PRECISION RADIAL VELOCITY SPECTROMETER

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Document Prepared By:	David Henry, UKATC	**Signature and Date**	David Henry 15th September 2006
Document Approved By:	Martyn Wells, UKATC	**Signature and Date**	Martyn Wells 15th September 2006
Document Released By:	David Lunney, UKATC	**Signature and Date**	David Lunney 15th September 2006

CHANGE RECORD

Issue	Date	Section affected	Change Description
0.2	8/08/06	All sections	Changed formatting of Headers
0.3	11/09/06	All sections	Updated for proposal submission
1.0	15/09/06	All sections	Final review before release to Gemini by DWL

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List of Abbreviations

PSF	Point Spread Function – The response of the optical system to a point source in the object plane
SRF	Spectral Response Function – The convolution of the Point Spread Function with the geometric image of the slit, i.e. the response of a spectrograph to monochromatic radiation filling the input slit
CTE	Coefficient of thermal expansion

Table of Definitions

TBD	To Be Defined : a requirement to be developed during the preliminary design stage of the instrument.
TBC	To Be Confirmed : a requirement that is correct with the current design information but requires confirmation during the preliminary design stage of the instrument.
TBR	To Be Reviewed : a requirement specified to meet the PRVS top-level requirements, but which might over-constrain the design.

1. INTRODUCTION

This document describes the design of the Spectrograph Sub-system (SS) of the PRVS Precision Radial Velocity Spectrograph for the Gemini telescope.

2. APPLICABLE AND REFERENCE DOCUMENTS

Reference	Document Title	Document Number	Issue & Date
AD01	Science Requirements	PRVS-SPEC-00005-0001	1.0
AD02	Initial Functional Performance & Requirements Document	PRVS-SPEC-00003-0001	1.0

3. ITEM DEFINITION

The Spectrograph SS consists of the following sub-assemblies (SA):

- Optical Bench SA, comprising the main optical bench
- Collimator SA, comprising collimator mirror and mount
- Echelle SA, comprising echelle grating and mount
- Spectral mirror SA, comprising spectral mirror and mount
- Cross disperser SA, comprising cross disperser grating and mount
- Camera SA, comprising camera lenses and mount
- Shutter SA, comprising shutter, mount, mechanism and control electronics
- Focal plane SA, comprising IR detector, readout electronics and mount
- Detector controller SA, comprising detector control electronics
- Flat field illumination source SA, comprising illumination source and mount

3.1 KEY FUNCTIONAL REQUIREMENTS

The Spectrograph Sub-system takes the light emerging from the pseudo-slit produced by the image slicer (part of the Fore-Optics Fibre Sub-system) and disperses this light by means of a set of optical components into a spectrum. This spectrum falls onto a detector assembly where the light is converted to a photocurrent. This is then converted by the detector controller into an image file which can be fed into the Data Pipeline Software Sub-system.

A secondary requirement is to provide illumination of the detector array to allow detector flat fields to be taken. This is done by the flat field illumination source.

3.2 KEY PERFORMANCE REQUIREMENTS

Parameter	Requirement	Comment
Resolving power	> 70 000	
Sampling	> 2.5 pixels	Effective slit width of 0.08mm
Image quality – 50% encircled energy diameter	< 0.8 pixel	
Image quality – 80% encircled energy diameter	< 1.6 pixels	
Transmission	TBD	

4. DESIGN DESCRIPTION

4.1 SPECTROGRAPH OPTICAL DESIGN

The optical design of the spectrograph is similar to other white pupil spectrographs such as UVES on the VLT, HRS on the HET and, in particular, HARPS on the ESO 3.6m La Silla telescope.

The spectrograph is fed by a fibre from the telescope, which terminates in a fibre slicer. The slicer takes the light from the 0.3mm core diameter main fibre and divides it into seven smaller 0.1mm core diameter fibres. These smaller fibres, together with an eighth calibration fibre are reformatted into a pseudo-slit which forms the input to the spectrograph. The effective size of the pseudo slit is 0.08mm wide by 0.9mm long. This is equivalent to approximately 0.36 x 4.22 arcsec on the sky.

The fibre is fed with a beam of f/5.5 from the telescope. To allow for 10% focal ratio degradation, an output f-ratio of f/5 from the fibre slicer is assumed, and the optical components are sized to allow for an f/5 beam. During the final design phase, the focal ratio degradation of the real, as-built fibre slicer will be measured and the input f-ratio optimised to match the actual value.

The output from the fibre slicer is fed into a doublet lens acting as a focal reducer. This changes the f-ratio from f/5 to ~f/13.

This beam then passes onto the parabolic collimator mirror (focal length 2000mm, 500 x 446mm clear aperture), which is used in triple pass. The first pass off the pupil mirror collimates the beam onto the echelle (140mm beam diameter). The 2nd and 3rd passes transfer the pupil from the echelle to a pupil image (the "white" pupil) where the cross disperser is placed. Between the 2nd and 3rd passes is an intermediate image plane where a flat fold mirror (the spectrum mirror, 386 x 30mm clear aperture) is placed.

The long focal length of the pupil mirror is necessary to reduce the aberrations of the white pupil collimator to a manageable level, allowing a relatively simple camera design to be used. Whilst this results in a long path length, there are two advantages to the long focal length. Firstly, it allows the use of a very small out of plane angle (0.4°) on the echelle, whilst still achieving adequate beam separation. This has the advantage of reducing the tilt of the slit image on the detector. Secondly, the reduction of the collimator aberrations reduces the wavelength dependant field curvature to a level where a cylindrical detector lens (as used in HARPS) is no longer needed.

The R4 echelle used is the same as that used in HARPS, UVES and other spectrographs. It has 31.6 lines/mm with an effective blaze angle of 75 deg. It is used in order numbers 35 - 61. The clear aperture of the echelle is 610 x 200mm. The cross disperser is a 100 line/mm reflective grating used in 1st order and of diameter 210mm. Blaze angle is 4°. It is tilted at 20° to allow the reflected beam to clear the input beam.

The camera consists of 6 lens elements plus a flat detector window. The lenses have all spherical surfaces, and the materials are a mixture of Schott and Ohara glass types. The largest lens has a diameter of ~270mm. The camera focal length is 437mm, and the f-ratio is f/2.78. Orders 35 - 61 fit onto a 2x1 mosaic of Hawaii 2RG detectors (2048 x 2048 pixels, 18um pixel size), with some truncation of longer wavelength orders. The pixel scale on the detector is 0.148 arcsec/pixel.

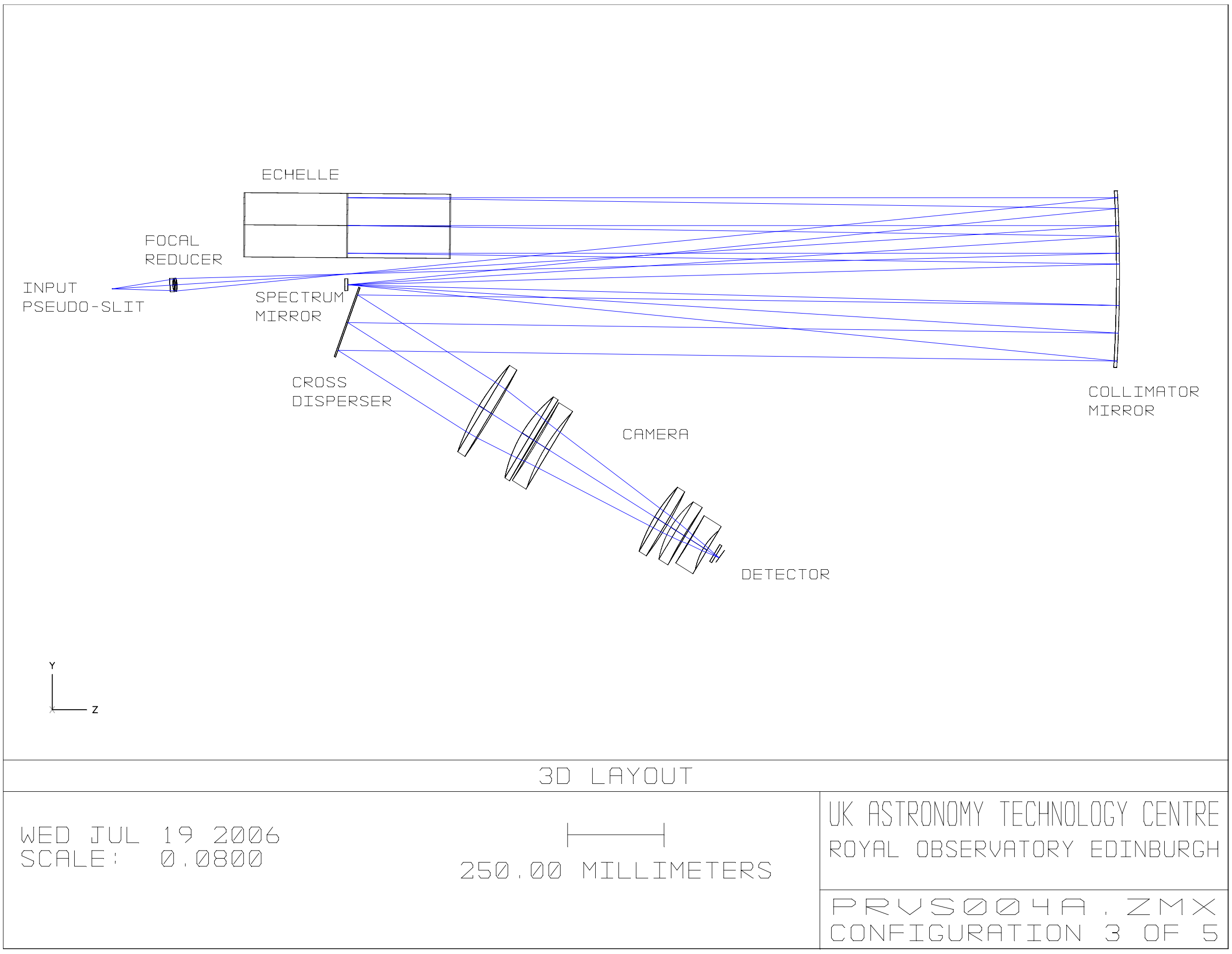

Figure 1 - Optical Layout of the PRVS Spectrograph

Figure 1 shows the optical layout of the spectrograph. For clarity the layout omits the additional fold mirror between the focal reducer lenses and the first intermediate focus.

The table below shows the wavelength coverage, sampling and resolving power of the spectrograph for various spectral orders. The sampling is stated in pixels per resolving element, for an effective slit width of 0.08mm. The resolving power is the nominal system resolving power, and ignores degradation due to the image quality of the spectrograph.

Order number	Blaze Wavelength (um)	Sampling	Resolving Power
35	1.746694	2.527	72035
41	1.491067	2.517	72102
48	1.273605	2.505	72237
55	1.111510	2.497	72326
61	1.002181	2.492	72360

Table 1 - Nominal spectral properties

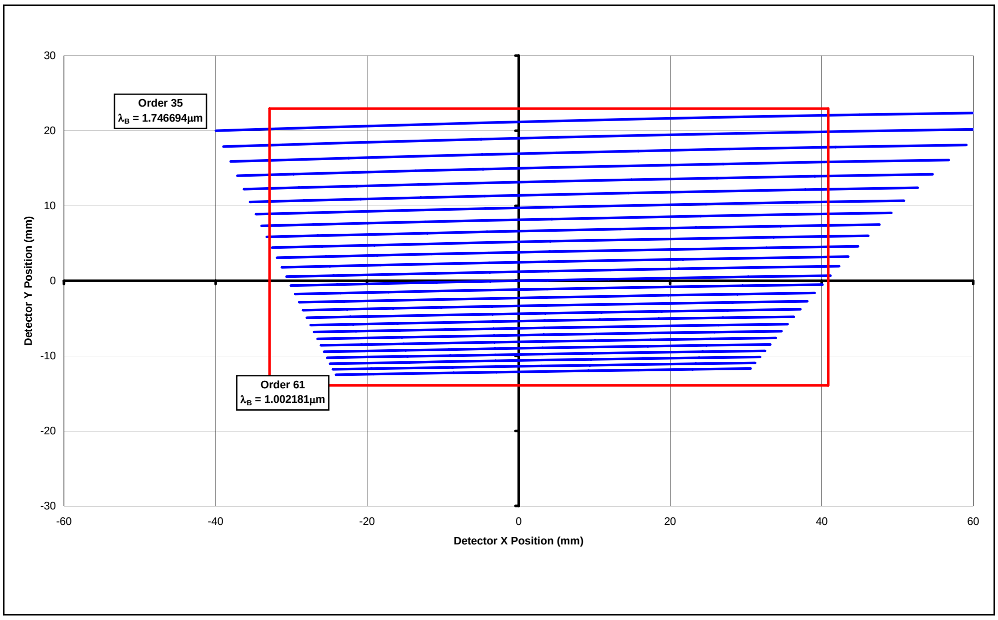

Figure 2 - Spectral format

Figure 2 shows the format of the cross dispersed spectrum on the detector. All orders from 35 to 61 are shown. The red box shows the 2x1 detector layout. As can be seen from the plot, whilst the shorter wavelength orders fit comfortably on the detector, there is truncation of the longer wavelength orders. Approximately 92% of the spectral range from 0.9981um to 1.7716um is covered on the detector array.

