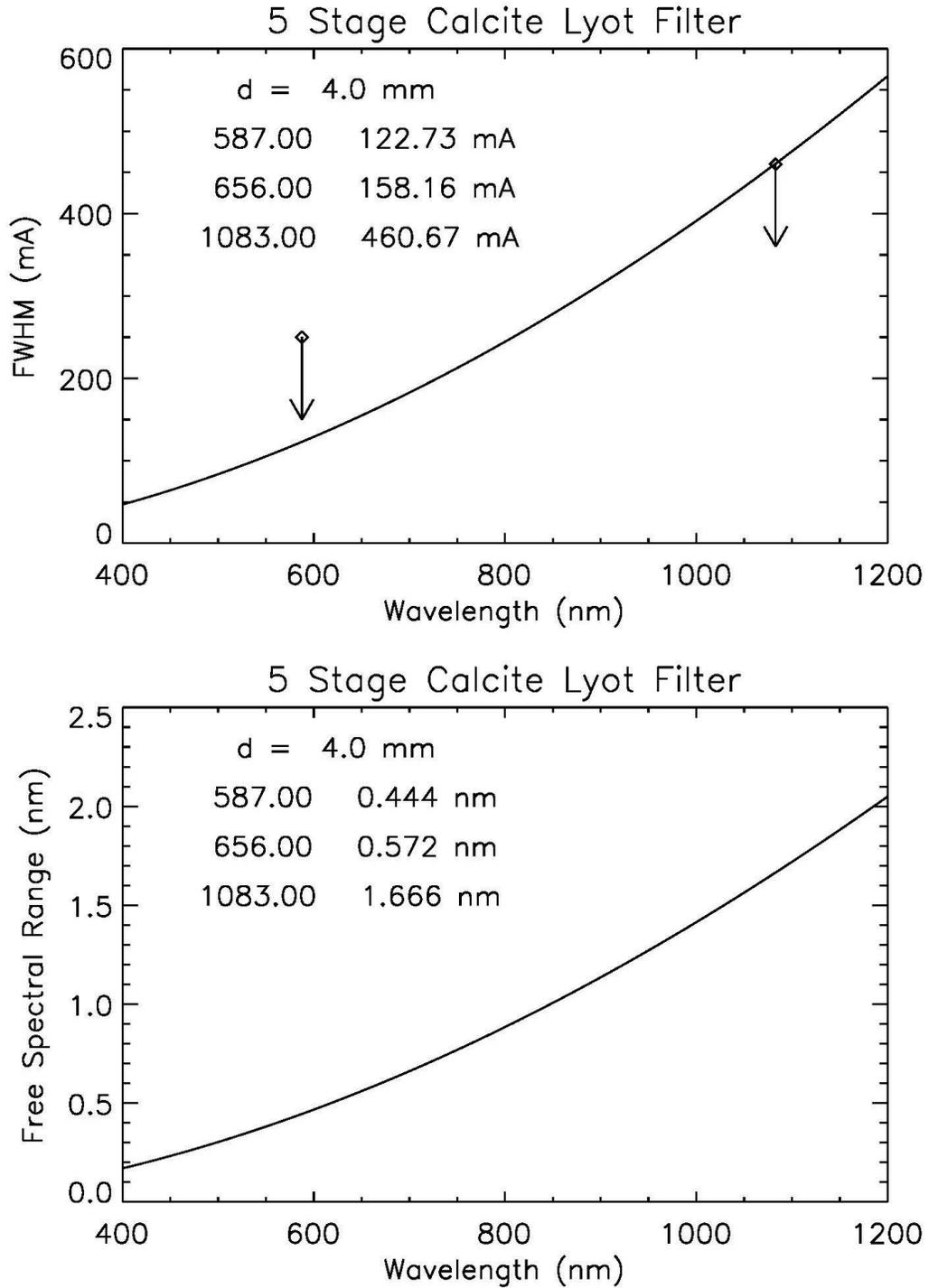
Figure 6 - Expected Lyot Filter properties

Wavelength [nm]	Lyot Filter FWHM [nm]	Lyot Filter Free Spectral Range [nm]
587.0	0.012	0.444
656.0	0.016	0.572
1083.0	0.046	1.666

Table 6 - Lyot filter spectral properties.
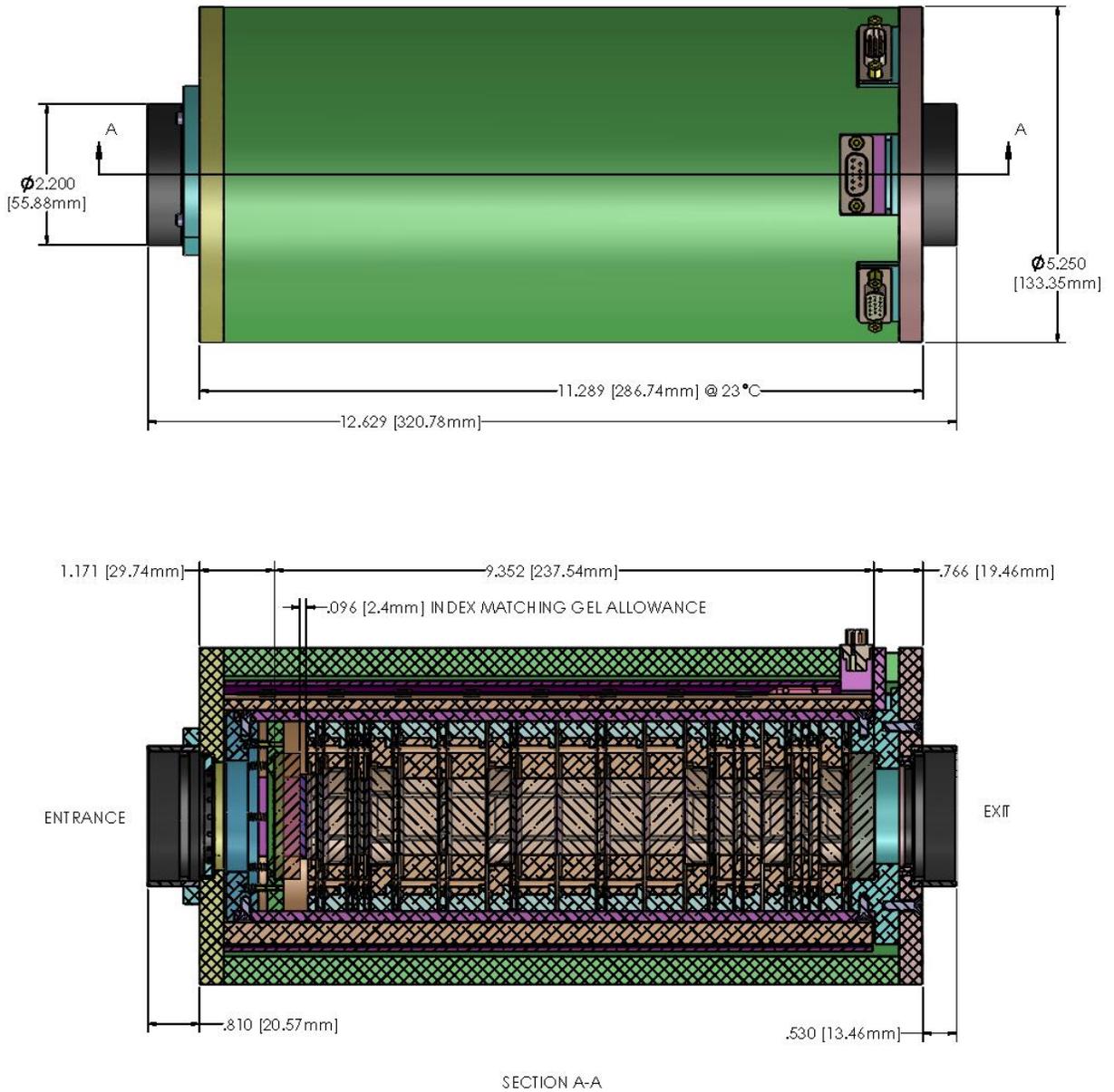
Figure 7 Mechanical envelope and section view drawings for SCD Lyot Filter. Entrance and Exit tube 'baffles' are removable.

2.9 CAMERAS

The camera has been specified as an Andor Neo (specsheet here, website here). This camera has 2560 x 2160 pixels (6.5 µm pitch) for a total sensor area of 16.6mm x 14.0 mm. The camera has a full-frame frame rate of 30 fps (cameralink 3-tap) and a well depth of 30,000 electrons. Andor provides QE values up to 1 micron. HAO performed tests to determine the detector QE up to 1.1 µm. These are detailed in Section 2.11.5.

2.10 SPECTRAL RANGE / FOCUS STAGES

In this optical design, the objective lens does not move with respect to the instrument. The only focusing movement required is the camera stage (Figure 8). This does not include any FOV changing stages. Table

