Southern African Large Telescope

Prime Focus Imaging Spectrograph

Optics Design

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1 Scope

This document presents the top level optical design for the Prime Focus Imaging Spectrograph. The following subsystems are described in more detail in the following Subsystem Design or Trade Study Documents:

- SALT3120AA0002 Grating and Filter Trade Study
- SALT3120AA0003 Polarimetric Optics Design Study
- SALT3120AE0005 Camera/Collimator Optics Specification
- SALT3150AA0001 Slitmask Requirements and Fabrication Document
- SALT3180AA0001 Etalon and Filter Trade Study
- SALT3190AA0001 Detector Subsystem Design Study

2 Design Procedure

The optical design was modeled using the ZEMAX optical CAD package, version 10 - EE.

2.1 SALT Telescope model

The input for the optical system started with a ZEMAX model of the telescope and Spherical Aberration Corrector ("SAC") provided by the SALT project. The design described here uses the SAC specification for an 11m telescope pupil at F/4.2, and an eight arcmin field of view. The prescription is given in the document "SALT Optical Model", SALT-3300AS0001, 13 June 2002. The telescope focal plane is flat, and the entrance pupil is 586 mm from the focal plane. Since the spectrograph is designed to be able to use slits that are smaller than the seeing disk, it was designed for best imaging of the slit, not the sky, so that the aberrations of the SAC were deliberately ignored. To facilitate this, a “perfect” telescope/ SAC model was constructed using ZEMAX paraxial elements having the same effective focal length, F/ratio, and entrance pupil size and position as the actual SAC, but with perfect imaging. It was also important to model the SAC vignetting of the marginal rays as a function of field angle, since this fortuitously reduces element diameters and reduces the “waist” of the collimated beam. This was done using ZEMAX “vignetting factors”. They had to be adjusted by hand to match the actual SAC pupil, since the automatic ZEMAX vignetting factor algorithm fails for the complex SAC pupil.

2.2 Design goals

Overall scientific goals for PFIS are described in "PFIS Instrument Description", SALT-3170AE0001. The rationale behind the optical design goals listed therein is described below

- Coverage 320 - 900 nm. Maintain simultaneous IR beam (850 nm - 1.7μ) upgrade possibility.

There was a strong desire within the consortium to have coverage down to the atmospheric limit at the Prime Focus. At the same time, there is a strong desire for a near IR instrument. Given space and weight constraints, these would have to have a common collimator. This seems feasible, if one uses very broadband (possibly Solgel) coatings in the common optics (see Coatings below). The IR beam should be sub-thermal (wavelengths less than 1.7μ) because the telescope is not optimized to minimize thermal emissivity. The visible- IR break should be
about 850 nm since that is where the efficiency curves of CCD and HgCdTe IR detectors cross. Since there is no room for a third beam, the visible beam should cover all wavelengths below 850 nm. The original specification called for 320 - 850 nm for the visible beam. This was stretched to 900 nm to cover the CaII triplet and to allow for some overlap with the future IR beam. The UNC SOAR spectrograph covers 320 - 850 nm with conventional coatings, but requires NaCl elements for good color correction. This spectrograph was used as a starting point for the visible beam optics.

- All- transmission optics for high efficiency and compactness;

The highest possible transmission is a general goal for this instrument. The gain in compactness comes from avoiding the wasted collimated beam space required with a reflective collimator, and from the use of transmission gratings. Also, a reflective camera would introduce vignetting after the polarizing beam-splitter, which greatly compromises polarimetric precision.

- A maximum of one asphere. The original PDR design called for all spherical surfaces to reduce risk and cost. This goal has since been revisited, resulting in a single asphere surface at the entrance to the camera. The cost/risk tradeoff is described below.

- UV Crystals and fused silica only.

This is required for good UV throughput down to 320 nm. The current model uses only fused silica, fused quartz, CaF₂, and NaCl.

- Beam size 150 mm, the maximum for practical Fabry-Perot etalons.