Figure 3 shows (on the left) a diagram of the image of the end of the fibre slicer on the detector array. Due to the out of plane angle of the echelle there is a tilt of the slit relative to the spectral direction. The slit tilt is the distance d measured in pixels. The plot shows the slit tilt as a function of order number and wavelength. The tilt varies between 1.18 and 3.08 pixels.

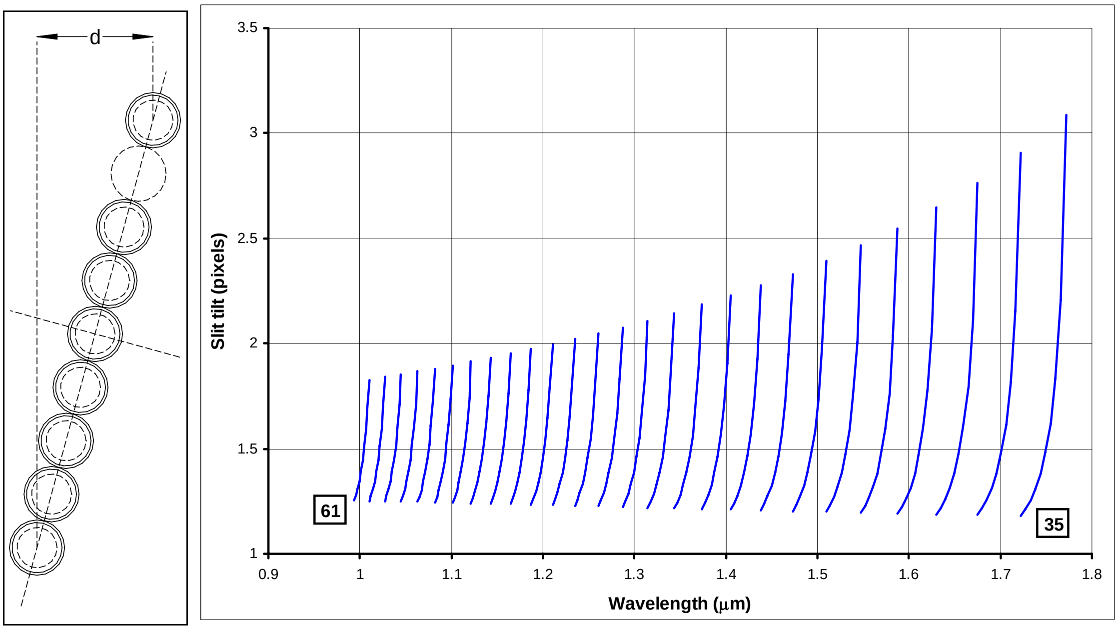

Figure 3 - Slit tilt as a function of order number and wavelength

The inter order gap varies from 14.1 pixels (between orders 60 and 61) to 93.6 pixels (between orders 35 and 36).

4.1.1 Image Quality

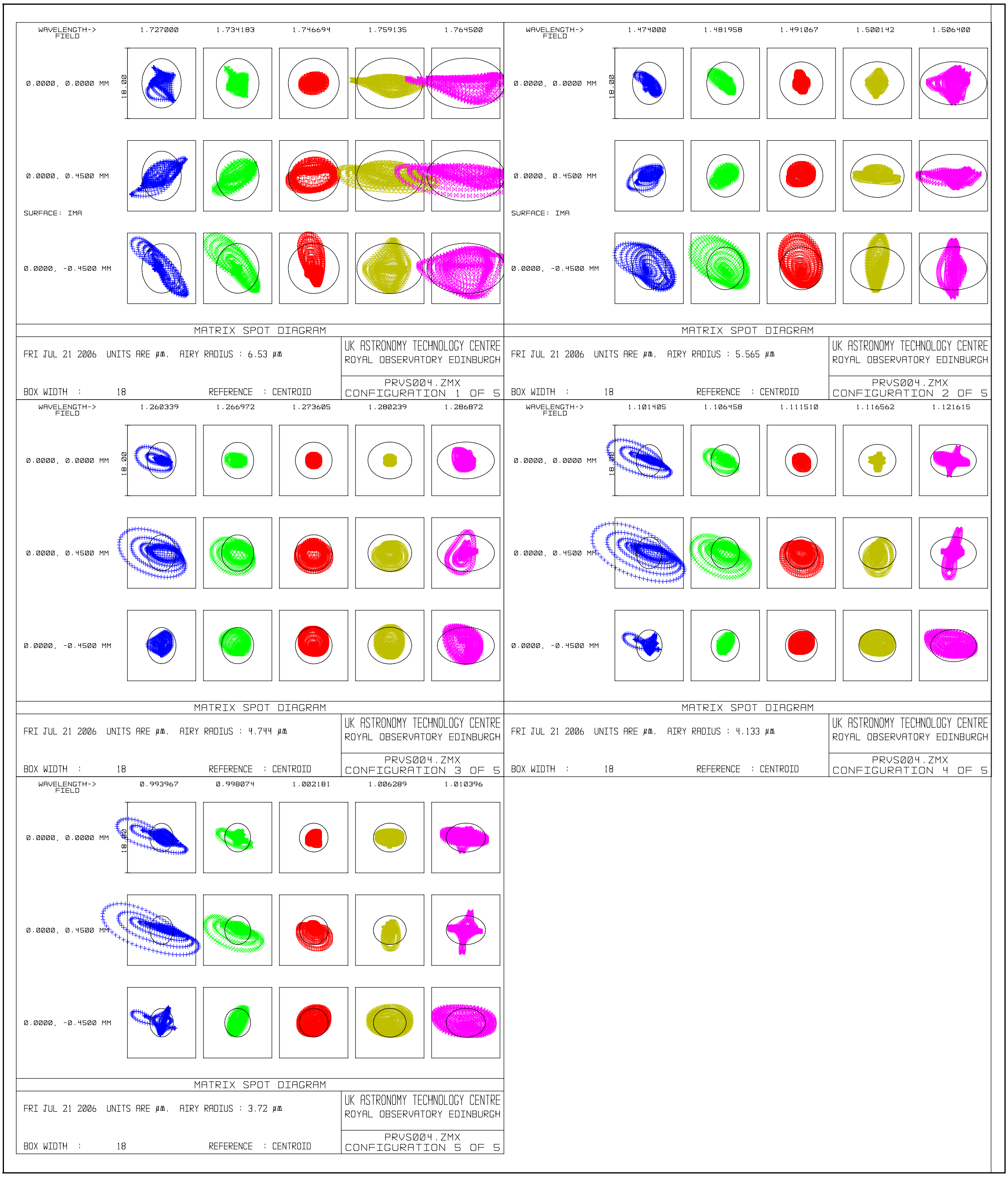

Figure 4 - Spectrograph Spot Diagrams

Figure 4 shows the spot diagram of the optical design. Each of the five large boxes shows a different spectral order. For each order, a range of wavelengths across the order is shown from left to right. The spot diagram along the slit is shown from top to bottom. Each box is 18µm square (one detector pixel). Also shown on each box is the Airy disk.

The image quality requirements for the spectrograph are:

- 50% encircled energy diameter < 0.8 pixel (14.4 μm)
- 80% encircled energy diameter < 1.6 pixels (28.8 μm)

The table below shows the nominal image quality from the optical design at different wavelengths and order numbers.

Order Number	Wavelength (μm)	RMS Spot Radius (μm)	RMS Spot Diameter (pixels)	Encircled Energy Diameter (pixels)	
				50%	80%
35	1.727000	2.6574	0.295	0.344	0.704
	1.734183	2.1299	0.237	0.338	0.638
	1.746694	1.9920	0.221	0.351	0.765
	1.759135	4.4717	0.497	0.428	1.034
	1.764500	6.5412	0.727	0.574	1.280
41	1.474000	1.8331	0.204	0.281	0.423
	1.481958	1.8414	0.205	0.283	0.416
	1.491067	1.4496	0.161	0.288	0.426
	1.500142	1.9056	0.212	0.314	0.623
	1.506400	3.1485	0.350	0.393	0.815
48	1.260339	1.7692	0.197	0.243	0.394
	1.266972	1.0098	0.112	0.240	0.352
	1.273605	0.8212	0.091	0.245	0.365
	1.280239	0.7804	0.087	0.258	0.405
	1.286872	1.8583	0.206	0.299	0.618
55	1.101405	3.2211	0.358	0.261	0.537
	1.106458	1.6714	0.186	0.220	0.450
	1.111510	0.8349	0.093	0.215	0.320
	1.116562	0.9488	0.105	0.223	0.354
	1.121615	2.3070	0.256	0.257	0.619
61	0.993967	3.2240	0.358	0.240	0.493
	0.998074	1.5056	0.167	0.195	0.348
	1.002181	1.1086	0.123	0.197	0.317
	1.006289	1.9081	0.212	0.216	0.515
	1.010396	3.2852	0.365	0.273	0.678

Table 2 - Summary of image quality

From the table it can be seen that the nominal image quality is well within the requirement.

4.1.2 Optical Component Manufacturing

The echelle grating used has a ruling density of 31.6 lines/mm and a blaze angle of 75°. This ruling is a standard ruling available from Newport-RGL, and is the same as that used in other astronomical spectrographs such as UVES and HARPS. To cover the required collimated beam diameter (140mm) needs a grating clear aperture of 610 x 200mm. This will require a 2x1 mosaic. The grating will be replicated on Zerodur substrate. UKATC has experience of using replicated gratings in cryogenic instruments (e.g. CGS4 on UKIRT) with no problems. An aluminium grating substrate is not suitable for PRVS due the much larger CTE value for aluminium as compared to Zerodur, which would increase the thermal sensitivity of the grating. The coating will be chosen to optimise performance over waveband.

The cross disperser required is a 100 lines/mm reflective grating with 4° blaze angle of approximately 200mm diameter. Such a ruling does not exist. This grating can either be replicated (which will require a new master) or directly ruled. A number of companies (e.g. Newport-RGL or Bach Research) could make such a grating. Again, this grating will be fabricated on a Zerodur substrate to minimise thermal sensitivity.

The collimator mirror has a rectangular clear aperture of 500 x 440mm size. Overall focal ratio is f/3. This mirror will likely be fabricated in Zerodur for best thermal stability. It is similar in size, focal ratio and operating temperature to the WFCAM tertiary mirror. A number of companies (e.g. SESO, SAGEM) have the capability to manufacture such a mirror. The large size of the mirror makes fabrication in aluminium unattractive due to cost, delivery and technical risk.

The lenses required all have spherical surfaces and are made from standard Schott and Ohara catalogue glasses. The largest required has a diameter of <300mm. There are a number of potential manufacturers for these lenses.

4.1.3 Opto-mechanical Alignment Philosophy

The opto-mechanical alignment philosophy for the spectrograph follows these basic principles:

- As far as possible, the system is designed so that no adjustments are necessary, and the required performance is achieved by precise optical and mechanical tolerances.
- Where adjustments are necessary, they are made using precision mechanical adjustments such as ground shims.
- All necessary alignment operations are carried out during the integration and test phase.
- There are no adjustment mechanisms (e.g. focus mechanism) which are used during normal operation.
- System alignment is carried out at the sub-assembly level – detector, camera, cross disperser, collimator mirror, spectrum mirror, echelle.
- The camera lenses are mounted in a lens barrel, and are held in alignment by mechanical tolerances, with no individual adjustment.

A full list of the one-off adjustments required will be derived in the next phase of the project, following a full opto-mechanical tolerance analysis. However, based on past experience it is likely that the spectrograph will need at least the following one-off adjustments:

- Detector focus adjustment
- Detector tilt adjustment
- Camera tilt and/or decentre adjustment
- Echelle, cross disperser and spectrum mirror tilt adjustment

4.2 FLAT FIELD ILLUMINATION SOURCE

The flat field illumination source consists of a small pinhole (~0.1mm diameter) uniformly illuminated by an LED or similar source. The source is mounted near the edge of the cross disperser and is arranged so the beam illuminates the detector array through the camera assembly.

Figure 5 shows the optical layout of the illumination source.