7 details the raytraced focus position for the detector at various wavelengths. The distance is the distance from the end of the exit baffle on the Lyot Filter to the front face of the camera (not the sensor itself). Note that these distances are assuming a 5mm thick calibration optic.
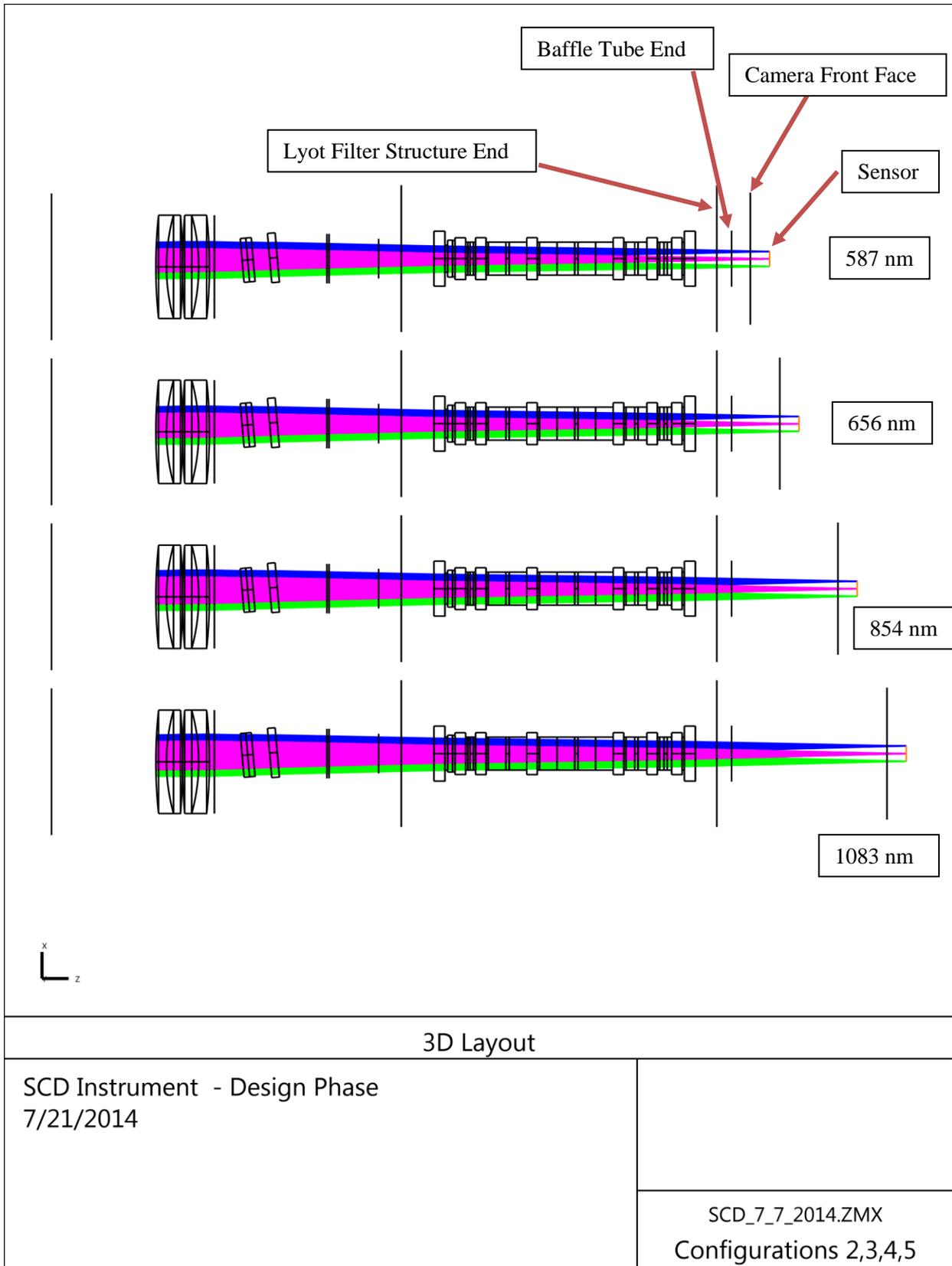
Figure 8 - Focal plane location as a function of wavelength.

Central Wavelength [nm]	Camera Stage Position [mm]
587.6	17.023
656.3	43.792
854.2	96.662
1083.0	141.226
Total Travel needed	124.203

Table 7 – Preliminary camera focus position.

The motion stage identified to accomplish the above motions is the [PLS-85](#). This stage has 155mm of travel with a repeatability of ≤ 1 μm.

2.11 EXPECTED PERFORMANCE

2.11.1 Field of View

Figure 9 shows the location of the extreme FOV points on the detector sensor. The total FOV varies as a function of wavelength, but at 587.6 nm the FOV is $702'' \times 835''$.
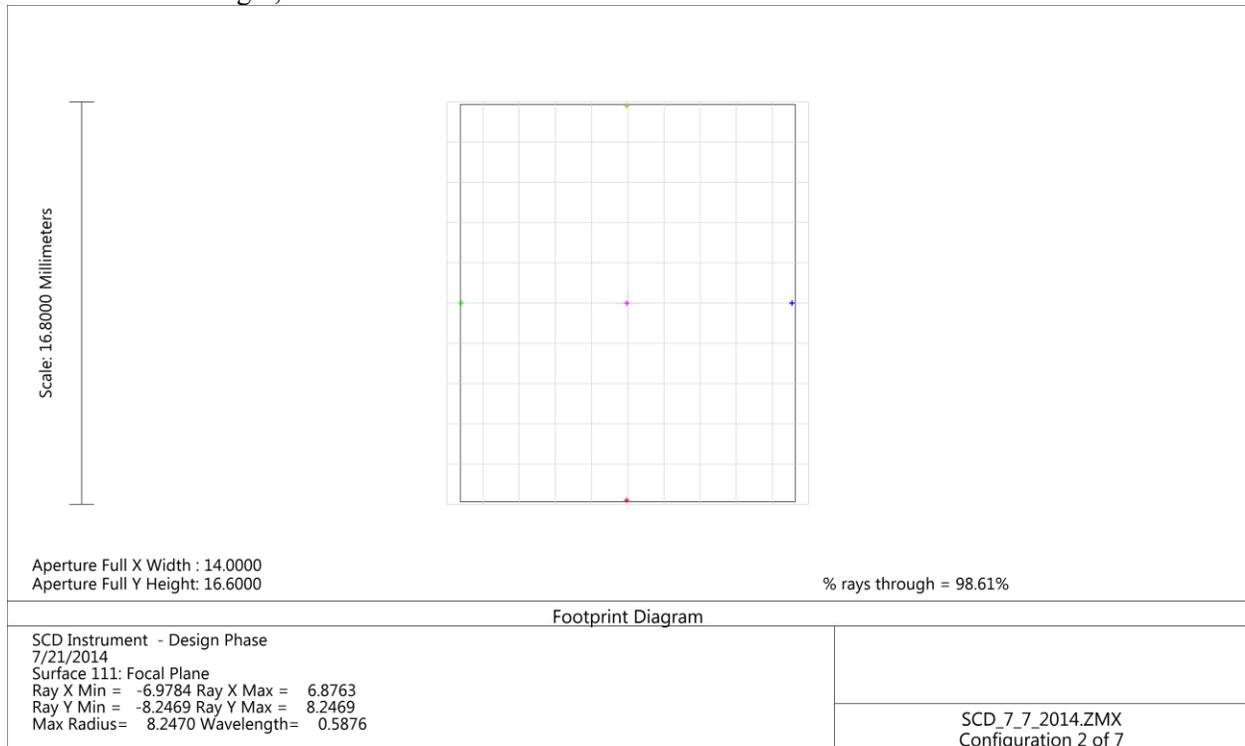
Figure 9- Sensor image showing field of view