A major goal of the instrument is the highest possible first-order spectral resolution. For a grating spectrograph at Littrow, the resolution in first order is given by

$$ R = \frac{2 \tan \theta_i}{2 \tan \theta_s} (d/D) $$

where $\theta_i$ is the grating tilt, $\theta_s$ is the slit width, $d$ is the beam diameter, and $D$ is the primary mirror diameter. With $D$ fixed, the maximum grating tilt fixed by mechanical constraints, and the minimum slit width set by the seeing, the only free parameter is the beam diameter. (Similar arguments apply to Fabry-Perot, where $d/D$ is the parameter which fixes the angular size of the "bullseye", where the wavelength is constant to within the etalon resolution). The practical limiting beam diameter is set by the maximum diameter available etalons of 150 mm. We have chosen the beam to be 150 mm, so that there is some vignetting at the edge of the field for the Fabry-Perot. VPH gratings are available in larger sizes, so that in grating mode there will be no vignetting.

- Images < 0.40 arcsec in the dispersion direction over the full wavelength range.

The specification is as follows:

- < 0.4 arcsec RMS width in dispersion direction for field angles < 3 arcmin
- < 0.5 arcsec RMS width in dispersion direction for field angles 3-4 arcmin
- < 0.55 arcsec RMS diameter for 340 - 850 nm
- < 0.65 arcsec RMS diameter for 320 - 340 nm
The tightest imaging requirements are in spectroscopic mode with a reduced slit, so the RMS width is a more appropriate specification. Since the field of view in spectroscopic mode is not symmetric, some astigmatism can be tolerated perpendicular to the dispersion with this method of optimization. For grating spectroscopy with a 0.65 arcsec slit, the slit image is degraded by no more than 17% for field angles < 3 arcmin, and 26% for field angles 3-4 arcmin. (This slit, the narrowest envisioned, transmits 50% of the telescope image in the best seeing, and 40% in median seeing). The RMS diameter specification is appropriate for imaging without a slit. The median SALT seeing has RMS diameter of 1.2 arcsec (at 37° zenith angle, with 0.6 arcsec telescope images). For imaging, the median image is degraded by no more than 10% (14% at 320 nm). These specifications include the optics as designed (including thermal effects in the range -5 - 20 deg C), plus manufacturing errors and alignment errors. The specification is monochromatic: the design will allow lateral color (about 1.6 arcsec from 320 to 900 nm), since it is assumed that broadband imaging will be performed by the SALT scientific grade acquisition camera.

The original goal called for these imaging specifications to be met with no refocus between grating configurations. This has been judged to be unnecessarily strict, since there will be a camera focus mechanism which will be required to compensate for filter thickness differences and uncompensated thermal effects. The current design has a 200μm refocus range.

2.3 Optical Indices

The optical design is very sensitive to the assumed optical indices and their variation with temperature. Fortunately, for the chosen crystals, the indices do not vary appreciably with manufacturer. Unfortunately, there is disagreement in the literature as to what the indices are. The following indices were chosen based on consultation with Harland Epps and Darragh O'Donoghue. Table 1 lists the adopted coefficients for n(λ) and dn(λ)/dT. The formulae are as follows:

(Sellmeier) \[ n^2(\lambda) - 1 = K_1 \frac{\lambda^2}{(\lambda^2 - L_1)} + K_2 \frac{\lambda^2}{(\lambda^2 - L_2)} + K_3 \frac{\lambda^2}{(\lambda^2 - L_3)} \]

(Schott) \[ n^2(\lambda) = A_0 + A_1 \lambda^2 + A_2 \lambda^4 + A_3 \lambda^6 + A_4 \lambda^8 \]
\[ dn(\lambda)/dT = [ D_0 + E_0 / (\lambda^2 - \lambda_{d0}^2) ] (n^2 - 1)/(2n) \]

The dn/dT representation is that used by ZEMAX. The coefficients were derived by fitting the quantity D(\lambda) = 2n/(n^2 - 1) dn/dT to data from the literature (Figure 1).
A tolerance analysis was performed on the current design to determine the accuracy with which the indices must be known. Table 2 lists $\Delta n_d$ and $\Delta v_d$, the error in the index and the Abbe' number at 586 nm that results in an rms image size degradation of 1%.