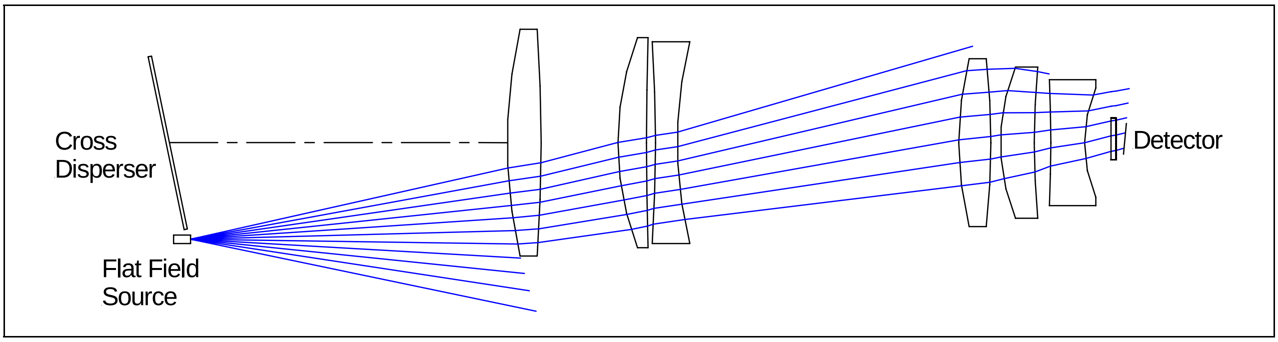

Figure 5 - Flat field illumination source optical layout

Figure 6 shows the illumination on the detector from the flat field source. The illumination over the detector surface is uniform to better than 5%.

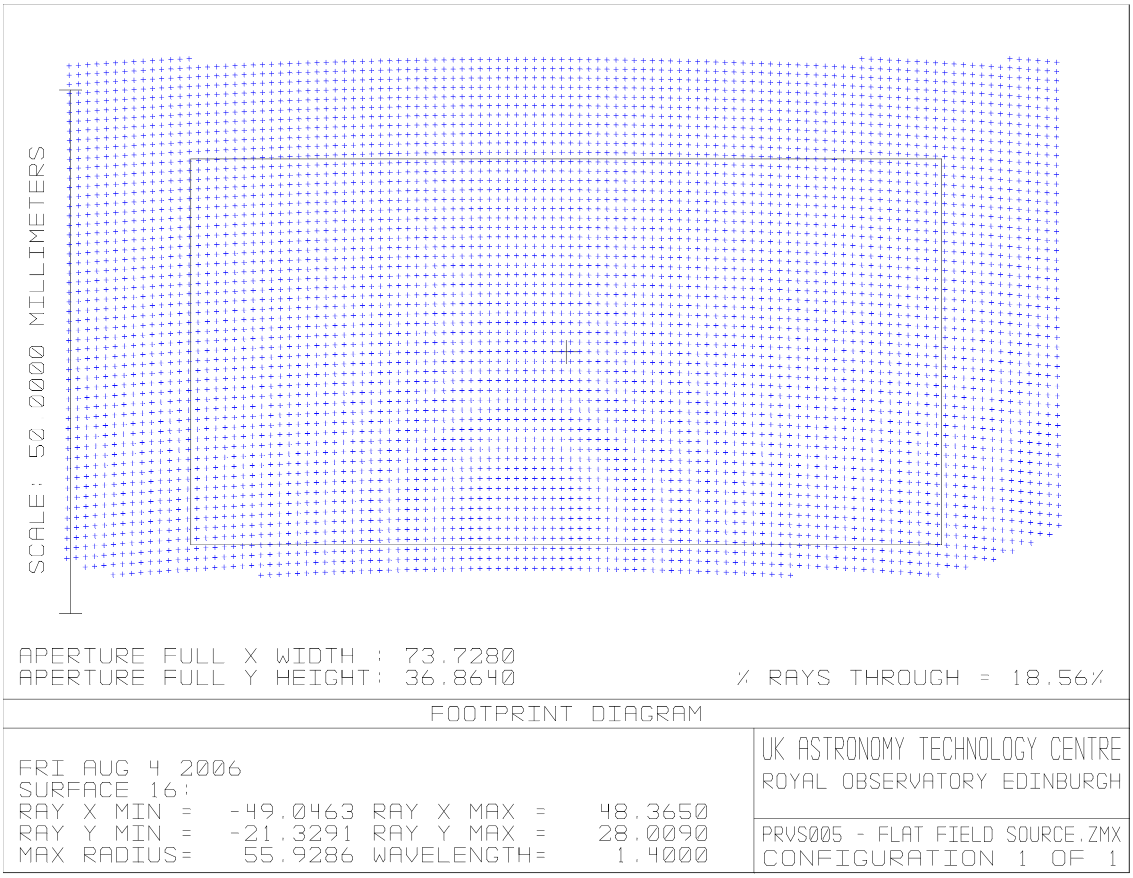

Figure 6 - Flat field source detector illumination

4.3 MECHANICAL DESIGN

Figure 7 and Figure 8 show the mechanical layout of the spectrograph.

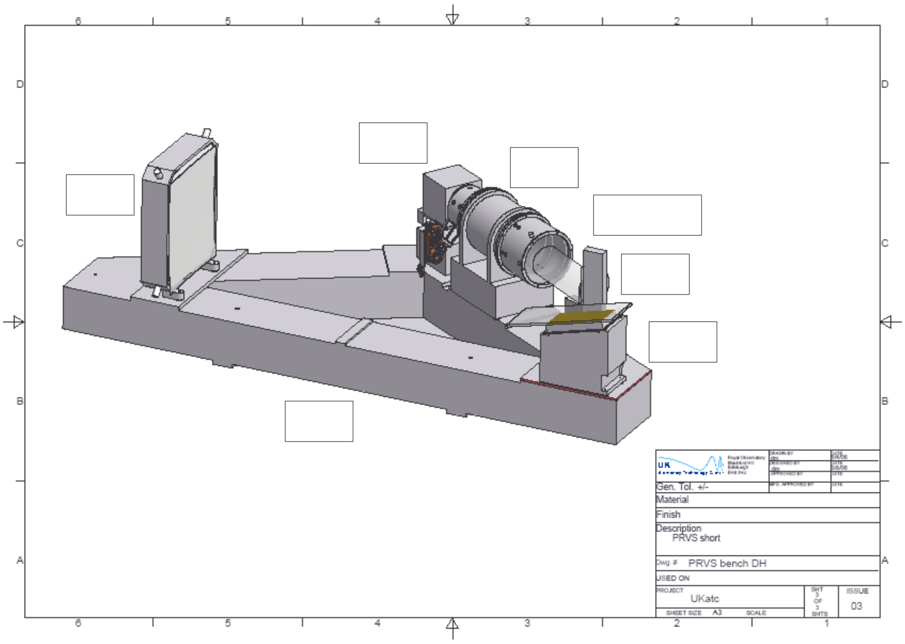

Figure 7 - Spectrograph mechanical layout

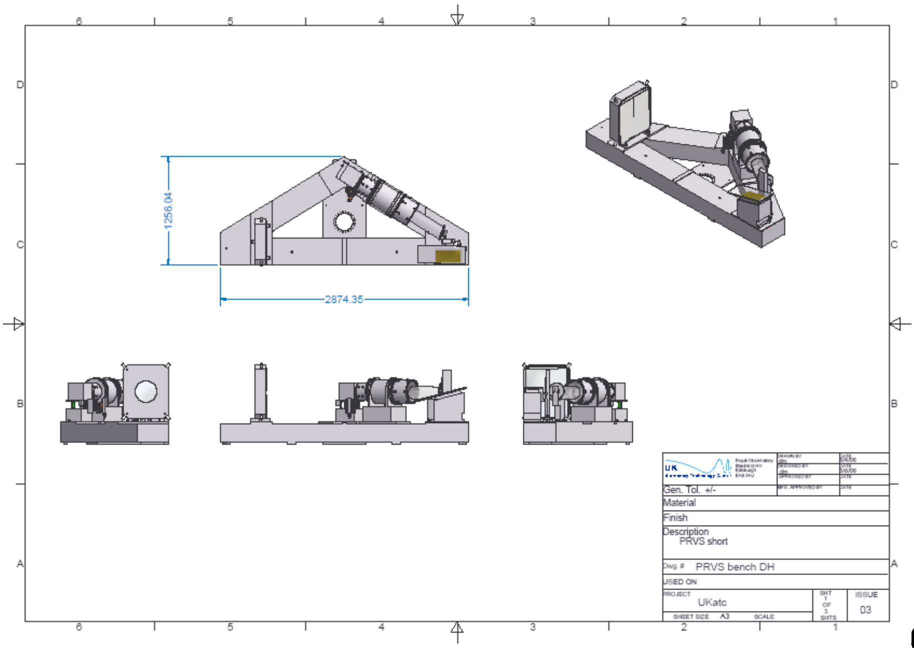

Figure 8 - Spectrograph mechanical layout

Collimator
Mirror

Further details of the mechanical design of the spectrograph can be found in the Infrastructure Design Document (PRVS-TRE-00001-0001).

4.4 DETECTOR CONTROL SYSTEM DESIGN

The focal plane and detector control sub-systems are described in detail in PRVS-TRE-00003-0002 – Detector Sub-System.

5. ANALYSIS

5.1 TOLERANCE SENSITIVITY ANALYSIS

Section 4.1.3 outlines the opto-mechanical alignment philosophy for the Spectrograph system. The philosophy is that there will be a series of one-off alignment adjustments (e.g. focus adjustment) during the integration and test phase of the project. There are no adjustments during normal operation.

For this initial sensitivity analysis it has been assumed that the only tolerance compensation is a one-off adjustment of the back focus distance of the camera. This leads to tolerances which can be used to set manufacturing limits on components, define initial alignment tolerances, etc.

To simplify the analysis, a single order (m=48) and wavelength (1.273605 um) are chosen. This is near the optical axis of the system.

5.1.1 Tolerance Sensitivity Analysis

Table 3 shows the tolerance values assumed for the tolerance analysis.

Tolerance	Value	Comment
Radius of curvature	± 0.1%	
Regular form error	± 0.2 fringes	
Irregular form error	± 0.5 fringes	
Lens wedge angle	± 10 arcsec	
Refractive index	± 0.001	
Abbe number	± 1%	
Lens thickness	± 0.2mm	
	± 0.05mm	Focal reducer
Element spacing	± 0.2mm	
	± 0.05mm	Focal reducer
Element/Group decentre	± 0.2mm	
	± 0.1mm	Individual camera lenses
	± 0.025mm	Individual focal reducer lenses
Element/Group tilt	± 0.2mrad	
	± 0.1 mrad	Camera & focal reducer lenses

Table 3 - Tolerance values (with focus compensation)

These values are then used to calculate image quality (50% encircled energy radius) sensitivity. The full results of the analysis are shown in appendix B.

The estimated cumulative effect of these tolerances is shown in Table 4. The estimated image quality is below the requirement of 0.8 pixels (14.4μm).

Effects of tolerances on 50% Encircled Energy Diameter (μm)	
Nominal Image Quality	4.42
Estimated change	1.70
Estimated Image Quality	6.12

Table 4 - Effect of tolerances on image quality

Table 5 shows the ten worst offenders – the tolerances which give the largest change in image quality. It can be seen from this table that the decentre, thickness and separation of the F-converter lenses are the most sensitive tolerances.

Tolerance Type	Element	Tolerance	Change in 50% EED (μm)
Decentre	F-Converter Lens 2	-0.025	0.776
Thickness	F-Converter Lens 1	0.05	0.769
Separation	F-Converter Lens 1-2	-0.05	0.765
Decentre	F-Converter Lens 1	0.025	0.749
Decentre	F-Converter Lens 1	-0.025	0.698
Refractive Index	F-Converter Lens 2	0.001	0.697
Decentre	F-Converter Lens 2	0.025	0.683
Refractive Index	F-Converter Lens 2	-0.001	0.605
Decentre	Camera	-0.2	0.493
Radius	Collimator Mirror	4	0.418

Table 5 - Tolerance analysis worst offenders

Since the focal reducer lenses are small and mounted close together the tight tolerances will be achievable by precision mounting.

5.1.2 Detector focus and tilt tolerance

The plots below show the sensitivity of the spectrograph image quality (50% EED) to detector defocus. The plot on the left shows 50% EED as a function of detector defocus, the one on the right shows the fractional change in 50% EED as a function of defocus. Assuming that a change in image quality of ~10% is acceptable, the tolerance on defocus is approximately **±20μm**.

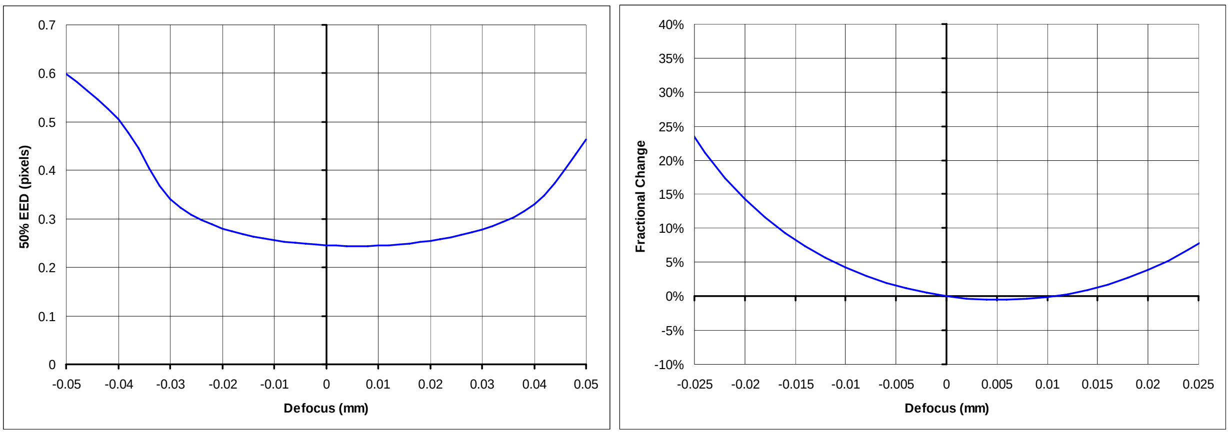

Figure 9 - Defocus sensitivity and fractional change

An estimated detector tilt tolerance can be calculated by considering this focus tolerance over the maximum linear dimension of the detector. The detector array is a 2x1 mosaic of dimension 36.864 x 73.728 mm. The diagonal is therefore 82.4mm. This gives a detector tilt tolerance of approximately **0.5 mrad**.