2.11.2 Spatial Performance / Spot Diagrams
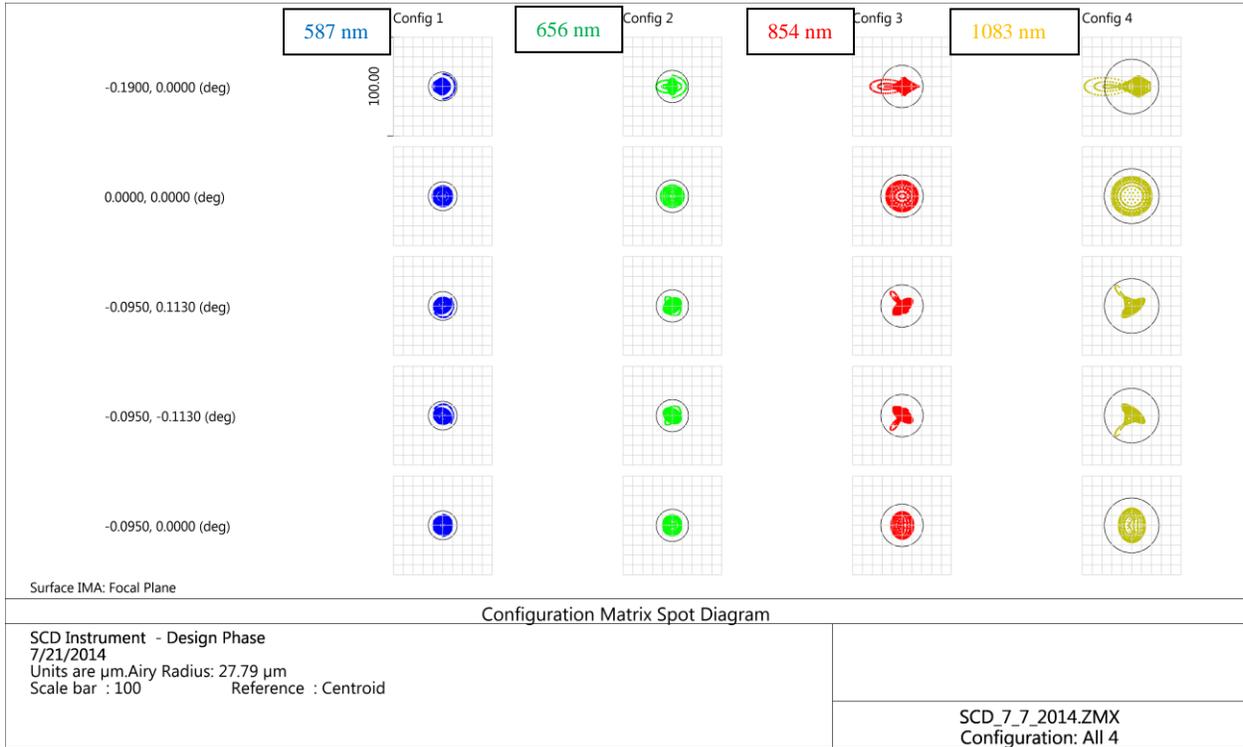
Figure 10 – Spot Diagram Summary – Original Zeiss Objective Design
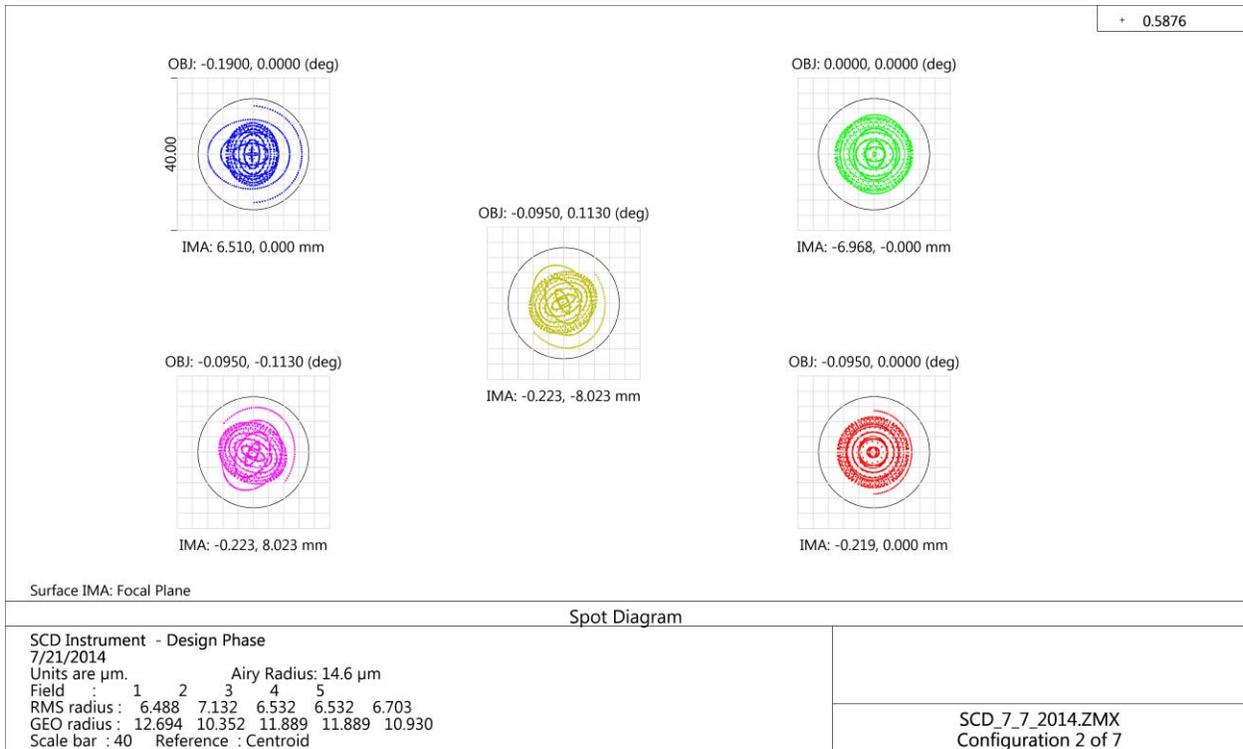
Figure 11 - Spot diagrams at 587nm
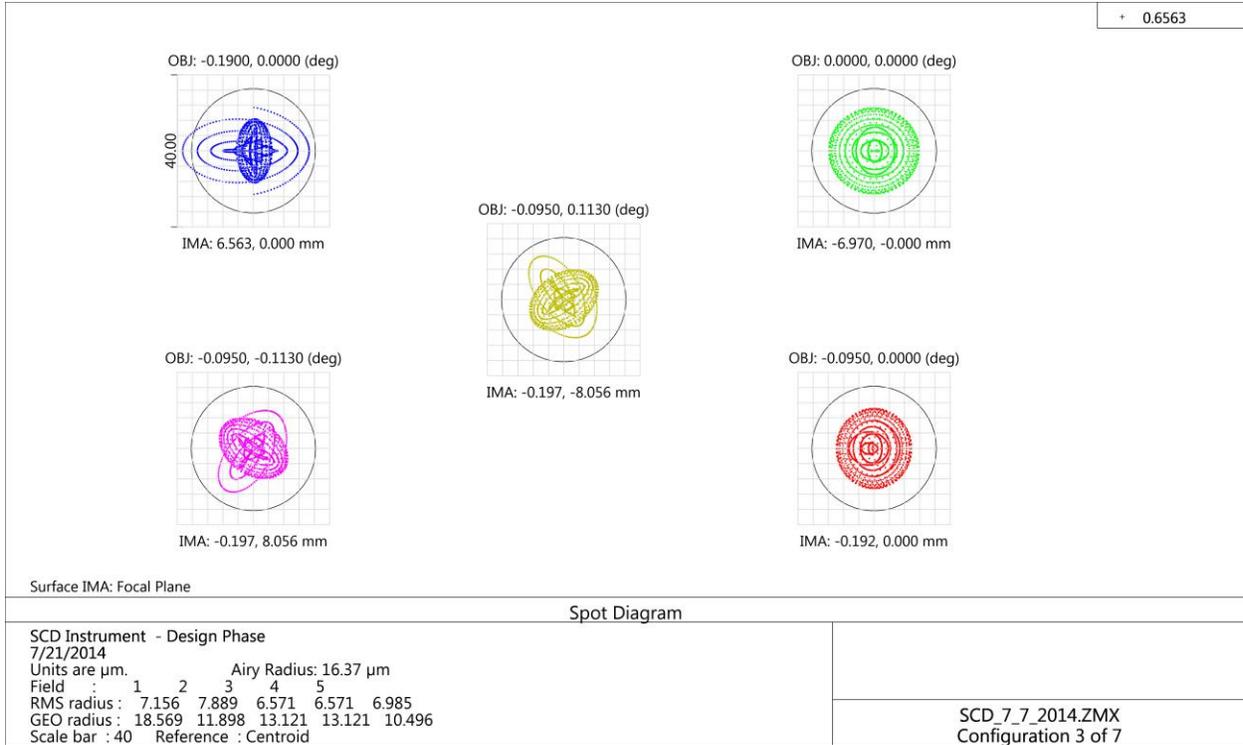
Figure 12 - Spot diagrams at 656nm
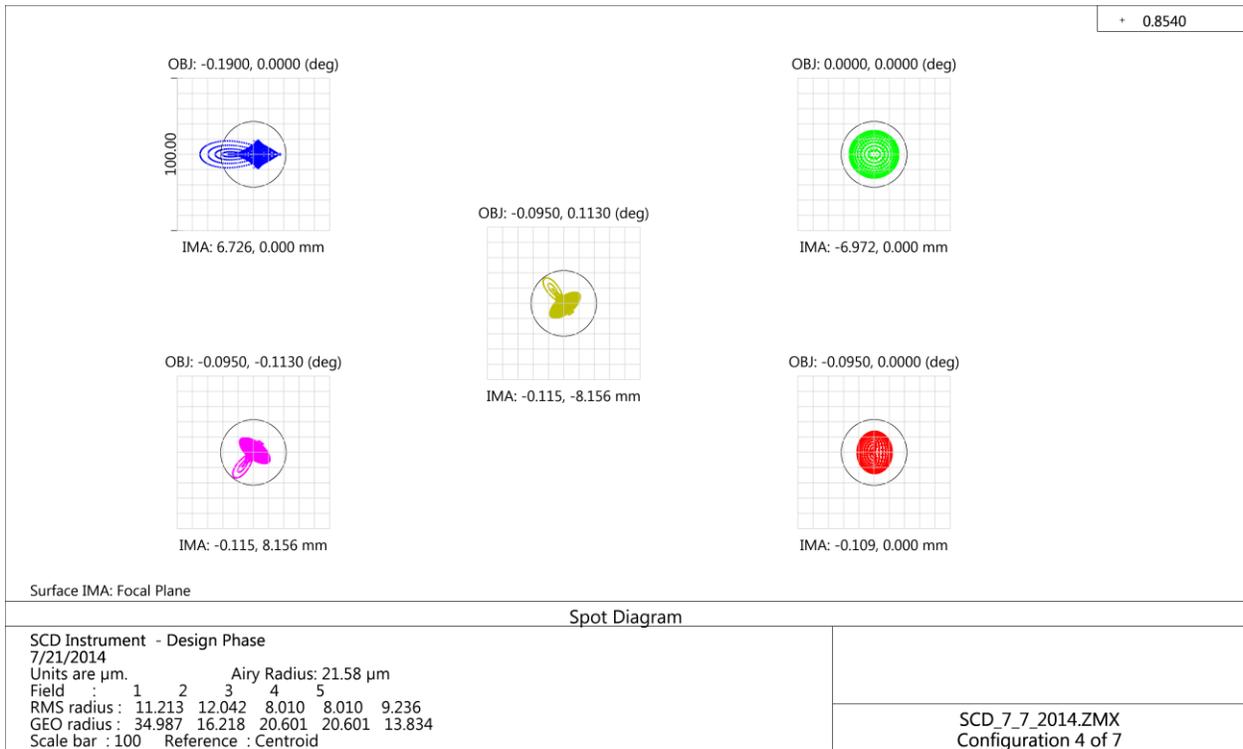
Figure 13 - Spot diagrams at 854 nm
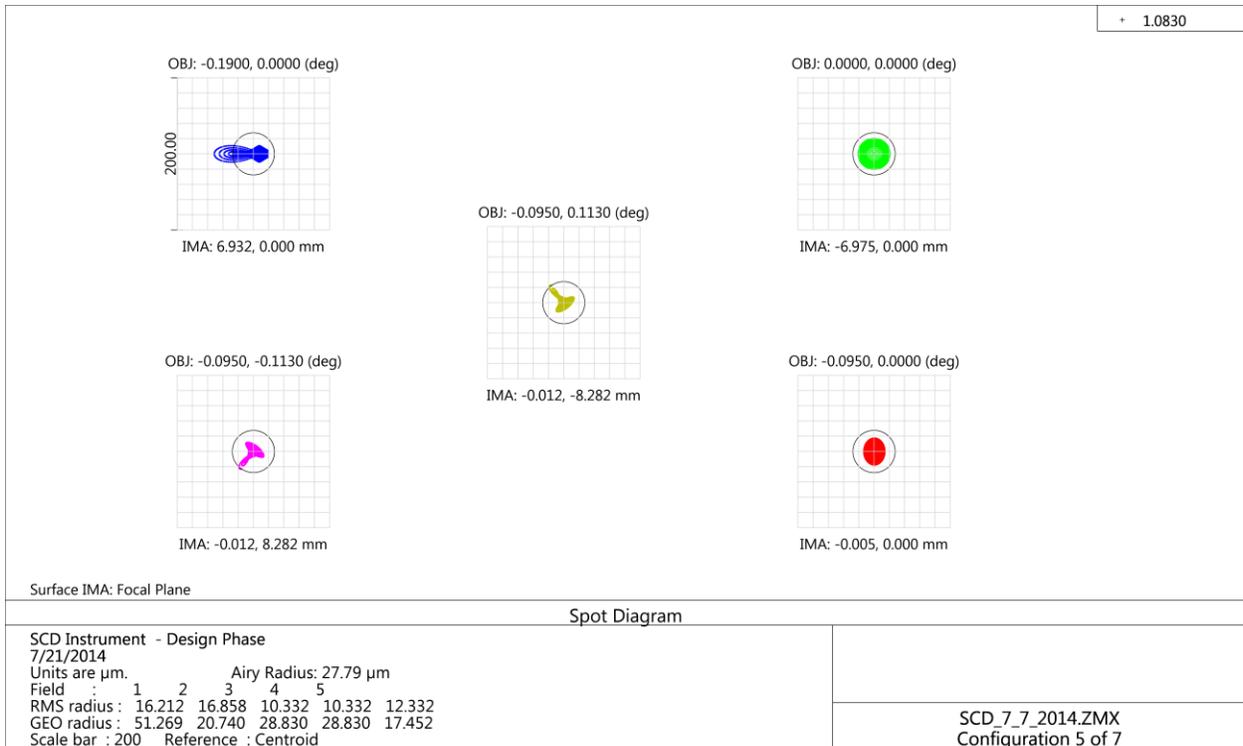
Figure 14 - Spot diagrams at 1083nm