### 2.3.1 Fused Silica and Fused Quartz

The Sellmeier fit for fused silica was taken from Malitson (1965, *JOSA* 55, 10). It is valid for 0.21 - 3.71 $\mu$m at 20°C. Comparing the adopted indices with those used by Epps (private communication) for the SOAR Goodman spectrograph, we find $(\Delta n_d \times 10^6, \Delta v_d) = (1, 0.04)$. Malitson (1965) also compared four samples of Corning 7940, and found (10 - 30, 0.04). The data used for the $dn/dT$ fit is from the manufacturers data sheet for Corning 7980 fused silica. Comparing the resulting index at 0°C with the Epps 0°C indices, we find (5, 0.08). The uncertainty in index and dispersion thus seems acceptable.

The Sellmeier fit for fused quartz is a ZEMAX fit of index data for Heraeus Infrasil taken from the manufacturer's specification. It is valid for 274nm - 1.7$\mu$m at 20°C. The data for the $dn/dT$ fit was taken from the same manufacturers specification, for 238 - 643 nm, extrapolated to 1.7 $\mu$m. Both fused silica and fused quartz have a rather small thermal variation of the index of refraction, so the optical design is insensitive to this data.
2.3.2 Calcium Fluoride

For CaF$_2$ we have adopted the Schott fit used by Epps for SOAR Goodman at 20°C. The data used for the dn/dT fit is from Malitson (1963, *Appl Opt* 2, 1103). It was fit in two pieces, VIS: 0.297 - 0.89 µ and NIR: 0.89 - 1.7 µ, because the ZEMAX formula cannot represent data with an extremum. The PFIS model uses the VIS formula for the Visible beam and the NIR formula for the NIR beam. Malitson also gives an index fit for 24 °C; if this is corrected with the VIS dn/dT to 20 °C, we find ($\Delta n \times 10^6, \Delta v_d$) = (0, 0.01). Similarly comparing with the Epps 0°C indices, we find (4, 0.01). The CaF$_2$ indices appear to be well in hand.

2.3.3 Sodium Chloride

NaCl is the most problematic material. We have again chosen the Schott fit used by Epps for SOAR Goodman at 20°C. This is based on a re-analysis of data in Li (1976, *J. Phys. Chem. Ref. Data*, 5, 329). These indices have been used successfully in previous Epps designs using NaCl. Li (1976) gives a fit which differs from the Epps indices by ($\Delta n \times 10^6, \Delta v_d$) = (-155, 0.04), an unacceptable difference. The data in Li is very heterogeneous in quality and temperature, so a careful choice of data and temperature correction is important, especially considering the large dn/dT for NaCl. The dn/dT adopted is based on data in Feldman (1978, *NBS Technical Note* #993, p50) for 0.46 - 3.39 µ, and Epps (private communication) for 0.26 - 0.4 µ. This gives a rather larger value for dn/dT than data in Li ($D_0 ~ 84$ vs 76), which may account for the discrepancy. Applying our dn/dT fit to arrive at indices for 0°C, and comparing with the Epps 0°C indices gives an error of ($\Delta n \times 10^6, \Delta v_d$) = (64, 0.01), which is acceptable.

3 Optics Subsystems

The current PFIS optical design is shown in Figure 2. Here we describe the design proceeding from the detector backwards along the beam.