5.2 TRANSMISSION

To perform the transmission analysis, the ZEMAX transmission calculation is used to calculate reflectivity losses and material absorption effects in the spectrograph. Typical grating efficiency curves for the echelle and the cross disperser are then factored in to arrive at an overall transmission estimate.

The analysis calculates the transmission from the spectrograph slit plane to the focal plane. The following effects are included:

- Reflection losses at air/glass interfaces. This is assumed to be 1.5% per surface, independent of wavelength.
- Mirror reflectivity, assumed to be 99%, independent of wavelength.

- Bulk absorption in glass (wavelength dependant)
- Echelle and reflective cross disperser efficiency (wavelength dependant)
- A transmission of 80% (independent of wavelength) for the order sorting filter is assumed

The analysis does not include any detector QE effects.

The echelle grating is a Newport RGL grating with 31.6 lines/mm and 76° nominal blaze angle. The average of the efficiency for the two polarisations is used. Figure 10 shows the measured efficiency of this grating from the Newport-RGL catalogue.

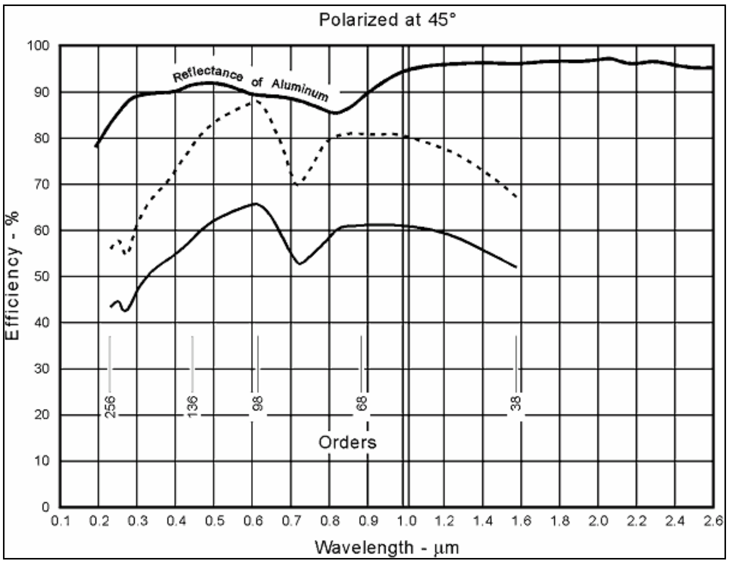

Figure 10 – Efficiency of Newport RGL 31.6 line/mm, 76° blaze angle echelle, showing S (dash) and P (full line) polarisation efficiency

The grating cross disperser is a 1st order reflective grating, 100 lines/mm, blaze angle 4° which gives a peak of the blaze function at ~1.3um. To estimate the efficiency, a theoretical blaze function[1] was scaled by the peak efficiency (85%) of a similar Newport-RGL reflective grating (100 lines/mm, 4.6° blaze angle). Figure 11 shows the model blaze function together with the measured efficiency of the 4.6° blaze angle grating.

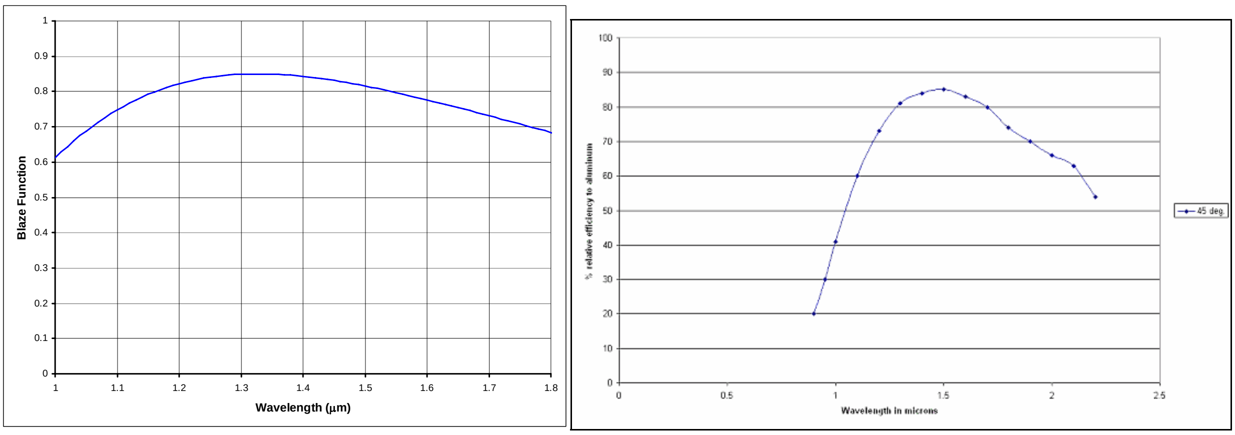

Figure 11 – Theoretical efficiency of 100 line/mm, 4° blaze angle grating and measured efficiency of Newport-RGL 100 line/mm, 4.6° blaze angle grating.

[1] "Astronomical Optics", D. J. Schroeder, page 244

Figure 12 shows the optical transmission of the spectrograph. The transmission is shown at the blaze wavelength of each order.

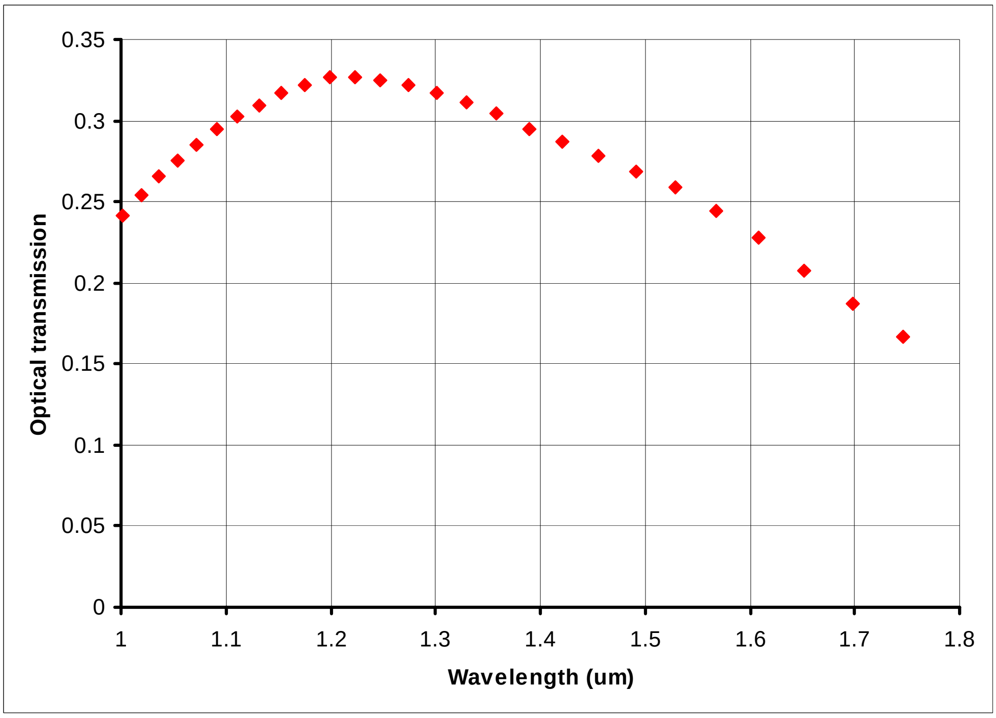

Figure 12 - Spectrograph optical transmission

5.3 SCATTERED LIGHT

To analyse stray light caused by ghost reflections from optical surfaces a non-sequential raytrace model has been constructed. This has been used to estimate the level of stray light caused by ghosting for different anti-reflection (AR) coating efficiencies on the refractive lens elements (i.e. the focal reducer and camera lenses).

The model assumes an idealised AR coating of reflectivity **R** and transmission **T=1-R**. Coating absorption, wavelength dependence and angle of incidence dependence effects are ignored. Mirror and grating reflectivity is assumed to be 100%. Reflectivity from the detector surface is assumed to be 7.4%.

Figure 13 shows an example of the distribution of light over the detector array caused by ghost imaging. The input is a point at a wavelength of 1.00218125μm - the blaze wavelength of order 61, which is the lowest wavelength order on the array. Note the logarithmic scale on the distribution plot.

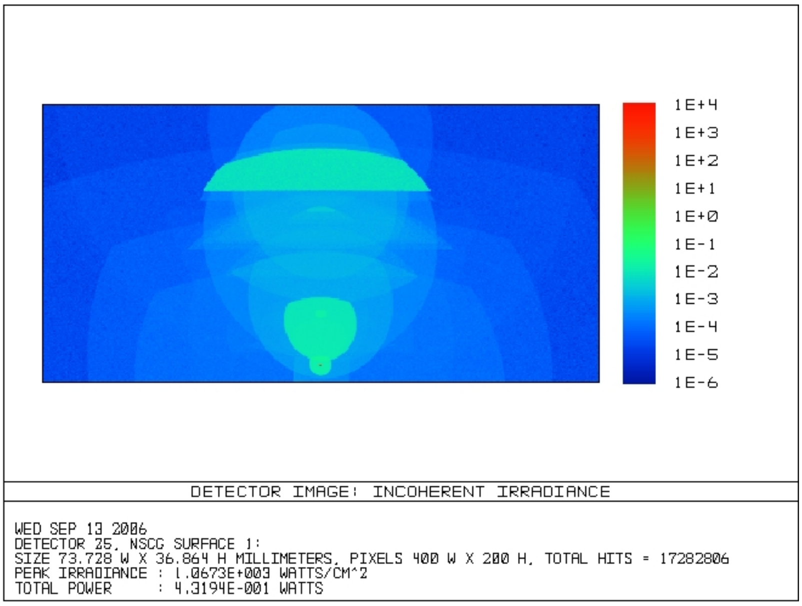

Figure 13- Example of distribution of ghost images over detector array

Figure 14 shows the variation of stray light with AR coating efficiency for a vertical slice across the detector array (i.e. across the diffraction orders). The plot shows that even with an AR coating of 2% efficiency the amount of scattered light is less than 10^{-5}. Typical AR coating efficiencies for this waveband are likely to be 1.0 – 1.5%.

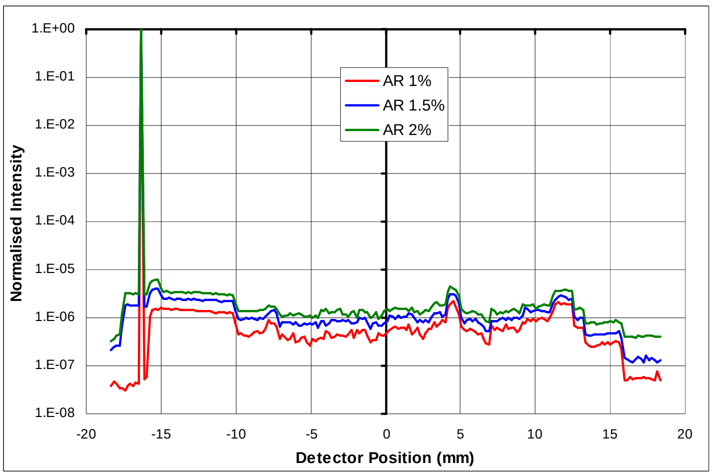

Figure 14 - Variation of stray light with AR coating efficiency across full detector array

Due to the large blaze angle of the echelle, light in the zero order will be reflected away from the main beam. This will be directed towards an absorbing beam dump.

The small blaze angle of the cross dispersing grating combined with the relative closeness of the camera to the cross dispersing grating means that light in the zero order reflected from the grating will get into the camera. However, none of this light is imaged directly onto the detector array, but instead comes to a focus ~40mm away from the detector (see Figure 15). A beam dump will be placed here to trap this light. Light can reach the detector through multiple reflections from the camera lenses. This was analysed in the non-sequential raytrace model and is estimated to be $5x10^{-6}$.