2.11.3 Spatial Performance / Ensquared Energy Curves
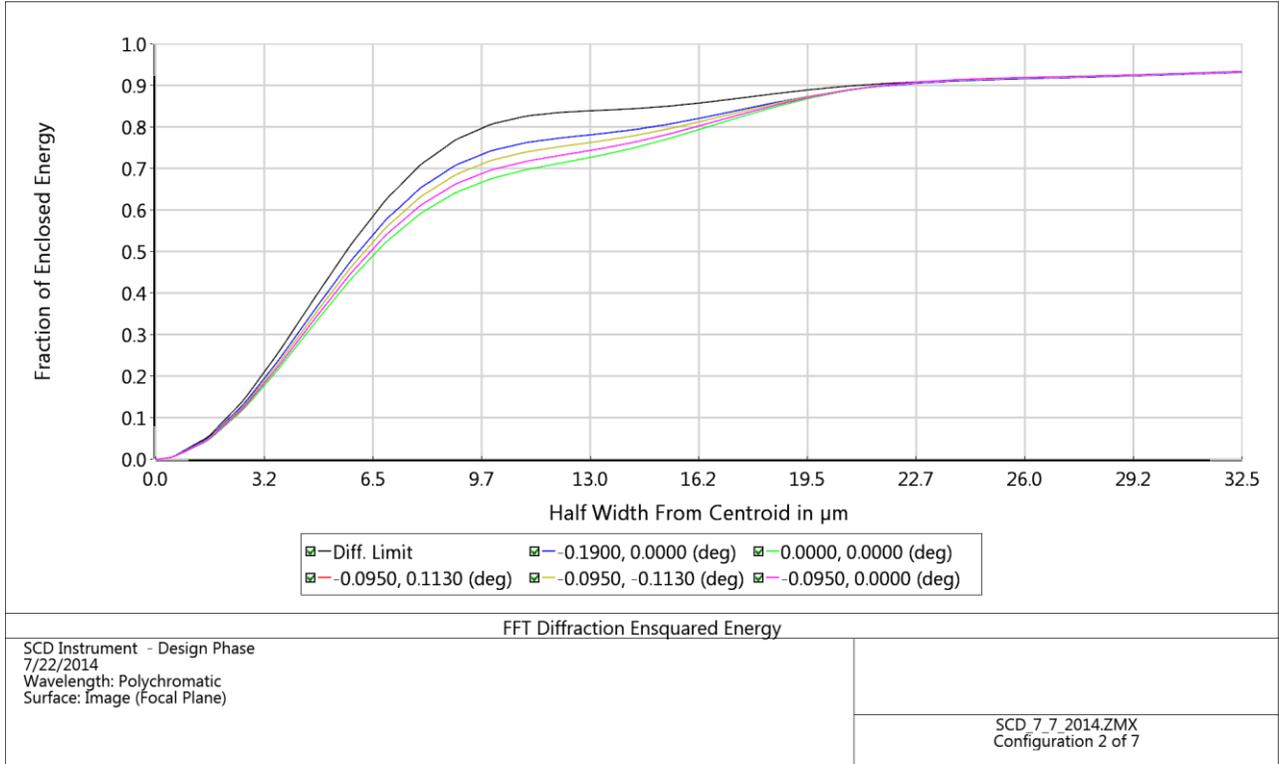
Figure 15 - Ensquared Energy curve at 587nm
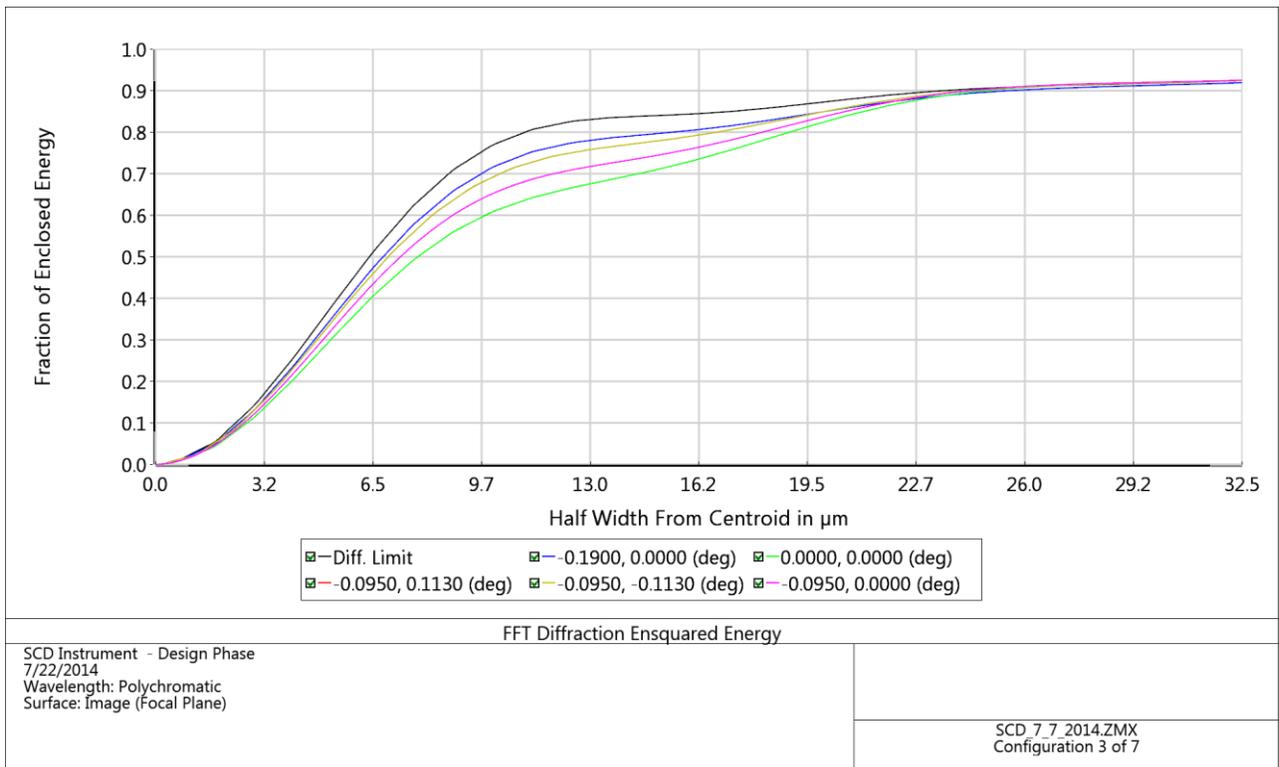
Figure 16 - Ensquared Energy curve at 656nm
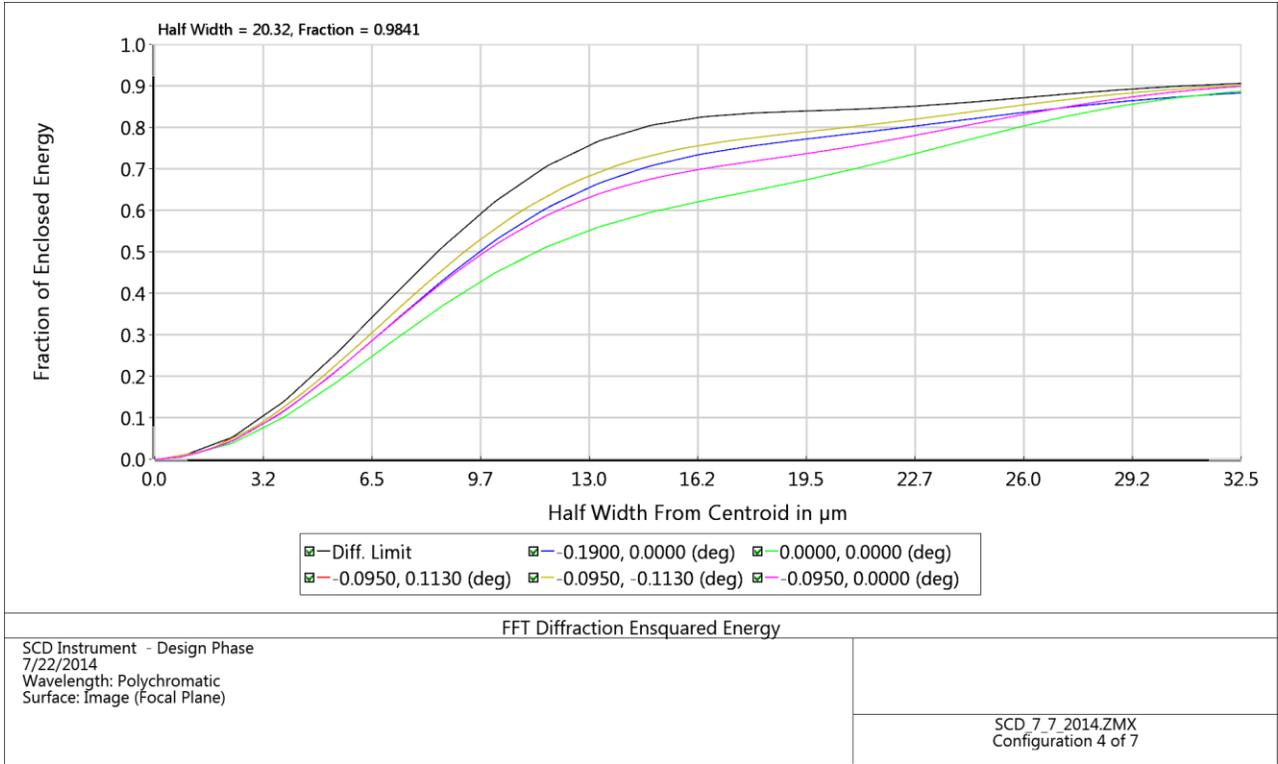
Figure 17 - Ensquared Energy curve at 854nm
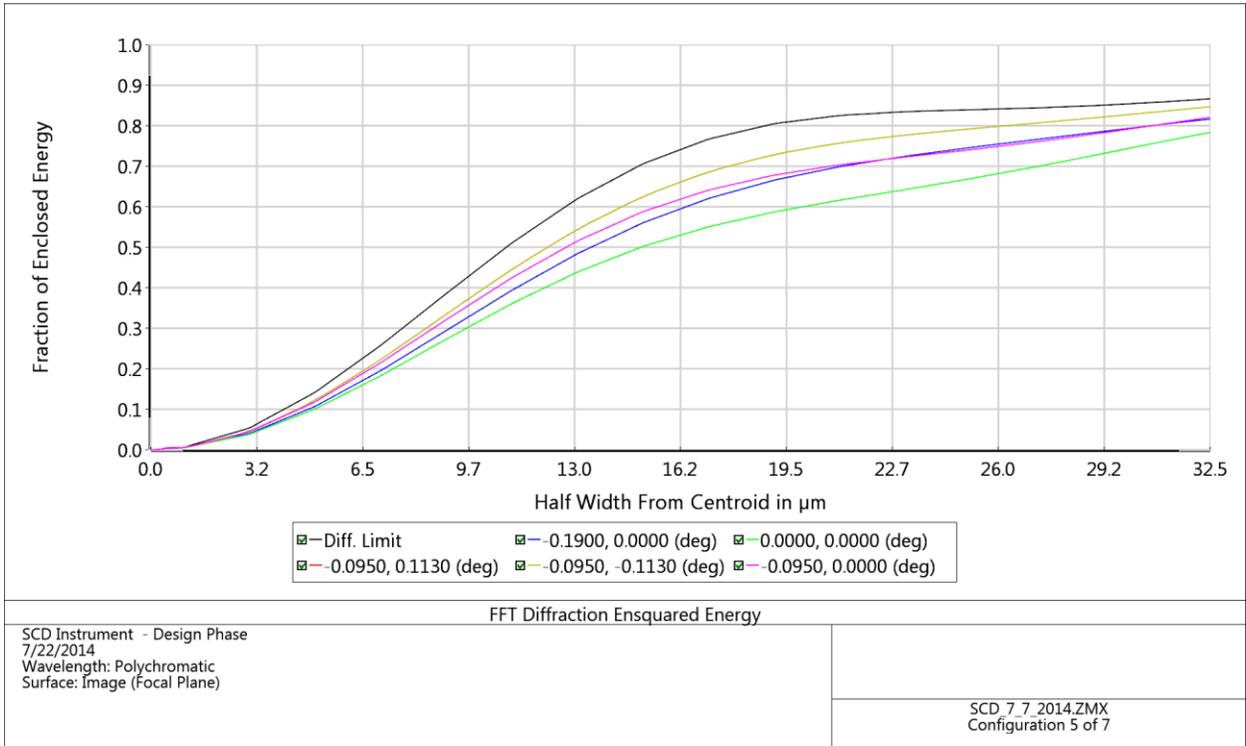
Figure 18 - Ensquared Energy curve at 1083nm