![PFIS Optical Layout](image)
3.1 Detector

The detector geometry was chosen based on issues of sampling and CCD availability. The fastest affordable refractive UV camera was judged to be F/2.2. For an 11m telescope, the 8 arcmin SALT field is then 56 mm across, which almost fills the long dimension (61 mm) of the most common modern 2048 x 4096, 13.5 - 15 micron pixel CCDs. A mosaic of two of these chips is often chosen, but another factor to consider is the number of spectral resolution elements. For a slit matching the median SALT images of 1.2 arcsec, there are 400 spatial resolution elements, and a square array would provide only 435 resolution elements for grating spectroscopy. This is well short of the number of spectral resolution elements on large telescope slit spectrographs, which are in the range 600 - 1200. Since simultaneous resolution elements define the multiplex advantage of a spectrograph, it was felt that this number should be competitive, so that a 3 mosaic, with the long dimension in the dispersion direction, was baselined.

The baseline CCD chosen (see Detector Subsystem Design Study) is a mosaic of three Marconi/EEV 42-82 (2048x4096 15 μ pixels) chips, for a total of 6144 x 4096 pixels (95 x 61 mm). For an F/2.2 camera, the pixels are 0.13 arcsec, so that the 1.2 arcsec seeing disk is critically sampled for 2 × 2 binning, and a 0.5 arcsec slit is critically sampled for unbinned readout. The number of 1.2 arcsec spectral resolution elements is 655.

3.2 Camera

For VPH observations, the camera is articulated about the grating axis as the grating is tilted to allow tuning of the grating blaze while the wavelength range is shifted. Since the VPH blaze peak is at Littrow, the camera articulating angle is twice the grating tilt. A maximum grating tilt of 50° has been chosen (from mechanical and grating efficiency considerations), leading to a maximum camera articulation of 100°. The camera aperture has been sized to accept this range of configurations with no vignetting for any wavelength on axis, and < 5% vignetting for the extreme wavelengths at the extreme articulation angles 4 arcmin off axis.

An unavoidable result of the length of the detector is a rather large camera field of view, 16°. Typical spectrograph cameras are in the range 10 - 16°, so this is a design driver. The large wavelength range is another design driver. The starting design took elements from the SOAR Goodman spectrograph.
Harland Epps; this camera has a similar wavelength range, but only a $10.4^\circ$ FOV. The use of NaCl triplets is notable in this design. Another source was the Epps camera for the Keck LRIS-B, which has a smaller wavelength range but an FOV of $14.6^\circ$. The PFIS design has 9 elements in 4 groups (Figure 3). The first group is a large fused silica /CaF$_2$ quadruplet. The first surface is an asphere, on fused silica. The original camera design was all spherical, having 12 elements in 5 groups, including 2 NaCl triplets, and starting with a CaF$_2$/silica doublet. Putting an asphere on the initial CaF$_2$ surface eliminated 4 elements, including one NaCl triplet. However, it was judged to be too risky to put an asphere on CaF$_2$, and an extra silica element was added to the group to take the asphere. The resulting asphere is well within the experience of astronomical spectrographs: it has a Maximum Aspheric Deviation ("MAD") of about 430 $\mu$m, compared to a MAD of >1 mm in DEIMOS. An order of magnitude estimate from Hilyard shows that the extra cost of the asphere is offset by cost of the elements saved. The reduction of air-glass interfaces and the reduced risk resulting from removal of a NaCl triplet weighs in favor of the asphere design. The quadruplet is followed a CaF$_2$ singlet, which provides much of the power, and a Silica/NaCl/silica triplet, which provides additional power with color correction. The field flattener is fused silica. The flattener is also the detector cryostat window.

A filter magazine for Fabry-Perot interference filters and order blockers is located just before the detector. The choice for filter location is between this position and the collimated beam. The latter would result in very large, expensive, heavy filters which would require very good optical quality, so this was ruled out. The disadvantage of locating the filters close to the detector is the possibility of out-of-focus ghosts from reflections off the CCD surface, and the effect of the fast beam on the interference filters.