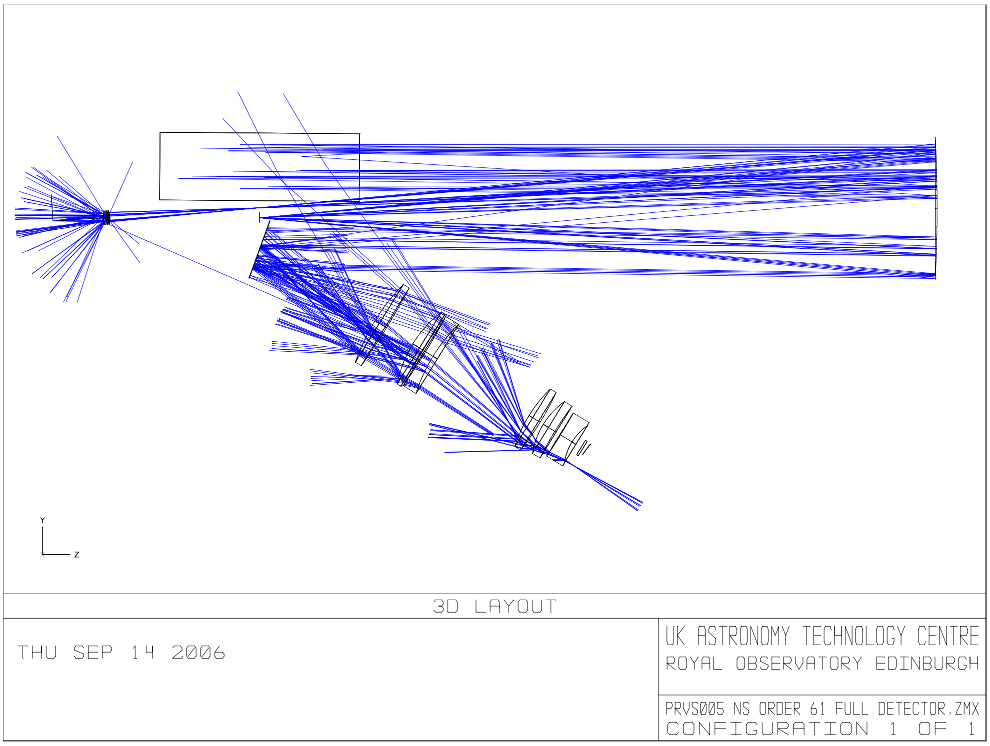

Figure 15 - Zero order reflection from cross disperser

5.4 THERMAL ANALYSIS

There are two major thermal effects on the optical performance of PRVS. Firstly, temperature changes of the echelle grating cause changes in the groove spacing, which causes the wavelength separation on the detector to vary. Secondly, thermal expansion and contraction of the structure and optical elements, and changes in the refractive index of the transmissive lenses cause changes in both the position and shape of the optical PSF.

5.4.1 Echelle grating thermal stability

Changes in the temperature of the echelle grating will, to first order, change the groove separation, which will change the angle of the light diffracted from the grating and move the position of the image on the detector.

The echelle used has a groove density of 31.6 lines/mm, which is equivalent to a line spacing of **σ = 31.645 μm**. The Zemax model was used to calculate the change in position on the detector as a function of change in grating groove spacing. This is shown in Figure 16 (wavelength = 1.2736μm, order = 48).

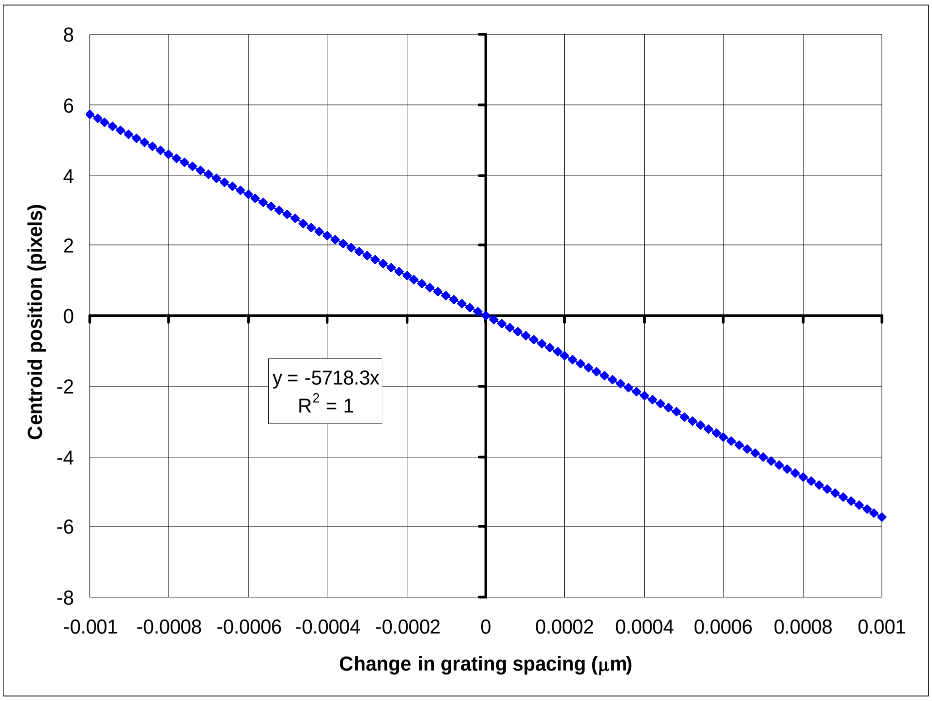

Figure 16 - Variation of centroid position with change in groove spacing (m=48, λ=1.2736μm)

From this plot, for a shift of 0.1 pixels the change in grating spacing is **$\Delta\sigma$ = 0.0000175μm**. If the grating substrate is Zerodur, then the thermal expansion coefficient is **α = 7x10^{-8}** at 200K. The change in temperature to give a shift of 0.1 pixels is then

$$\Delta T = \frac{1}{\alpha} \cdot \frac{\Delta\sigma}{\sigma} = \mathbf{7.9K}$$

This value is much larger than the proposed temperature stability requirement. Therefore temperature variations of the grating will have little effect on the overall stability.

5.4.2 Optical system thermal stability

5.4.2.1 Details of Model

To calculate the effects of temperature changes on the image quality and centroid position a Zemax thermal model was constructed. This includes the following effects:

- Changes in position (linear displacement and tilt) of the optical components caused by thermal expansion of the optical bench
- Changes in refractive index of the transmissive lens materials with temperature
- Change in radius of curvature and thickness of mirrors and lenses caused by CTE of the optical materials

The collimator mirror, spectrum mirror and gratings are all made of Zerodur. The CTE of Zerodur at 200K is approximately $7x10^{-8}$.

The camera has six lens elements, made from a mixture of Schott and Ohara glasses. Manufacturers data from Schott gives the refractive index as a function of temperature and wavelength over a range -40°/+80° C and 0.435 – 0.644 um. This can be extrapolated to 1.06um with a loss of accuracy. Therefore there is no accurate Schott glass refractive index data at the temperature and wavelength ranges of PRVS operation. Data for Ohara glasses is even sparser. Similarly, Schott give room temperature values for the CTE of each glass. A brief literature search has yielded no better data.

To estimate the effects of temperature changes on the optical system, it is therefore necessary to estimate the refractive index and thermal expansion coefficients at the operational temperatures and wavelengths. This is done by extrapolation from the available room temperature data.

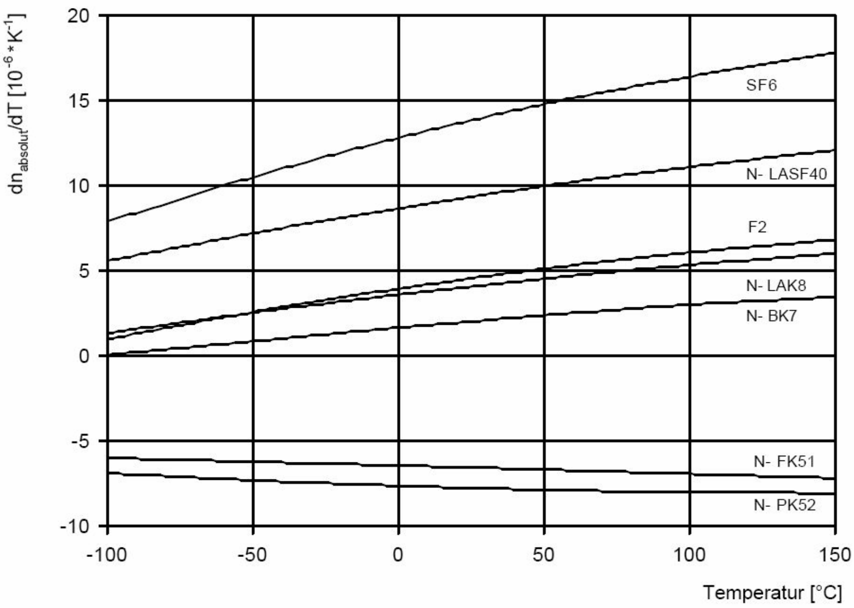

Figure 17 - Change in dn/dt with temperature for several Schott glasses

Figure 17 shows the change of dn/dT with temperature for several Schott glasses. Over the temperature range shows, the absolute value of dn/dt for all of the glasses decreases with temperature. For this analysis, it is assumed that the value of dn/dt at room temperature scales linearly with absolute temperature.

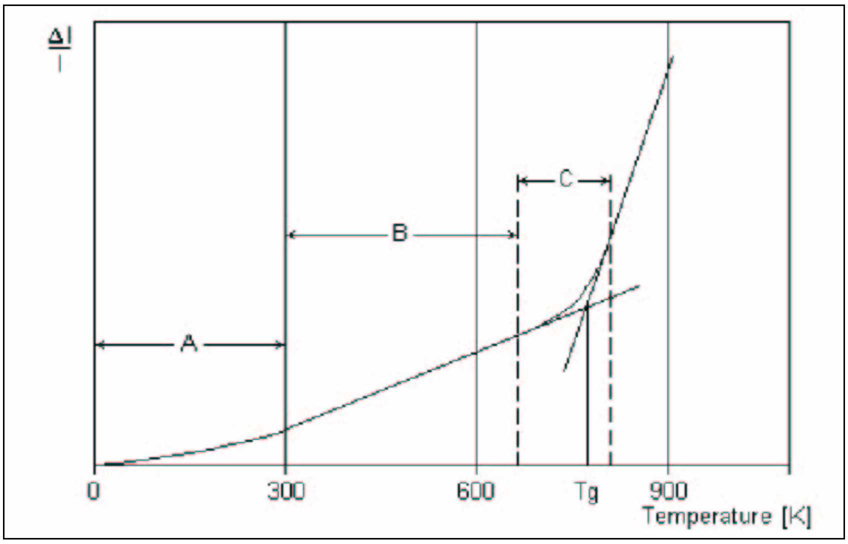

Figure 18 - Change in CTE for typical glass

Figure 18 shows the change in CTE with temperature for a typical glass. Again, for this analysis, it is assumed that the room temperature CTE value scales linearly with absolute temperature.

Using these assumptions, room temperature data for each of the camera glasses was extrapolated to 200K – see table below.

Glass	Supplier	TCE ($x10^{-6}$)		Refractive Index				
				293K			200K	
		293K	200K	n (1.13um)	Dn/DT ($x10^{-6}$)	D_0 ($x10^{-6}$)	Dn/DT ($x10^{-6}$)	D_0 ($x10^{-6}$)
S-BSM9	Ohara	6.4	4.37	1.60007	2.8	4.491	1.91	3.92
S-NPH1	Ohara	8.3	5.67	1.77084	-1.9	-2.275	-1.30	-2.15
S-LAL58	Ohara	7.5	5.12	1.67689	2.0	1.75	1.37	2.53
S-NBH5	Ohara	6.6	4.51	1.63448	3.5	6.455	2.39	4.67
N-F2	Schott	7.84	5.35					
N-PSK57	Schott	13.2	9.01					
SF6	Schott	8.1	5.53					
N-BK7	Schott	7.1	4.85					

Table 6 - Assumed 200K data for camera glasses

The validity of these initial results should be treated carefully given the extrapolations involved in the glass refractive index and TCE data. A fuller analysis, based on better data, will be carried out in the next phase of the work. Better data will initially be sought via a more thorough literature search or, failing that, from measurements of glass samples.

Data for the temperature and positional changes of the optical components is taken from the thermal analysis (see PRVS-TRE-00001-0001, PRVS Infrastructure, Section 5.9.2). This gives the changes in position (linear displacement and tilt) of the optical components for a 10K change in ambient temperature.

Changes in the temperature of the optical components were estimated from the plot in section 5.5 of PRVS-TRE-00001-0001.

Estimated temperature changes on optical bench for a 10K change in ambient temperature	
Slit, focal reducer, echelle, spectrum mirror, cross disperser	0.1K
Collimator	0.1K
Camera	0.075K
Detector	0.06K

Table 7 - Changes in optical component temperature for a 10K change in ambient temperature

The model therefore allows calculation of the changes in optical properties for a 10K change in ambient temperature, which gives a 0.1K change in temperature of the optical bench.