2.11.4 Spatial Performance / MTF Curves
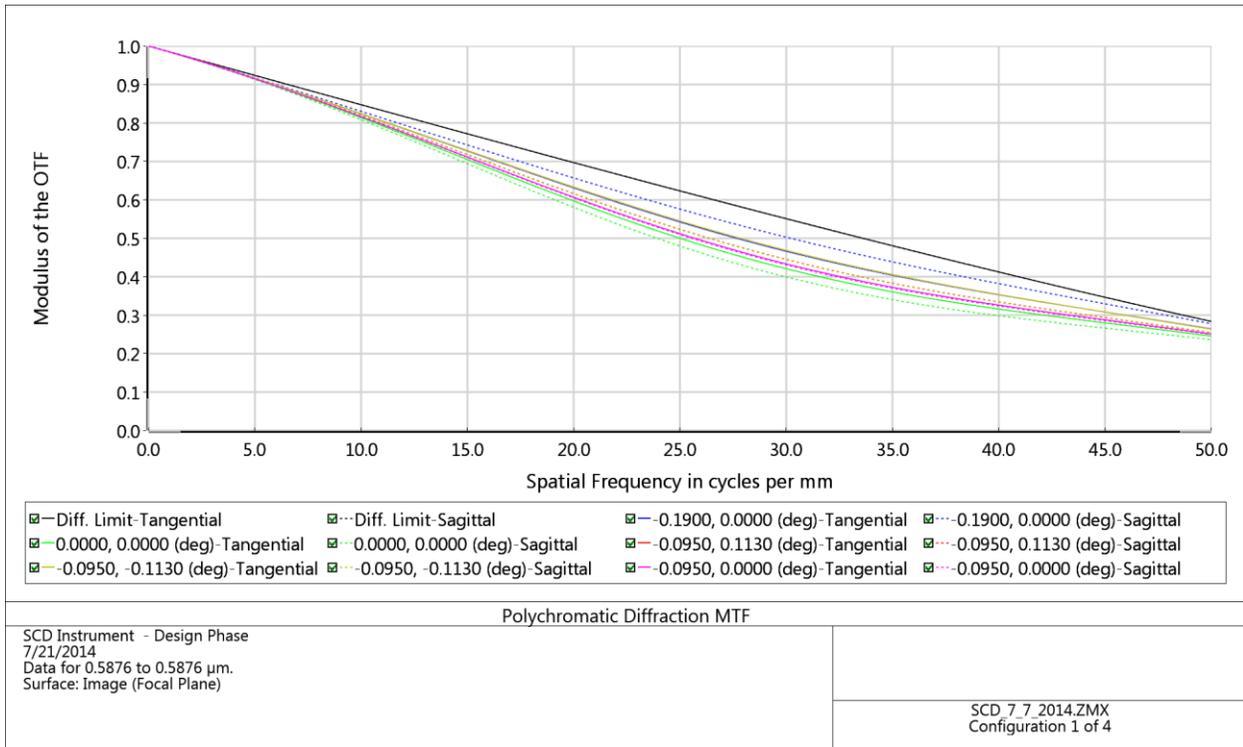
Figure 19 - MTF at 587nm
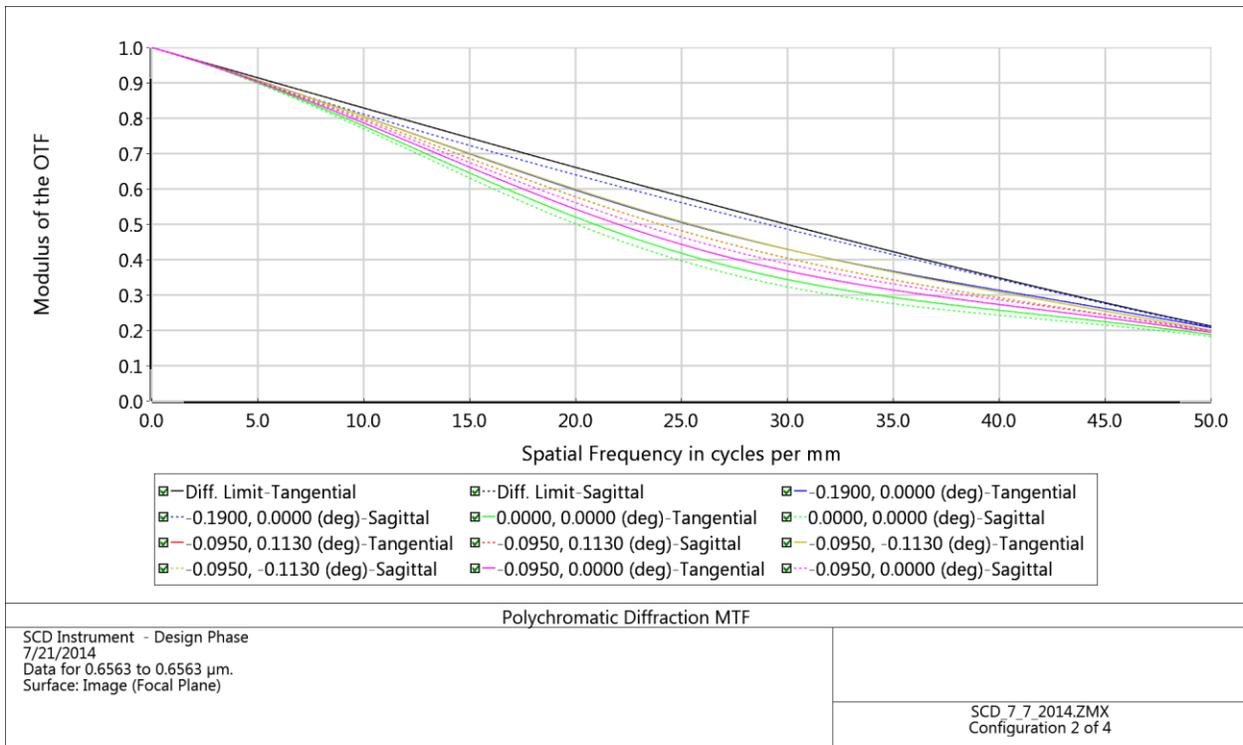
Figure 20 - MTF at 656nm
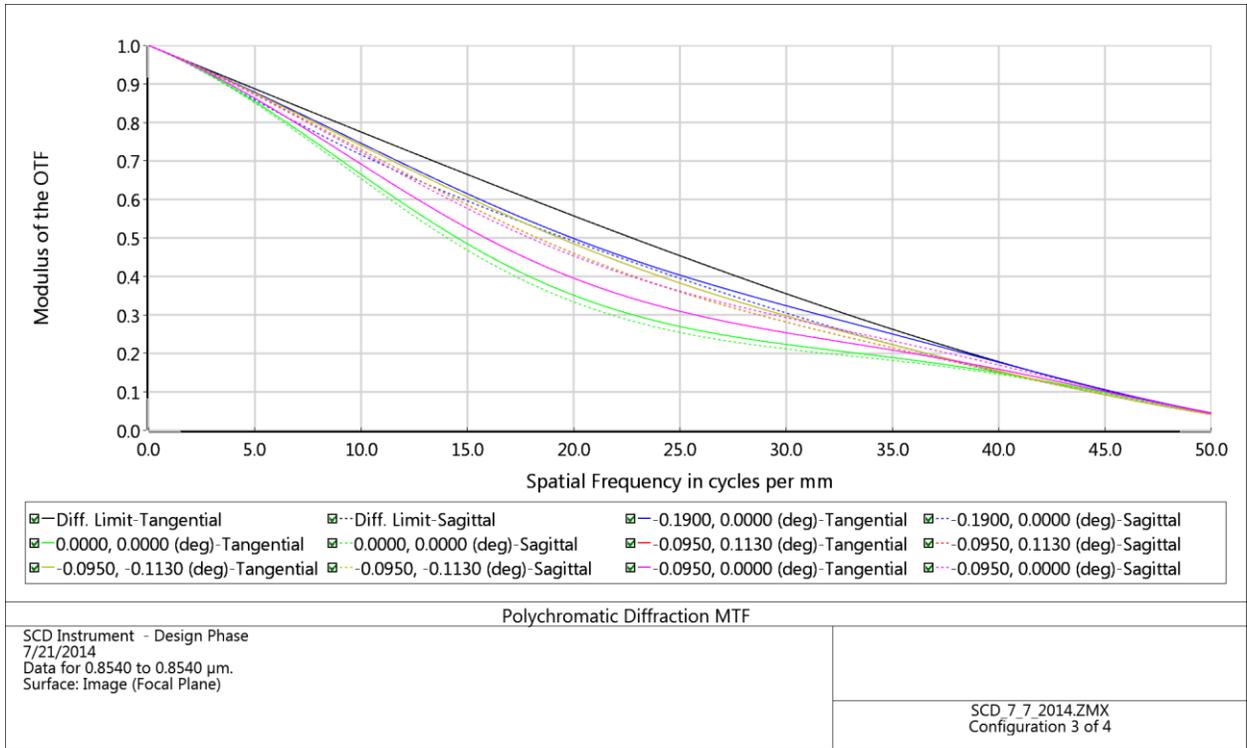
Figure 21 - MTF at 854nm
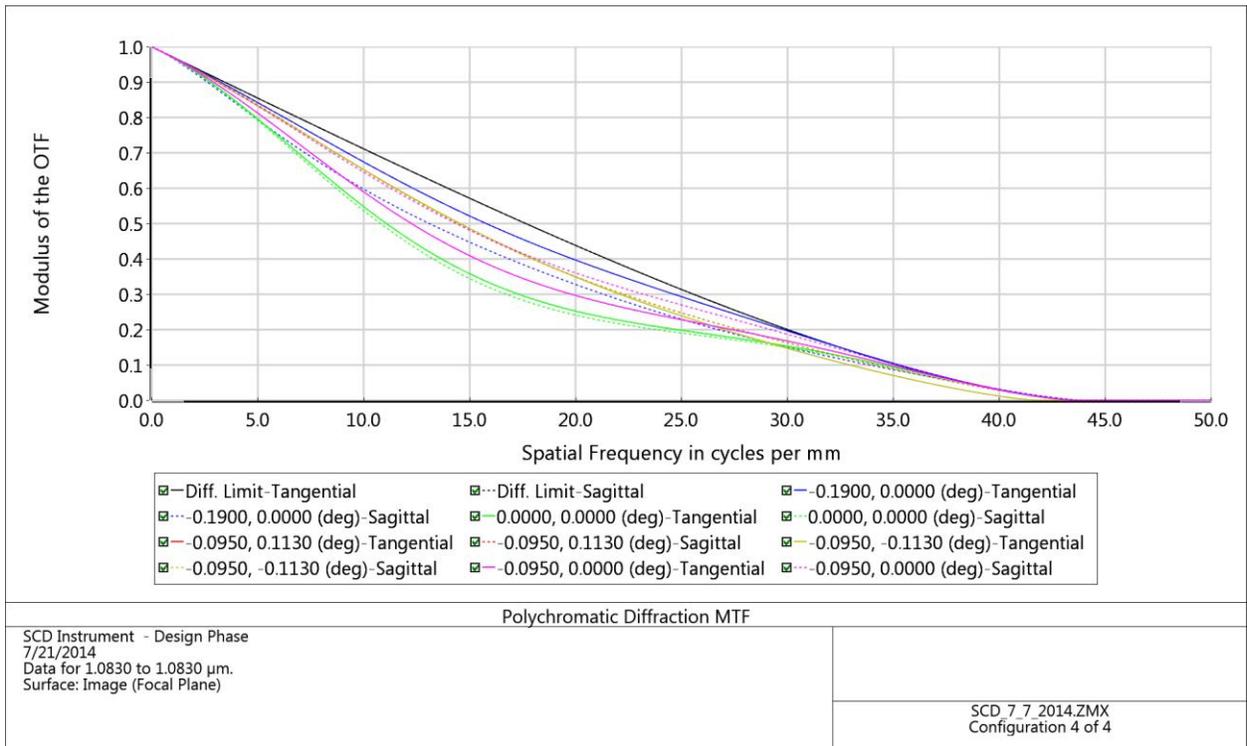
Figure 22 - MTF at 1083nm