The camera was first optimized using the perfect SALT telescope model described above, plus a perfect collimator yielding the 150mm beam and the desired pupil placement. The field flattener back focal distance was constrained to be greater than 9 mm, and the space between the last camera element and the field flattener was constrained to be big enough for the filters. The overall length was constrained to be < 625 mm, required by the overall envelope of the instrument. The merit function consisted of image rms in the dispersion direction for field angles of 0, 2, 3, and 4 arcmin, plus image diameter at the same field angles, but with a relative weight of 1/3. The dominant aberration is longitudinal color, so the system was optimized with the camera in three configurations of the lowest-dispersion VPH grating (900 l/mm), with the camera at Littrow and the grating tilted at 12.3°, 14.5° and 19.95°: this gives wavelength coverage, respectively, of 320 - 640 nm, 400 - 700 nm, and 610 - 900 nm. These are the most demanding configurations of the spectrograph; the higher dispersion configurations have better imaging because of the smaller range of wavelengths. The goal for the camera design images was a dispersion -direction RMS width < 0.2 arcsec (23 microns), 2/3 the goal of the total system rms of 0.3 arcsec (35 microns). This leaves 30% margin for fabrication and alignment errors. Roughly one hundred lens configurations were evaluated; no configuration without NaCl was found to be acceptable.

### 3.3 Collimated Beam

The dispersors are located in the 150mm diameter, 350 mm long collimated beam. The collimated beam will accommodate either two Fabry-Perot etalons (each 250 mm in diameter
and 155 mm thick), or one rotatable VPH grating. The etalon positions straddle the VPH position near the pupil. A standard Prontor 150mm shutter is just before the dispersors in the collimated beam. The shutter cannot be placed in the collimator because of the desire for future simultaneous visible/IR observing. It could have gone near the detector, allowing a smaller shutter. However, the position in the collimated beam is advantageous because very short exposures such as would be necessary for flux calibration would have no field angle exposure correction. It is true that the shutter is not at the pupil, and requires an aperture of 161mm, which is larger than any commercially available shutter. However, we have determined that a standard Prontor 150 mm shutter may be modified to apertures of 160 - 165 mm without affecting reliability.

The optical properties of the Fabry-Perot etalons and the VPH gratings is described in detail in their Trade Study documents.

3.4 Polarimetric Optics

The polarimetric optics utilizes a "wide-field" design. As described in the Polarimetric Optics Design Document, such a system has a polarizing beamsplitter in the collimated beam which takes the central half of the field and splits it into two orthogonally polarized fields, the "ordinary" and "extraordinary" beams. A polarization modulator preceding the beamsplitter modulates the polarization state with time, and the difference between the intensities of the O and E images as a function of time yields the polarization.

The beamsplitter, an array of calcite Wollaston prisms, may be inserted just before the camera in the collimated beam. This ensures that there is no vignetting of the split beam by the dispersors, especially the Fabry-Perot etalons, which would compromise the polarimetric precision. Also, by placing the beamsplitter after the etalons, both the E and O fields have the same wavelength gradient in Fabry-Perot mode, enabling direct differencing of the two fields. Since it has no power and is in the collimated beam, a perfect beamsplitter would have no effect on the image quality of the optical system. However, the prism surfaces must be flat and of good quality to avoid degrading the imaging. Also, there is a concern for ghost images arising in double reflections within the prism and between the prism and the detector.

The modulator consists of two rotating superachromatic waveplates near the beam waist in the collimator. The modulator should be ahead of any optical elements with polarization sensitivity, like the fold mirror and the dispersors. The collimator beam waist was chosen because it minimizes the waveplate size, a serious cost driver. This puts the modulator in a diverging beam, which must be considered in the modulator design (see Design Document). Also, when the modulator (a plane-parallel element) is removed, it must be replaced by a plane-parallel element of the same material (fused quartz) and thickness (20 mm) as the waveplate to match the substantial focus change and spherical aberration of the waveplate. The collimator must be designed to include this plate. The first waveplate is a mosaic 110mm diameter halfwave plate. This is followed either by a fused quartz blank, for linear spectropolarimetry covering the full 4×8 arcmin field of view, or by a single 60mm quarterwave plate, providing a 3.9 unvignetted field for circular or all-Stokes polarimetry. When neither waveplate is inserted, a single double thickness blank provides focus compensation. Thus the only compromise on non-polarimetric modes imposed by the polarization capability is the introduction of two air-glass interfaces,
which may be anti-reflection coated. Because the waveplates (and compensator) are located so close to the telescope focal plane, the flatness requirements on the elements are quite loose.