5.4.2.2 Optical Analysis

The model was used to calculate the effect of temperature changes on PSF centroid position, PSF image quality and skewness of the Spectral Response Function.

Figure 19 shows the spectral response function (SRF). This is the image of one of the exit fibres of the fibre slicer on the detector, and is the convolution of the geometric image of the fibre (0.08mm effective diameter) with the point spread function. The main spectral dispersion direction is from left to right.

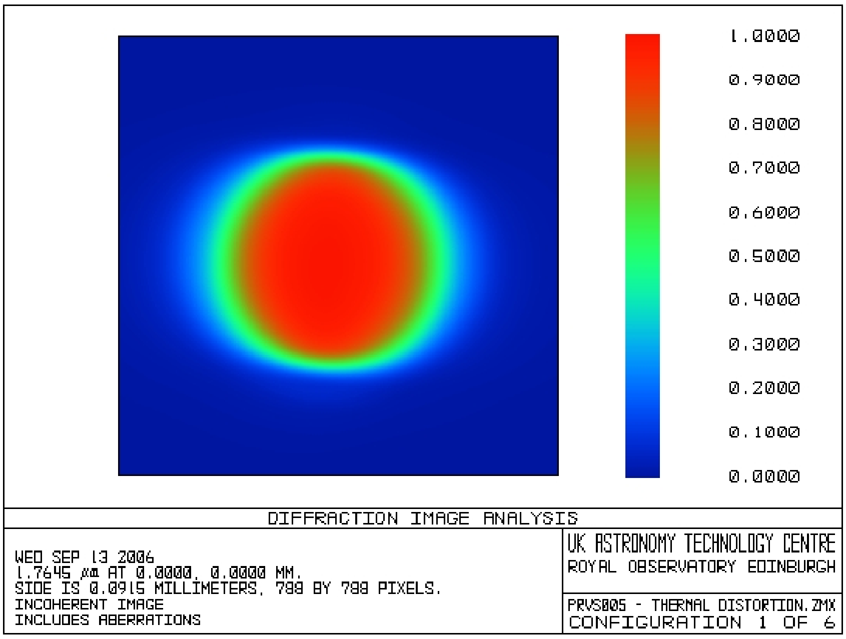

Figure 19 - Example of Spectral Response Function

To calculate the change in skewness of the SRF, the profile across the centre of the SRF in the spectral direction (at the nominal temperature) is extracted and the dimensionless third moment (μ_3) is calculated (see Science Case Document). The procedure is then repeated for the SRF with the 10K ambient temperature change and the difference between the two values calculated.

Table 8 shows the change in PSF centroid position and SRF skewness for a 10K change in ambient temperature, at different wavelength positions on the detector array...

Order	Wavelength (μm)	Centroid Position (mm)				Change in centroid position (pixels)		Change in third moment (x10^{-3})
		Nominal		+10K				
		X	Y	X	Y	Spectral	Spatial	
35	1.727000	-32.3730	20.2420	-32.3741	20.2424	-0.0610	0.0222	-1.411
	1.734183	-21.4367	20.5762	-21.4378	20.5766	-0.0629	0.0219	-0.479
	1.746694	0.0549	21.1689	0.0537	21.1693	-0.0672	0.0217	-0.054
	1.759135	26.3269	21.7775	26.3256	21.7779	-0.0747	0.0216	0.239
	1.764500	40.3711	22.0518	40.3696	22.0522	-0.0808	0.0217	0.432
48	1.260339	-30.0549	-0.6272	-30.0560	-0.6268	-0.0609	0.0219	-1.586
	1.266972	-15.8936	-0.3203	-15.8948	-0.3199	-0.0634	0.0217	0.538
	1.273605	-0.0106	-0.0014	-0.0118	-0.0010	-0.0667	0.0216	0.168
	1.280239	18.4036	0.3349	18.4023	0.3352	-0.0716	0.0215	0.174
	1.286872	41.1688	0.7010	41.1674	0.7014	-0.0809	0.0216	0.180
61	0.993967	-24.1098	-12.5278	-24.1109	-12.5274	-0.0616	0.0217	-0.693
	0.998074	-12.6276	-12.3360	-12.6287	-12.3356	-0.0637	0.0216	1.839
	1.002181	-0.0106	-12.1349	-0.0118	-12.1345	-0.0664	0.0214	-0.257
	1.006289	14.1518	-11.9211	14.1506	-11.9207	-0.0701	0.0214	-0.052
	1.010396	30.6168	-11.6885	30.6154	-11.6881	-0.0758	0.0214	-1.599

Table 8 - Summary of PSF centroid and SRF third moment variation

From the table it can be seen that the change in centroid position in the spectral direction is less than 0.1 pixels over the detector. The largest change in skewness is 1.839x10^{-3}, which is larger than the requirement of 1x10^{-3}. This suggests that the required temperature stability on the optical bench is closer to ±0.05K than ±0.1K.

Table 9 shows the change in 50% EED and 80% EED for a 10K change in ambient temperature.

Order	Wavelength (μm)	Encircled Energy Radius (μm)				Change in EED (pixels)		Fractional Change in EED (pixels)	
		Nominal		+10K					
		0.5	0.8	0.5	0.8	50%	80%	50%	80%
35	1.727000	3.0692	6.4206	3.0886	6.4658	0.0022	0.0050	1.27%	1.41%
	1.734183	2.9066	6.3400	2.9267	6.3946	0.0022	0.0061	1.38%	1.72%
	1.746694	3.1144	7.2680	3.1508	7.3422	0.0040	0.0082	2.34%	2.04%
	1.759135	4.2473	9.6741	4.3919	9.7920	0.0161	0.0131	6.81%	2.44%
	1.764500	6.1497	12.1107	6.2730	12.2986	0.0137	0.0209	4.01%	3.10%
48	1.260339	2.6571	5.5174	2.7391	5.6373	0.0091	0.0133	6.17%	4.35%
	1.266972	2.2570	5.0384	2.3004	5.1197	0.0048	0.0090	3.85%	3.23%
	1.273605	2.1717	5.1096	2.2031	5.2042	0.0035	0.0105	2.90%	3.70%
	1.280239	2.1907	4.3479	2.2095	4.6881	0.0021	0.0378	1.72%	15.65%
	1.286872	2.3229	4.6970	2.3250	4.7039	0.0002	0.0008	0.19%	0.30%
61	0.993967	3.4434	7.1549	3.5422	7.2983	0.0110	0.0159	5.74%	4.01%
	0.998074	1.9279	4.2283	1.9761	4.3446	0.0054	0.0129	5.00%	5.50%
	1.002181	1.6071	2.6897	1.6203	3.3170	0.0015	0.0697	1.64%	46.65%
	1.006289	1.6725	3.3971	1.6712	3.3396	-0.0001	-0.0064	-0.15%	-3.39%
	1.010396	2.1636	5.3011	2.1251	5.2187	-0.0043	-0.0092	-3.56%	-3.11%

Table 9 - Summary of PSF 50% and 80% encircled energy diameter variation

There is no requirement on change in image quality with temperature variation, only that the overall image quality meets the requirements under all operating conditions. Although some of the fractional changes in EED are large, the absolute values are still within the overall requirements.

A large change in EED does not necessarily imply a large change in the overall shape of the PSF. If the 50% or 80% EED diameter happens to coincide with a null of the PSF, then this is at a flat part of the encircled energy curve. A relatively small change in PSF shape can therefore lead to a large change in EED diameter.

Appendix A – Optical Design Prescription

```
System/Prescription Data

File : M:\Projects\PRVS\Zemax\PRVS004a.zmx
Title:
Date : WED JUL 19 2006
Configuration 3 of 5

GENERAL LENS DATA:

Surfaces                :                38
Stop                    :                 1
System Aperture         : Object Space NA = 0.0909091
Glass Catalogs          : OHARA_CURRENT SCHOTT_PRVS HOYA_CURRENT
Ray Aiming              : Off
Apodization             : Uniform, factor =   0.00000E+000
Temperature (C)         :    2.00000E+001
Pressure (ATM)          :    1.00000E+000
Adjust Index Data To Environment  : Off
Effective Focal Length  :        27.13681 (in air at system temperature and pressure)
Effective Focal Length  :        27.13681 (in image space)
Back Focal Length       :       -5.321811
Total Track             :        2461.759
Image Space F/#         :       0.9908961
Paraxial Working F/#    :        3.098858
Working F/#             :        3.053377
Image Space NA          :       0.1592896
Object Space NA         :             0.1
Stop Radius             :        13.69306
Paraxial Image Height   :       0.2545971
Paraxial Magnification  :      -0.5657714
Entrance Pupil Diameter :        27.38613
Entrance Pupil Position :               0
Exit Pupil Diameter     :        7.283448
Exit Pupil Position     :       -22.53895
Field Type              : Object height in Millimeters
Maximum Radial Field    :            0.45
Primary Wavelength      :        1.273605 µm
Lens Units              :   Millimeters
Angular Magnification   :         3.76005
```

Fields : 3
Field Type: Object height in Millimeters

#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.000000	0.450000	1.000000
3	0.000000	-0.450000	1.000000

Vignetting Factors

#	VDX	VDY	VCX	VCY	VAN
1	0.000000	0.000000	0.000000	0.000000	0.000000
2	0.000000	0.000000	0.000000	0.000000	0.000000
3	0.000000	0.000000	0.000000	0.000000	0.000000

Wavelengths : 5
Units: µm

#	Value	Weight
1	1.260339	1.000000
2	1.266972	1.000000
3	1.273605	1.000000
4	1.280239	1.000000
5	1.286872	1.000000

SURFACE DATA SUMMARY:

Surf	Type	Comment	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD	Slit	Infinity	150		0.9	0
STO	STANDARD	Focal Reducer	957.8687	7	N-F2	34	0
2	STANDARD		46.59342	3.837648		34	0
3	STANDARD		56.13369	8	N-PSK57	34	0
4	STANDARD		-63.5513	442.921		34	0
5	COORDBRK	OAP axis tilt	-	2000		-	-
6	STANDARD	Paraboloid	-4000	0	MIRROR	397.1701	-1
7	COORDBRK	Chief Ray	-	-2000		-	-
8	COORDBRK	Rot Z 90	-	0		-	-
9	COORDBRK	Blaze angle	-	0		-	-
10	COORDBRK	Out of plane angle	-	0		-	-
11	DGRATING	Echelle	Infinity	0	MIRROR	541.4426	0
12	COORDBRK	- Out of plane angle	-	0		-	-
13	COORDBRK	- Blaze angle	-	0		-	-
14	COORDBRK	- Rot Z 90	-	0		-	-
15	COORDBRK	- Chief Ray	-	2000		-	-
16	STANDARD	Paraboloid	-4000	-2000	MIRROR	535.3732	-1