2.11.5 Flux Budget

The following figures (Figure 23 - Figure 24) illustrate preliminary estimations of throughput and effective area of the instrument. The flux budget document (5653-OD-6003 (Flux Budget)) provides further details on these calculations. The effective area numbers are assuming no aperture stop (i.e. using the full 20cm of the objective lens).
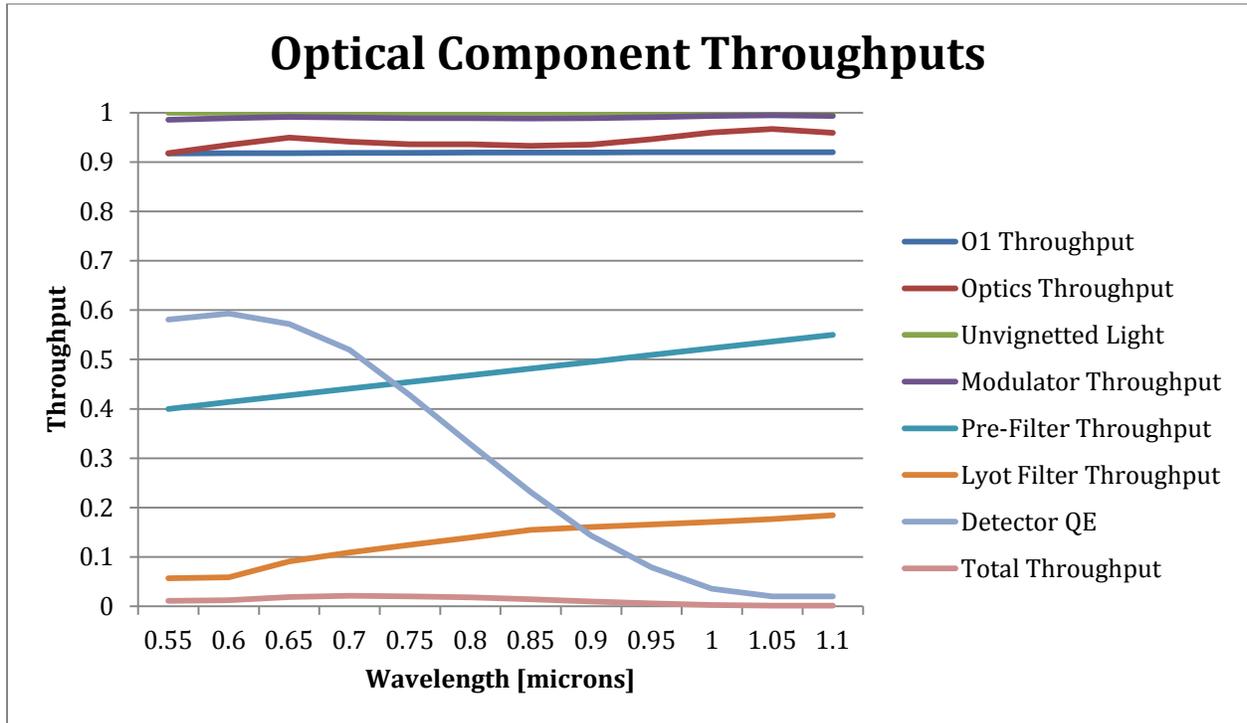
Figure 23 - Component throughput efficiency. These values are pre-procurement estimates only.
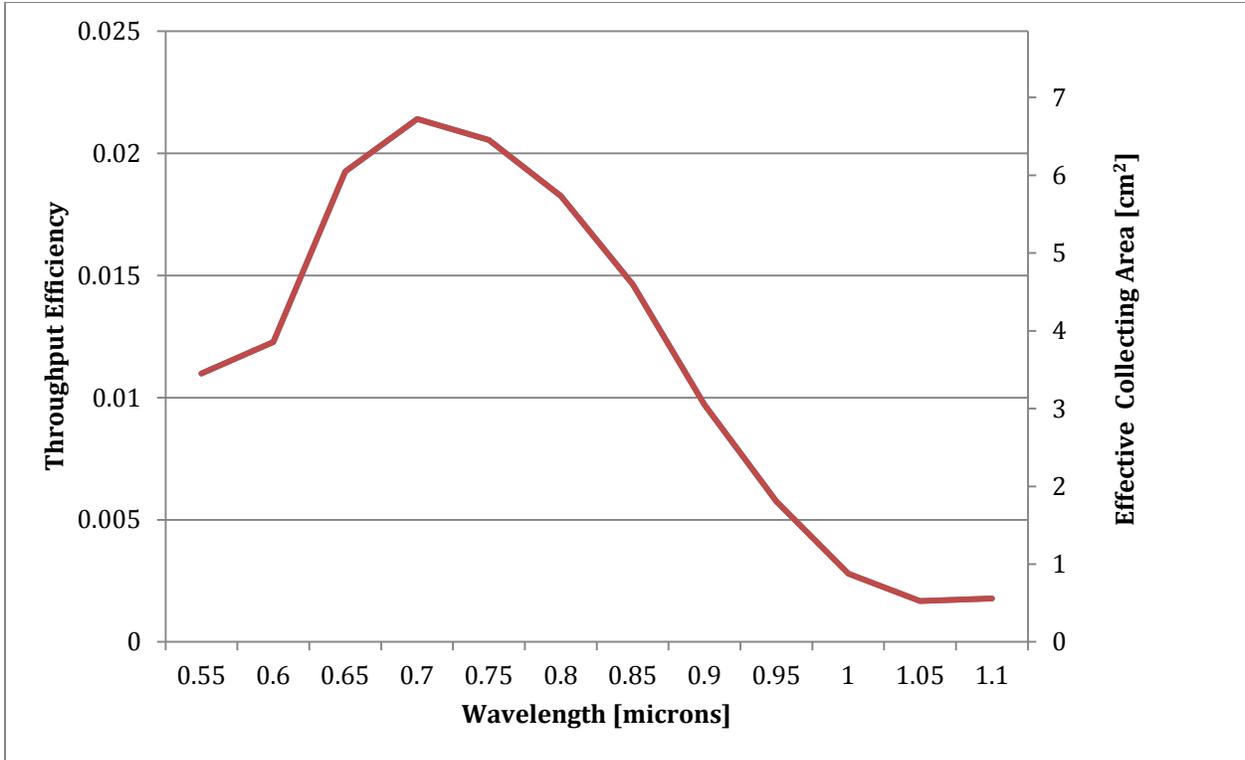
Figure 24 - Total throughput efficiency. These values are pre-procurement estimates only.

3   150/2250 ACHROMATIC DOUBLET DESIGN

A goal for the SCD optical design was to be able to operate in one of two configurations within the ZISAS Solar Observatory. (1) Mounted behind the original Zeiss singlet object as described in the previous section and (2) Mounted alongside the Zeiss telescope using a new 150/2250 Zeiss Achromatic Objective (doublet) as a separate telescope system but still using the same enclosure as in the first design.