All elements between the waveplate and the polarizing beam-splitter must have low stress-birefringence to avoid depolarizing the E and O polarization destined for the beam splitter. A total effective birefringence budget in the E-O axis of $< 20$ nm has been established for this optical train. This limits the depolarization to $<1, 2, \text{ and } 4\%$ at 586, 430, and 320 nm, respectively. Fused Silica, fused quartz, and CaF$_2$ with stress birefringence of $< 2$ nm/cm and NaCl $< 10$ nm/cm will meet this requirement, if the stress is not aligned in the elements. Annealing will be required on all these elements to meet this requirement.

### 3.5 Collimator

Compared to refractive collimators on other large telescopes, the requirements for the PFIS collimator are unusual in three ways:

- **High speed** (F/4.2)
- **Closeness of the entrance pupil** (586 mm)
- **Very large wavelength range**: 320 nm - 1.7 μ to accommodate simultaneous visible - near IR observations

The wavelength range and the speed again appear to require use of NaCl. Fused quartz is used in place of fused silica in the common NIR/visible optics, to avoid the 1.39μ absorption band in fused silica. The design (Figure 4: this shows the visible beam only, without fold/ dichroic) starts with a doublet field lens, fused quartz/ CaF$_2$, placed close to the focal plane. This rather strong field lens is due to the closeness of the entrance pupil; the requirement of good imaging down to 320 nm drives the use of a doublet rather than a singlet. This is followed by a space for the waveplates (a plane parallel fused quartz element) and a negative fused quartz element, which corrects the field curvature introduced by the field lens. This arrangement is required in imaging grating spectographs with large field of view perpendicular to the dispersion, because any residual field curvature due to the collimator is seen perpendicular to the dispersion but not along the dispersion, so it cannot be corrected by a spherical element in the camera. The negative element is followed by a singlet fused quartz element, and the main triplet, CaF$_2$ / NaCl / CaF$_2$. The final element in the visible beam collimator is a CaF$_2$ / fused silica doublet.

The collimator was designed to permit the future addition of the near-IR beam. The optical prescription must be optimized to allow good collimation over the entire 320 nm - 1.7μ wavelength range, and the pupil must be placed such that there is adequate room in the
collimated NIR beam. Figure 5 illustrates the NIR beam model that was used. A fold mirror before the final doublet will become the visible/IR dichroic when the IR beam is added. A separate NIR collimator doublet (CaF2/Schott K7) follows the dichroic. A fold follows this to bring the NIR beam within the instrument envelope. The visible camera is shown replicated on the NIR side; it was used to define the NIR support structure, since the NIR camera is as yet undefined.

The collimator was optimized using the perfect SALT model and a perfect 330mm focal length camera for each beam. The merit function minimizes the rms image diameter simultaneously for wavelength 320, 400, 700, and 900 nm in the visible beam, and 0.9, 1.2, 1.4, and 1.7 μ in the NIR beam. The exit pupil was constrained to be 360 mm from the last element of the collimator. This is farther than is required by the visible beam, but allows for the extra 200mm required in the NIR beam by the NIR fold flat. Final constraints set the minimum separation of the field lens from the focal plane to be 10 mm (to allow for the slitmasks), provided minimum clearance for the waveplates, and constrained the overall length to be less than 825 mm.