17	STANDARD	Spectrum Mirror	Infinity	2000	MIRROR	383.7366	0
18	STANDARD	Paraboloid	-4000	-2000	MIRROR	602.1051	-1
19	COORDBRK	Chief Ray	-	0		-	-
20	COORDBRK	XD rotation	-	0		-	-
21	DGRATING	Cross disperser	Infinity	0	MIRROR	178.5105	0
22	COORDBRK	Chief Ray	-	400		-	-
23	STANDARD	Camera	609.1966	40	S-BSM9	256	0
24	STANDARD		-1999.713	90.97852		256	0
25	STANDARD		350.698	33.80086	S-BSM9	240	0
26	STANDARD		4502.228	10.61341		240	0
27	STANDARD		-1862.93	25.82406	S-NPH1	230	0
28	STANDARD		493.8556	333.1251		220	0
29	STANDARD		411.3668	38.11958	S-LAL58	190	0
30	STANDARD		-890.4527	11.29329		190	0
31	STANDARD		235.935	39.99853	SF6	170	0
32	STANDARD		995.7999	19.58816		156	0
33	STANDARD		-1655.441	40	S-NBH5	140	0
34	STANDARD		166.7489	31.28561		116	0
35	STANDARD		Infinity	6	N-BK7	87.00041	0
36	STANDARD		Infinity	10		85.69961	0
37	COORDBRK	Detector Tilt	-	0		-	-
IMA	STANDARD		Infinity			82.39772	0

```
SURFACE DATA DETAIL:

Surface OBJ     : STANDARD Slit
Surface STO     : STANDARD Focal Reducer
 Aperture       : Floating Aperture
 Maximum Radius :           17
Surface   2     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :           17
Surface   3     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :           17
Surface   4     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :           17
Surface   5     : COORDBRK OAP axis tilt
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :             3.5
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface   6     : STANDARD Paraboloid
 Mirror Substrate : None
 Aperture       : Rectangular Aperture
 X Half Width   :          250
 Y Half Width   :          223
 X- Decenter    :               0
 Y- Decenter    :             -13
Surface   7     : COORDBRK Chief Ray
 Decenter X     :               0
 Decenter Y     :       122.21105
 Tilt About X   :               0
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface   8     : COORDBRK Rot Z 90
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :               0
 Tilt About Y   :               0
 Tilt About Z   :              90
 Order          : Decenter then tilt
Surface   9     : COORDBRK Blaze angle
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :              75
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface  10     : COORDBRK Out of plane angle
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :               0
 Tilt About Y   :               0
 Tilt About Z   :             0.4
 Order          : Decenter then tilt
Surface  11     : DGRATING Echelle
 Mirror Substrate : Curved, Thickness = 1.08289E+001
 Lines / µm     :          0.0316
 Diffract Order :              48
 Aperture       : Rectangular Aperture
```

```
 X Half Width   :           81
 Y Half Width   :          276
Surface  12     : COORDBRK - Out of plane angle
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :               0
 Tilt About Y   :               0
 Tilt About Z   :            -0.4
 Order          : Decenter then tilt
Surface  13     : COORDBRK - Blaze angle
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :             -75
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface  14     : COORDBRK - Rot Z 90
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :               0
 Tilt About Y   :               0
 Tilt About Z   :             -90
 Order          : Decenter then tilt
Surface  15     : COORDBRK - Chief Ray
 Decenter X     :               0
 Decenter Y     :      -122.21105
 Tilt About X   :               0
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface  16     : STANDARD Paraboloid
 Mirror Substrate : None
 Aperture       : Rectangular Aperture, Pickup From Surface 6
 X Half Width   :          250
 Y Half Width   :          223
 X- Decenter    :               0
 Y- Decenter    :             -13
Surface  17     : STANDARD Spectrum Mirror
 Mirror Substrate : Curved, Thickness = 7.67473E+000
 Aperture       : Rectangular Aperture
 X Half Width   :          193
 Y Half Width   :           15
 X- Decenter    :               0
 Y- Decenter    :             -27
Surface  18     : STANDARD Paraboloid
 Mirror Substrate : None
 Aperture       : Rectangular Aperture, Pickup From Surface 6
 X Half Width   :          250
 Y Half Width   :          223
 X- Decenter    :               0
 Y- Decenter    :             -13
Surface  19     : COORDBRK Chief Ray
 Decenter X     :               0
 Decenter Y     :      -122.21105
 Tilt About X   :               0
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface  20     : COORDBRK XD rotation
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :              20
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface  21     : DGRATING Cross disperser
 Mirror Substrate : Curved, Thickness = 3.57021E+000
 Lines / µm     :             0.1
 Diffract Order :               1
 Aperture       : Circular Aperture
 Minimum Radius :            0
 Maximum Radius :           93
Surface  22     : COORDBRK Chief Ray
 Decenter X     :               0
 Decenter Y     :               0
 Tilt About X   :       11.651767
 Tilt About Y   :               0
 Tilt About Z   :               0
 Order          : Decenter then tilt
Surface  23     : STANDARD Camera
 Aperture       : Floating Aperture
 Maximum Radius :          128
Surface  24     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :          128
```

```
Surface  25     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :           120
Surface  26     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :           120
Surface  27     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :           115
Surface  28     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :           110
Surface  29     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :            95
Surface  30     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :            95
Surface  31     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :            85
Surface  32     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :            78
Surface  33     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :            70
Surface  34     : STANDARD
 Aperture       : Floating Aperture
 Maximum Radius :            58
Surface  35     : STANDARD
 Aperture       : Rectangular Aperture
 X Half Width   :            50
 Y Half Width   :            25
 X- Decenter    :                4
 Y- Decenter    :              4.5
Surface  36     : STANDARD
 Aperture       : Rectangular Aperture, Pickup From Surface 35
 X Half Width   :            50
 Y Half Width   :            25
 X- Decenter    :                4
 Y- Decenter    :              4.5
Surface  37     : COORDBRK Detector Tilt
 Decenter X     :                0
 Decenter Y     :                0
 Tilt About X   :        5.0602631
 Tilt About Y   :                0
 Tilt About Z   :                0
 Order          : Decenter then tilt
Surface IMA     : STANDARD
 Aperture       : Rectangular Aperture
 X Half Width   :        36.864
 Y Half Width   :        18.432
 X- Decenter    :                4
 Y- Decenter    :              4.5

COATING DEFINITIONS:


MULTI-CONFIGURATION DATA:

Configuration   1:

  1 Wavelength  1 :         1.727
  2 Wavelength  2 :      1.734183
  3 Wavelength  3 :      1.746694
  4 Wavelength  4 :      1.759135
  5 Wavelength  5 :        1.7645
  6 Param 2    11 :            35

Configuration   2:

  1 Wavelength  1 :         1.474
  2 Wavelength  2 :      1.481958
  3 Wavelength  3 :      1.491067
  4 Wavelength  4 :      1.500142
  5 Wavelength  5 :        1.5064
  6 Param 2    11 :            41

Configuration   3:

  1 Wavelength  1 :      1.260339
  2 Wavelength  2 :      1.266972
  3 Wavelength  3 :      1.273605
  4 Wavelength  4 :      1.280239
```

5 Wavelength 5 : 1.286872
6 Param 2 11 : 48

Configuration 4:

1 Wavelength 1 : 1.101405
2 Wavelength 2 : 1.106458
3 Wavelength 3 : 1.11151
4 Wavelength 4 : 1.116562
5 Wavelength 5 : 1.121615
6 Param 2 11 : 55

Configuration 5:

1 Wavelength 1 : 0.9939666
2 Wavelength 2 : 0.9980739
3 Wavelength 3 : 1.002181
4 Wavelength 4 : 1.006289
5 Wavelength 5 : 1.010396
6 Param 2 11 : 61

INDEX OF REFRACTION DATA:

System Temperature: 20.0000 Celsius
System Pressure : 1.0000 Atmospheres
Absolute air index: 1.000269 at wavelength 1.273605 µm
Index data is relative to air at the system temperature and pressure.

Surf	Glass	Temp	Pres	1.260339	1.266972	1.273605	1.280239	1.286872
0		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
1	N-F2	20.00	1.00	1.59816741	1.59806189	1.59795681	1.59785216	1.59774792
2		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
3	N-PSK57	20.00	1.00	1.58053084	1.58047201	1.58041343	1.58035509	1.58029697
4		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
5	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
6	MIRROR	20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
7	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
8	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
9	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
10	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
11	MIRROR	20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
12	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
13	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
14	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
15	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
16	MIRROR	20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
17	MIRROR	20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
18	MIRROR	20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
19	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
20	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
21	MIRROR	20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
22	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
23	S-BSM9	25.00	1.00	1.59831671	1.59823217	1.59814787	1.59806380	1.59797996
24		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
25	S-BSM9	25.00	1.00	1.59831671	1.59823217	1.59814787	1.59806380	1.59797996
26		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
27	S-NPH1	25.00	1.00	1.76728544	1.76712125	1.76695818	1.76679620	1.76663527
28		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
29	S-LAL58	25.00	1.00	1.67493669	1.67484350	1.67475067	1.67465819	1.67456605
30		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
31	SF6	20.00	1.00	1.76908385	1.76895256	1.76882245	1.76869347	1.76856561
32		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
33	S-NBH5	25.00	1.00	1.63217471	1.63206408	1.63195386	1.63184402	1.63173455
34		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
35	N-BK7	20.00	1.00	1.50418239	1.50410216	1.50402199	1.50394188	1.50386181
36		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
37	<CRD BRK>			1.00000000	1.00000000	1.00000000	1.00000000	1.00000000
38		20.00	1.00	1.00000000	1.00000000	1.00000000	1.00000000	1.00000000

THERMAL COEFFICIENT OF EXPANSION DATA:

Surf	Glass	TCE *10E-6
0		0.00000000
1	N-F2	7.84000000
2		0.00000000
3	N-PSK57	13.20000000
4		0.00000000
5	<CRD BRK>	0.00000000
6	MIRROR	0.00000000
7	<CRD BRK>	0.00000000
8	<CRD BRK>	0.00000000
9	<CRD BRK>	0.00000000
10	<CRD BRK>	0.00000000
11	MIRROR	0.00000000
12	<CRD BRK>	0.00000000

```
13            <CRD BRK>     0.00000000
14            <CRD BRK>     0.00000000
15            <CRD BRK>     0.00000000
16               MIRROR     0.00000000
17               MIRROR     0.00000000
18               MIRROR     0.00000000
19            <CRD BRK>     0.00000000
20            <CRD BRK>     0.00000000
21               MIRROR     0.00000000
22            <CRD BRK>     0.00000000
23               S-BSM9     6.40000000
24                          0.00000000
25               S-BSM9     6.40000000
26                          0.00000000
27               S-NPH1     8.30000000
28                          0.00000000
29              S-LAL58     7.50000000
30                          0.00000000
31                  SF6     8.10000000
32                          0.00000000
33               S-NBH5     6.60000000
34                          0.00000000
35                 N-BK7    7.10000000
36                          0.00000000
37            <CRD BRK>     0.00000000
38                          0.00000000
```

Appendix B – Tolerance Sensitivity Analysis (with focus compensation)

```
Analysis of Tolerances

File : M:\Projects\PRVS\Zemax\Tolerancing\PRVS004 TOL 001.zmx
Title:
Date : TUE JUL 25 2006


Units are Millimeters.

Paraxial Focus compensation only.

WARNING: Solves should be removed prior to tolerancing.

WARNING: RAY AIMING IS OFF. Very loose tolerances may not be computed accurately.

WARNING: Boundary constraints on compensators will be ignored.

Criteria            : User defined merit function
Mode                : Sensitivities
Nominal Criteria    : 2.20866431
Test Wavelength     : 0.6328

Fields: User Defined Object height in Millimeters
 #      X-Field      Y-Field       Weight    VDX    VDY    VCX    VCY
 1   0.000E+000   0.000E+000   1.000E+000  0.000  0.000  0.000  0.000

Sensitivity Analysis:
```

Type			Minimum Value	Minimum Criteria	Minimum Change	Maximum Value	Maximum Criteria	Maximum Change
TRAD	1		-1.000000000	2.209191368	0.000527058	1.000000000	2.208419029	-0.000245280
TRAD	2		-0.050000000	2.361446267	0.152781958	0.050000000	2.262625042	0.053960732
TRAD	3		-0.050000000	2.231201657	0.022537347	0.050000000	2.301366825	0.092702515
TRAD	4		-0.050000000	2.223024203	0.014359894	0.050000000	2.221842007	0.013177697
TRAD	6		-4.000000000	2.337985154	0.129320844	4.000000000	2.417455438	0.208791128
TFRN	11		-0.200000000	2.213051550	0.004387241	0.200000000	2.206638129	-0.002026181
TFRN	17		-0.200000000	2.208665503	1.1931E-006	0.200000000	2.208663116	-1.1933E-006
TFRN	21		-0.200000000	2.207920080	-0.000744230	0.200000000	2.209484929	0.000820620
TRAD	23		-0.600000000	2.211144604	0.002480294	0.600000000	2.206448884	-0.002215425
TRAD	24		-2.000000000	2.208735050	7.0741E-005	2.000000000	2.208606409	-5.7900E-005
TRAD	25		-0.350000000	2.227588796	0.018924487	0.350000000	2.201865208	-0.006799102
TRAD	26		-4.500000000	2.208945324	0.000281014	4.500000000	2.208561126	-0.000103183
TRAD	27		-0.200000000	2.208430061	-0.000234249	0.200000000	2.208908067	0.000243757
TRAD	28		-0.500000000	2.204915696	-0.003748613	0.500000000	2.214194816	0.005530506
TRAD	29		-0.400000000	2.207025358	-0.001638951	0.400000000	2.210560457	0.001896147
TRAD	30		-1.000000000	2.210448735	0.001784425	1.000000000	2.207176258	-0.001488052
TRAD	31		-0.200000000	2.207121306	-0.001543004	0.200000000	2.210306194	0.001641884
TRAD	32		-1.000000000	2.209378060	0.000713750	1.000000000	2.207993399	-0.000670910
TRAD	33		-1.500000000	2.208533914	-0.000130395	1.500000000	2.208969121	0.000304811
TRAD	34		-0.150000000	2.209216699	0.000552389	0.150000000	2.208123291	-0.000541019
TFRN	35		-0.200000000	2.208665892	1.5827E-006	0.200000000	2.208662726	-1.5834E-006
TFRN	36		-0.200000000	2.208663211	-1.0988E-006	0.200000000	2.208665406	1.0960E-006
TTHI	0	0	-0.200000000	2.218817289	0.010152980	0.200000000	2.230402600	0.021738290
TTHI	1	2	-0.050000000	2.378796830	0.170132521	0.050000000	2.593058414	0.384394105
TTHI	2	4	-0.050000000	2.590965954	0.382301645	0.050000000	2.378910716	0.170246407
TTHI	3	4	-0.050000000	2.211885876	0.003221566	0.050000000	2.206447595	-0.002216715
TTHI	4	0	-0.200000000	2.223341065	0.014676755	0.200000000	2.216784838	0.008120528
TTHI	5	0	-0.200000000	2.219348673	0.010684363	0.200000000	2.215409339	0.006745029
TTHI	22	0	-0.200000000	2.230402504	0.021738195	0.200000000	2.218817122	0.010152812
TTHI	23	24	-0.200000000	2.208656015	-8.2947E-006	0.200000000	2.208887806	0.000223496
TTHI	24	26	-0.200000000	2.213556375	0.004892065	0.200000000	2.204800685	-0.003863625
TTHI	25	26	-0.200000000	2.207956482	-0.000707828	0.200000000	2.209744090	0.001079781
TTHI	26	28	-0.200000000	2.208810780	0.000146470	0.200000000	2.208785736	0.000121426
TTHI	27	28	-0.200000000	2.206598074	-0.002066236	0.200000000	2.211154654	0.002490344
TTHI	28	30	-0.200000000	2.205869764	-0.002794545	0.200000000	2.212098429	0.003434119
TTHI	29	30	-0.200000000	2.207345174	-0.001319136	0.200000000	2.210362259	0.001697950
TTHI	30	32	-0.200000000	2.203505700	-0.005158610	0.200000000	2.216054886	0.007390576
TTHI	31	32	-0.200000000	2.205234937	-0.003429373	0.200000000	2.213381164	0.004716854
TTHI	32	34	-0.200000000	2.218675249	0.010010940	0.200000000	2.202175641	-0.006488669
TTHI	33	34	-0.200000000	2.210763972	0.002099662	0.200000000	2.206805706	-0.001858604
TTHI	34	36	-0.200000000	2.208664310	7.5495E-014	0.200000000	2.208664310	-2.9754E-013
TTHI	35	36	-0.200000000	2.208214421	-0.000449888	0.200000000	2.209222702	0.000558392
TTHI	36	37	-0.200000000	2.205517284	-0.003147025	0.200000000	2.212575969	0.003911660
TEDY	1	2	-0.025000000	2.557622500	0.348958190	0.025000000	2.583183863	0.374519553
TETX	1	2	-0.005730000	2.219634704	0.010970395	0.005730000	2.233631759	0.024967450
TEDY	3	4	-0.025000000	2.596445160	0.387780850	0.025000000	2.549999947	0.341335638
TETX	3	4	-0.005730000	2.205308705	-0.003355605	0.005730000	2.205220998	-0.003443312
TEDY	1	4	-0.200000000	2.340348359	0.131684049	0.200000000	2.211720771	0.003056462
TETX	1	4	-0.011460000	2.207718773	-0.000945537	0.011460000	2.221246125	0.012581815
TEDY	6	6	-0.200000000	2.199144754	-0.009519556	0.200000000	2.237363813	0.028699503
TETX	6	6	-0.011460000	2.220121634	0.011457325	0.011460000	2.372770567	0.164106258
TEDY	11	11	-0.200000000	2.208664310	-2.5604E-011	0.200000000	2.208664310	2.4283E-011