This 2nd Zemax design started with the Ross Optical L-AOC609 standard achromat (used in HAO's ChroMag instrument upon which the SCD instrument is based) and scaled its focal length (and other parameters) to match the Zeiss 150/2250 lens. The precise prescription of the Zeiss 150/2250 was unavailable and therefore the exact performance of the SCD instrument when using this objective might deviate slightly from the following description. We believe the results are appropriate for benchmarking this design.
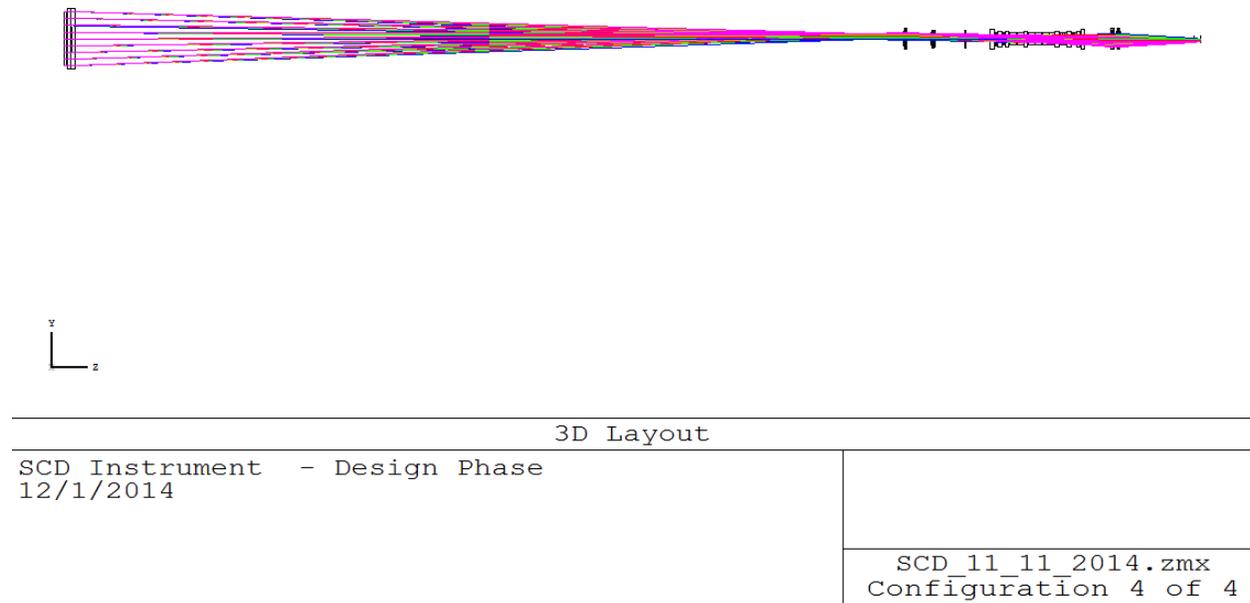
Figure 25 - 150/2250 Design - Top Level
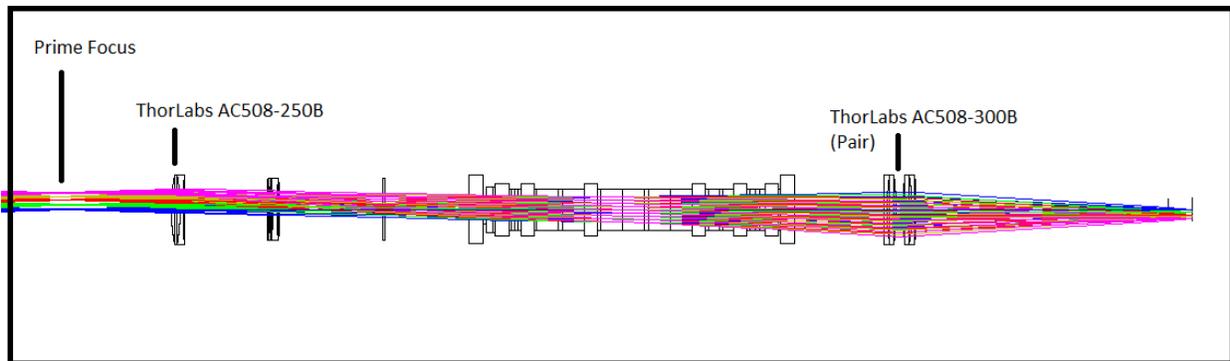
Figure 26 - 150/2250 Design - Rear Optics

Three off-the-shelf achromats from ThorLabs permit this externally mounted design option. Other elements are identical to those in Figure 2. (Heat Rejection filters, order selection pre-filters, Lyot Filter and andor Neo focal plane. In this design, the position of the focal plane varies by < 4mm over the wavelength range from 587-1083nm. The same computer controlled linear stage (PI-PLS85) for controlling the camera focal plane position is used in BOTH SCD optical designs.

3.1 150/2250 DESIGN PERFORMANCE SUMMARY

3.1.1 Field of View

Figure 27 shows the location of the extreme FOV points on the detector sensor. The total FOV varies as a function of wavelength, but at 587.6 nm the FOV is 2592″ × 3096″.

Figure 27 - 150/2250 Design Field of View Performance

3.1.2   Spatial Performance/Spot Diagrams
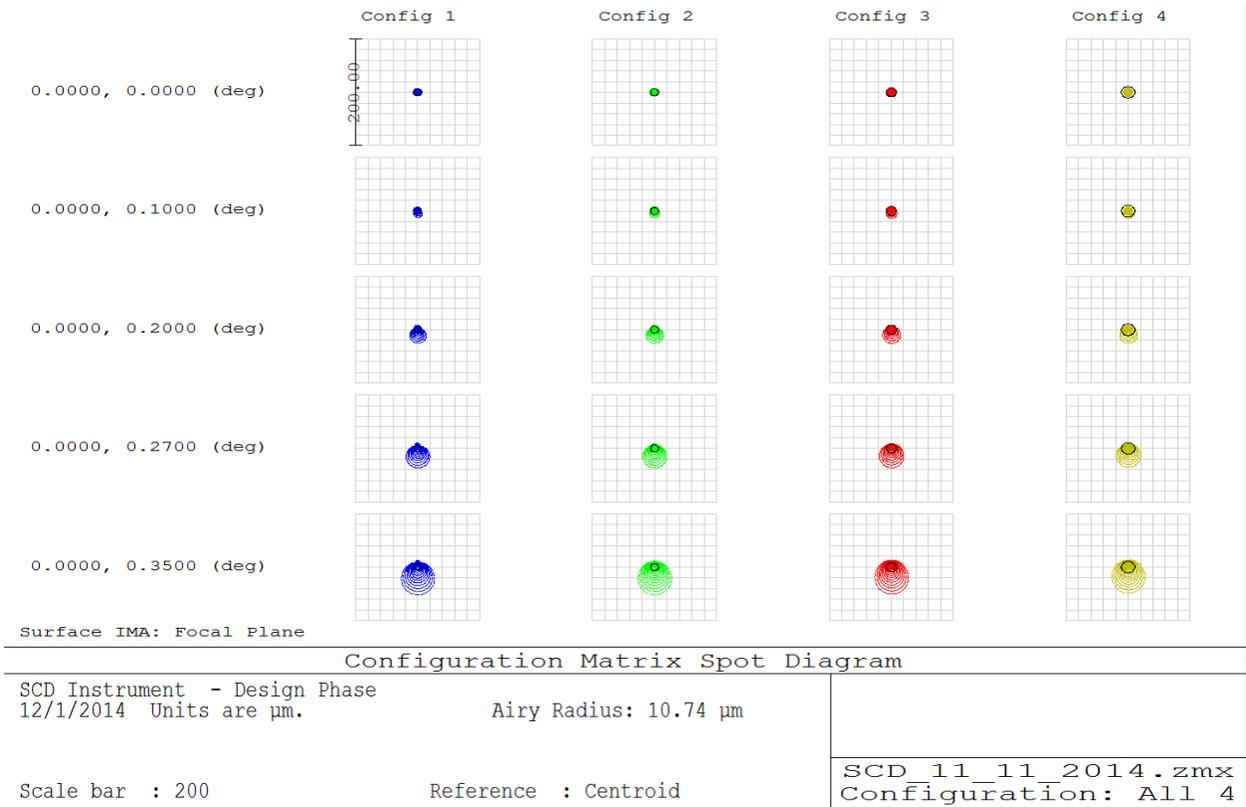
Figure 28 - 150/2250 Design – Spot Diagram Summary

3.1.3   Spatial Performance / Ensquared Energy Curves

The performance of the 150/2250 design is less that of the "Singlet" design, the latter of which uses a high quality, multi-element custom Zeiss imaging lens. The 150/2250 design was intended to be a copy of HAO's ChroMag instrument which utilizes off the shelf elements in carefully prescribed locations. Future AISAS upgrades may be achieved by replacing these off the shelf lenses with customized optics.

Even though this design images out to diameters of 3096", the following performance graphs use field points located at the limb of the sun where scientific interest is focused.