TETX	11	11	-0.011460000	2.207774497	-0.000889813	0.011460000	2.207364409	-0.001299901
TEDY	16	16	-0.200000000	2.198819507	-0.009844803	0.200000000	2.226604534	0.017940224
TETX	16	16	-0.011460000	2.233359530	0.024695221	0.011460000	2.350816279	0.142151969
TEDY	17	17	-0.200000000	2.208664310	0.000000000	0.200000000	2.208664310	0.000000000
TETX	17	17	-0.011460000	2.208897358	0.000233048	0.011460000	2.220092467	0.011428158
TEDY	18	18	-0.200000000	2.238274029	0.029609719	0.200000000	2.198955396	-0.009708914
TETX	18	18	-0.011460000	2.386640656	0.177976346	0.011460000	2.237049028	0.028384719
TEDY	21	21	-0.200000000	2.208664310	2.5135E-013	0.200000000	2.208664310	-5.0360E-013
TETX	21	21	-0.011460000	2.238627334	0.029963024	0.011460000	2.394156106	0.185491796
TEDY	23	24	-0.100000000	2.255627877	0.046963567	0.100000000	2.192394064	-0.016270246
TETX	23	24	-0.005730000	2.219588409	0.010924099	0.005730000	2.232045483	0.023381173
TEDY	25	26	-0.100000000	2.240220638	0.031556328	0.100000000	2.191589629	-0.017074681
TETX	25	26	-0.005730000	2.203055720	-0.005608589	0.005730000	2.204696621	-0.003967688
TEDY	27	28	-0.100000000	2.210390586	0.001726276	0.100000000	2.262823190	0.054158880
TETX	27	28	-0.005730000	2.204673909	-0.003990401	0.005730000	2.203820212	-0.004844098
TEDY	29	30	-0.100000000	2.222406239	0.013741930	0.100000000	2.194817219	-0.013847091
TETX	29	30	-0.005730000	2.219509495	0.010845186	0.005730000	2.232167313	0.023503004
TEDY	31	32	-0.100000000	2.238947850	0.030283540	0.100000000	2.212287937	0.003623628
TETX	31	32	-0.005730000	2.219406124	0.010741815	0.005730000	2.232372261	0.023707951
TEDY	33	34	-0.100000000	2.197443232	-0.011221077	0.100000000	2.231458205	0.022793895
TETX	33	34	-0.005730000	2.231147176	0.022482867	0.005730000	2.220607658	0.011943348
TEDY	35	36	-0.100000000	2.208664310	1.8652E-014	0.100000000	2.208664310	1.6875E-014
TETX	35	36	-0.005730000	2.208584606	-7.9704E-005	0.005730000	2.208745198	8.0888E-005
TEDY	23	36	-0.200000000	2.455319818	0.246655508	0.200000000	2.263596308	0.054931999
TETX	23	36	-0.011460000	2.196835911	-0.011828399	0.011460000	2.244570109	0.035905800
TSTX	1		-0.001964000	2.208160430	-0.000503880	0.001964000	2.209400600	0.000736290
TSTX	2		-0.001964000	2.222432735	0.013768425	0.001964000	2.221727127	0.013062818
TSTX	3		-0.001964000	2.221722078	0.013057769	0.001964000	2.222363974	0.013699664
TSTX	4		-0.001964000	2.209487498	0.000823189	0.001964000	2.219459960	0.010795650
TSTX	23		-0.001964000	2.216899564	0.008235254	0.001964000	2.212528242	0.003863932
TSTX	24		-0.001964000	2.223806946	0.015142637	0.001964000	2.228375864	0.019711554
TSTX	25		-0.001964000	2.205852325	-0.002811985	0.001964000	2.223437412	0.014773103
TSTX	26		-0.001964000	2.223153182	0.014488873	0.001964000	2.228857610	0.020193300
TSTX	27		-0.001964000	2.218558623	0.009894314	0.001964000	2.225333947	0.016669637
TSTX	28		-0.001964000	2.212317845	0.003653535	0.001964000	2.205533853	-0.003130456
TSTX	29		-0.001964000	2.218779556	0.010115246	0.001964000	2.210272106	0.001607797
TSTX	30		-0.001964000	2.221443361	0.012779052	0.001964000	2.230388911	0.021724602
TSTX	31		-0.001964000	2.218964106	0.010299796	0.001964000	2.210052291	0.001387981
TSTX	32		-0.001964000	2.209841955	0.001177645	0.001964000	2.230753999	0.022089690
TSTX	33		-0.001964000	2.219565739	0.010901430	0.001964000	2.209449191	0.000784882
TSTX	34		-0.001964000	2.209092105	0.000427795	0.001964000	2.208257636	-0.000406674
TSTX	35		-0.001964000	2.208593695	-7.0615E-005	0.001964000	2.208737035	7.2726E-005
TSTX	36		-0.001964000	2.208708998	4.4688E-005	0.001964000	2.208620703	-4.3606E-005
TIRR	1		-0.500000000	2.222565755	0.013901446	0.500000000	2.202580841	-0.006083469
TIRR	2		-0.500000000	2.202390862	-0.006273447	0.500000000	2.225490818	0.016826508
TIRR	3		-0.500000000	2.230568974	0.021904664	0.500000000	2.202051741	-0.006612569
TIRR	4		-0.500000000	2.202559646	-0.006104663	0.500000000	2.241188124	0.032523814
TIRR	6		-0.500000000	2.215200127	0.006535818	0.500000000	2.255229051	0.046564742
TIRR	16		-0.500000000	2.215887071	0.007222761	0.500000000	2.252150156	0.043485846
TIRR	17		-0.500000000	2.208665887	1.5770E-006	0.500000000	2.208662733	-1.5769E-006
TIRR	18		-0.500000000	2.224666690	0.016002381	0.500000000	2.239236301	0.030571992
TIRR	23		-0.500000000	2.238803550	0.030139241	0.500000000	2.203410113	-0.005254197
TIRR	24		-0.500000000	2.203581064	-0.005083246	0.500000000	2.238920924	0.030256615
TIRR	25		-0.500000000	2.238679735	0.030015425	0.500000000	2.203282828	-0.005381481
TIRR	26		-0.500000000	2.203656780	-0.005007530	0.500000000	2.239158698	0.030494388
TIRR	27		-0.500000000	2.252743005	0.044078695	0.500000000	2.206723703	-0.001940607
TIRR	28		-0.500000000	2.206278411	-0.002385898	0.500000000	2.252022444	0.043358135
TIRR	29		-0.500000000	2.244485251	0.035820941	0.500000000	2.204504869	-0.004159440
TIRR	30		-0.500000000	2.204631891	-0.004032419	0.500000000	2.244666586	0.036002276
TIRR	31		-0.500000000	2.252240506	0.043576197	0.500000000	2.206201764	-0.002462546
TIRR	32		-0.500000000	2.206516833	-0.002147477	0.500000000	2.252824069	0.044159759
TIRR	33		-0.500000000	2.241854193	0.033189884	0.500000000	2.203829395	-0.004834914
TIRR	34		-0.500000000	2.203650045	-0.005014265	0.500000000	2.241767506	0.033103197
TIRR	35		-0.500000000	2.208696114	3.1804E-005	0.500000000	2.208632585	-3.1725E-005
TIRR	36		-0.500000000	2.208647427	-1.6883E-005	0.500000000	2.208681214	1.6904E-005
TIND	1		-0.001000000	2.275443931	0.066779621	0.001000000	2.297248674	0.088584365
TIND	3		-0.001000000	2.510949147	0.302284837	0.001000000	2.557303517	0.348639208
TIND	23		-0.001000000	2.202311256	-0.006353053	0.001000000	2.219023196	0.010358887
TIND	25		-0.001000000	2.201740255	-0.006924054	0.001000000	2.229888328	0.021224018
TIND	27		-0.001000000	2.211172764	0.002508454	0.001000000	2.206749910	-0.001914400
TIND	29		-0.001000000	2.214643237	0.005978927	0.001000000	2.204191394	-0.004472916
TIND	31		-0.001000000	2.211178325	0.002514016	0.001000000	2.206470665	-0.002193645
TIND	33		-0.001000000	2.207057475	-0.001606834	0.001000000	2.210419082	0.001754773
TIND	35		-0.001000000	2.208710029	4.5720E-005	0.001000000	2.208618513	-4.5797E-005
TABB	1		-0.364309348	2.209775969	0.001111660	0.364309348	2.211786635	0.003122325
TABB	3		-0.683986670	2.210579653	0.001915343	0.683986670	2.210447862	0.001783552
TABB	23		-0.549900969	2.207700820	-0.000963490	0.549900969	2.209685826	0.001021517
TABB	25		-0.549900969	2.207182881	-0.001481429	0.549900969	2.210418633	0.001754324
TABB	27		-0.227608166	2.209523134	0.000858825	0.227608166	2.208073326	-0.000590984
TABB	29		-0.508106516	2.209494215	0.000829905	0.508106516	2.207908469	-0.000755840
TABB	31		-0.254320152	2.209547713	0.000883404	0.254320152	2.208004809	-0.000659501
TABB	33		-0.396827942	2.208455165	-0.000209144	0.396827942	2.209040791	0.000376482
TABB	35		-0.641673362	2.208668127	3.8176E-006	0.641673362	2.208660567	-3.7428E-006

Worst offenders:

```
Type                        Value       Criteria          Change
TEDY   3   4         -0.025000000    2.596445160    0.387780850
TTHI   1   2          0.050000000    2.593058414    0.384394105
TTHI   2   4         -0.050000000    2.590965954    0.382301645
TEDY   1   2          0.025000000    2.583183863    0.374519553
TEDY   1   2         -0.025000000    2.557622500    0.348958190
TIND   3              0.001000000    2.557303517    0.348639208
TEDY   3   4          0.025000000    2.549999947    0.341335638
TIND   3             -0.001000000    2.510949147    0.302284837
TEDY  23  36         -0.200000000    2.455319818    0.246655508
TRAD   6              4.000000000    2.417455438    0.208791128


Estimated Performance Changes based upon Root-Sum-Square method:
Nominal Merit Function   :    2.208664310
Estimated change         :    0.850415271
Estimated Merit Function :    3.059079580

Compensator Statistics:
Change in back focus:
Minimum            :        -0.390498
Maximum            :         0.390729
Mean               :         0.000067
Standard Deviation :         0.081955


End of Run.
```

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