Figure 29 - 150/2250 Desgin Ensquared Energy at 587nm.
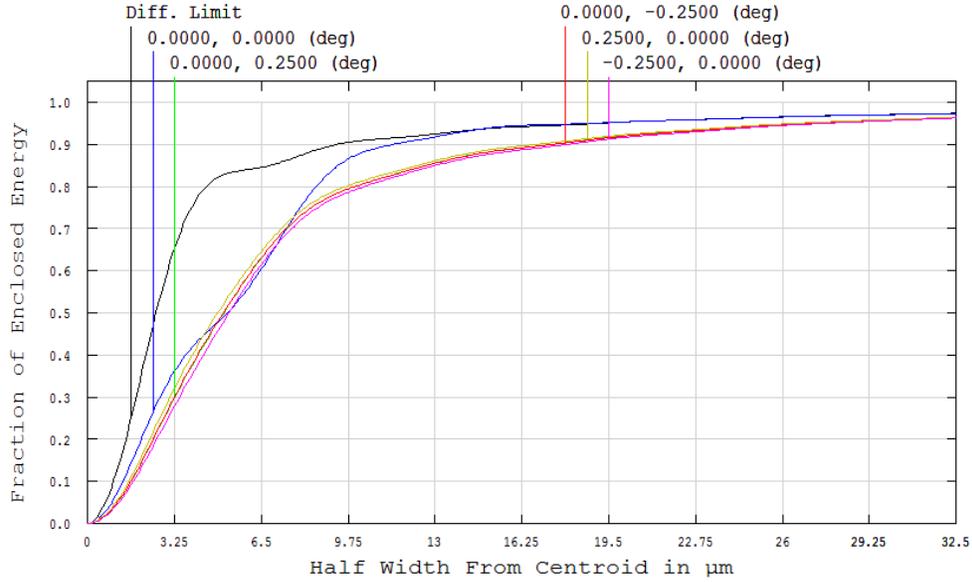
Figure 30 - 150/2250 Design Ensquared Energy at 656nm.
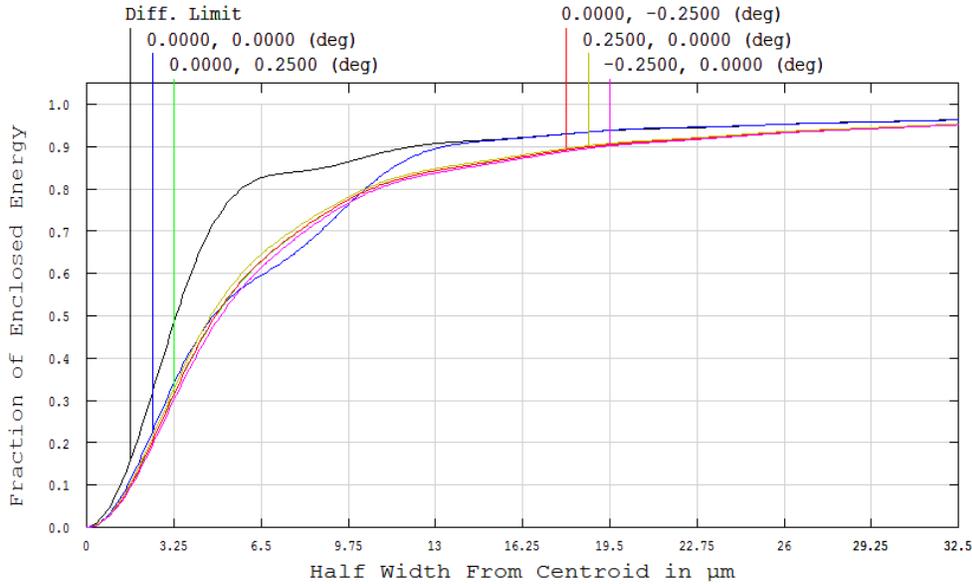
Figure 31 - 150/2250 Design Ensquared Energy at 854nm.
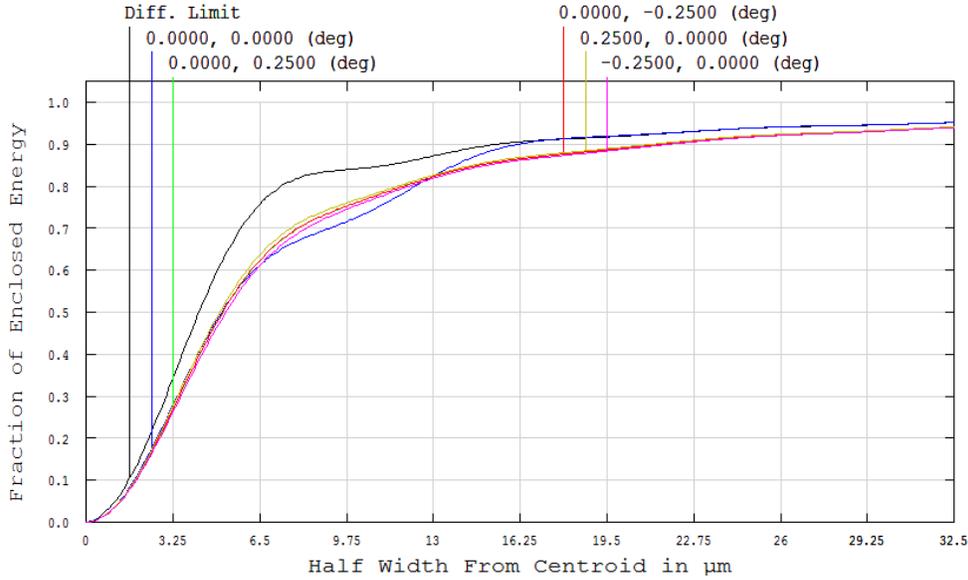
Figure 32 - 150/2250 Design Ensquared Energy at 1083nm.

3.1.4 Spatial Performance / MTF Curves
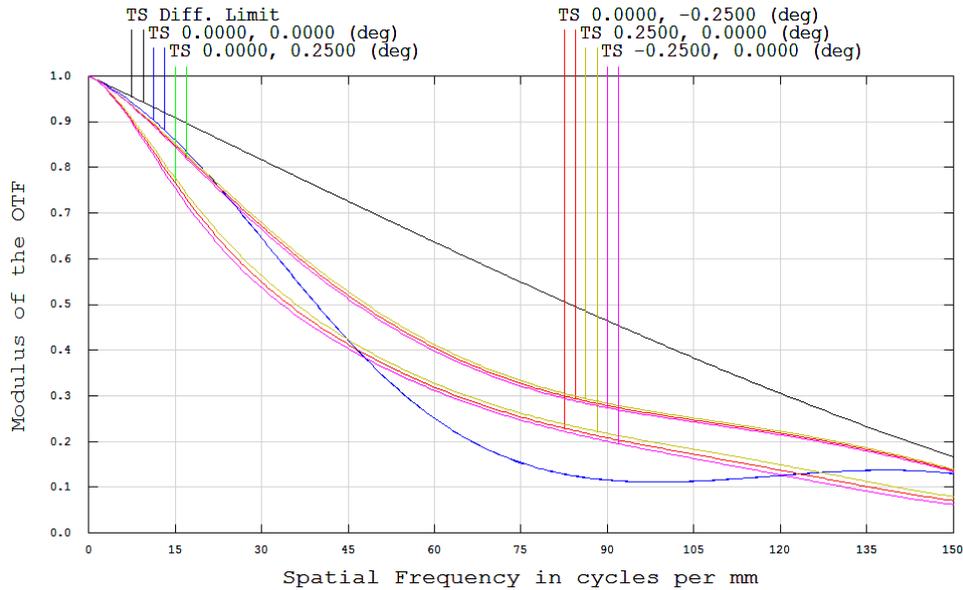
Figure 33 - 150/2250 Design MTF at 587nm.
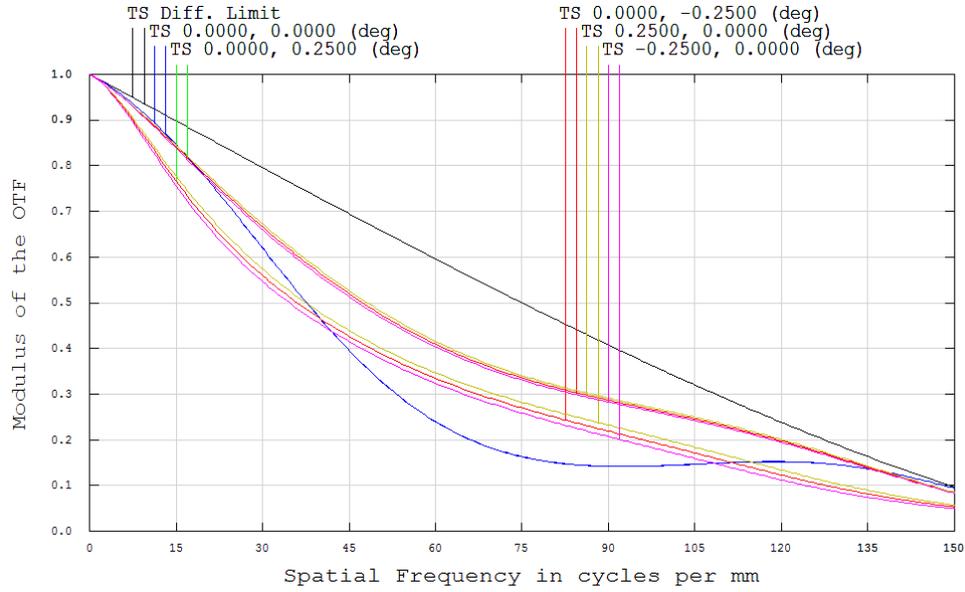
Figure 34 - 150/2250 Design MTF at 656nm.
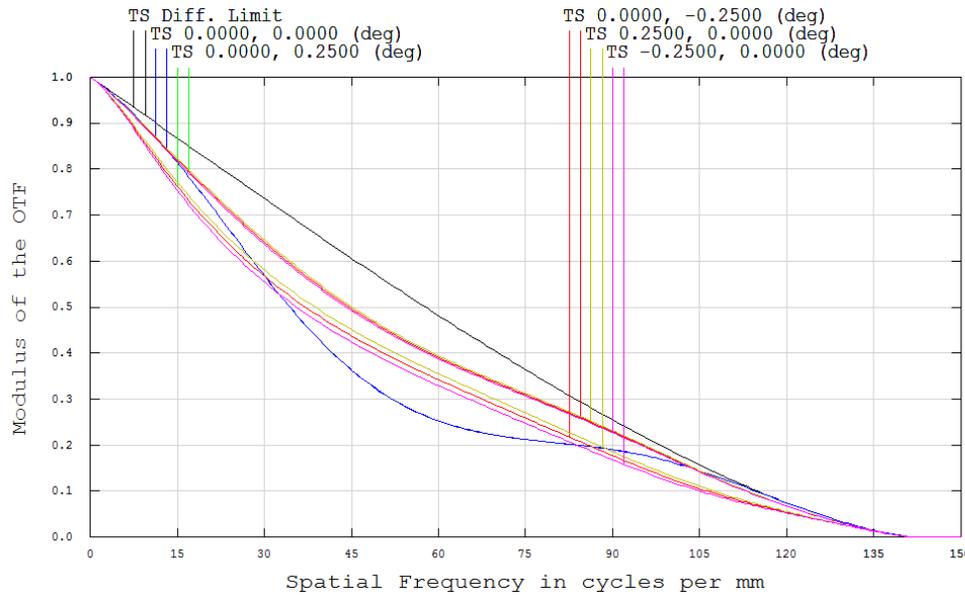
Figure 35 - 150/2250 Design MTF at 854nm.
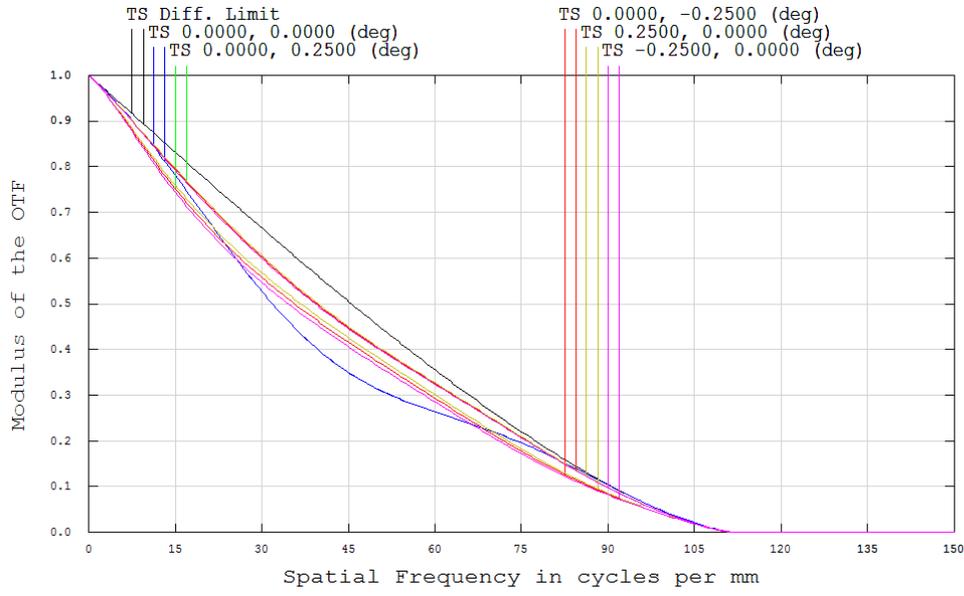
Figure 36 - 150/2250 Design MTF at 1083nm.