The goal for the collimator images was an rms diameter less than 0.15 arcsec (8 microns), 1/2 the goal of the total system rms of 30 μ. Again, a large number of lens configurations were evaluated; no configuration without NaCl was found to be acceptable.

### 3.6 Slitmask / Slitviewer

As described in the Slitmask Trade Study Document, multi-object spectroscopy is facilitated through custom slitmasks loaded into a slitmask magazine, selected and inserted at the focal plane. Two kinds of slitmasks are envisioned, thin flat carbon fiber masks which are placed coincident with the focal plane, so that they are useful over the full field of view, and tilted metallic slits for work on-axis in the direction of dispersion. The former, while more flexible in field, present well-known difficulties with acquisition since the slit cannot be viewed directly. The acquisition scenario for the carbon fiber slitmasks involves centering with the SALTICAM acquisition camera, followed by imaging the field with the PFIS camera unarticulated,
comparing this with a calibration lamp image taken through the mask, commanding a telescope offset to align these images, finally followed by science observations with the camera articulated, guided by off-axis probes. In contrast, the tilted metallic masks are provided to allow direct viewing of the slit using relay optics to the acquisition camera. We estimate that at least 50% of PFIS programs will be single object or longslit observations which are compatible with conventional slitviewing. This will allow very accurate acquisition/centering of difficult objects, and even guiding off lost light on the slit. It is felt that these programs should not be unnecessarily subject to the lost time and risk of the blind pointing scenario. The slit viewing optics, based on the Offner relay design, is shown in Figure 6. The optics is fixed: whenever the acquisition camera fold mirror is out, a view of the slit is presented to the acquisition camera if PFIS is using a tilted slit. The slitviewer imaging is better than 0.1 arcsec, and the field of view is 2 x 8 arcmin, unvignetted in the center, and 50% vignetted at the edges. These optics are in the crowded volume in front of the focal plane, and so must become part of the telescope payload.

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Table 3. Thermal Effects on Optical Performance

4 Thermal Design

Thermal effects on optical performance are very important for SALT/ PFIS because of the large temperature range experienced at the prime focus, and because the crystals used in the design for good UV performance have large thermo-mechanical and thermo-optical coefficients. Normal operating conditions are -5 - 20°C with a maximum rate of change of 1.5°C / hour; marginal operating conditions (20% reduced imaging performance) are -10 - 25°C (2°C/ hr), and survival conditions are -20 - 45°C. An exploration of the optical performance over the operating conditions shows that 90% of the effects on the imaging are due to the thermal coefficient of the
The index of refraction of CaF₂ and (especially) NaCl. These affect the focus, the focal plane scale, and the image size. These are all serious enough to demand a passive thermal compensation system to adjust the element positions with temperature.

Table 3 lists the uncompensated (white) and compensated (grey) values for the shift of the focal position, the focal plane scale (listed as the position of an image 4 arcmin off axis), and the image degradation, over the nominal operating temperature range of -5 - 20 °C. The total focal plane shift is so large (34μ/deg) that at the maximum temperature rate of change the spot size would be degraded by 25μ over the longest expected exposure of one hour. This means that adjusting the focus between observations is not sufficient, and passive focus correction is required. Also, the focal plane scale change and image degradation for the camera over the operating range are large and require compensation, particularly since it is desired that flat-field calibrations be performed during the day, when the temperature is typically 7°C warmer. Separate passive compensation schemes consisting of shifts of internal groups were evaluated for the camera and collimator.

For the collimator the focal plane and the final doublet were assumed to be fixed (they are attached to the main invar structure), and motions of the two singlets and triplet were considered. The focus shifts for the visible and NIR beams were quite different, and could not be simultaneously compensated, so a compromise was adopted that split the uncompensated focus motion between the two beams. This reduces the collimator focal shift by a factor of 5 in the visible beam and a factor of 2 in the NIR beam. Motion of no single group nor combination of two groups was sufficient to simultaneously compensate the remaining focus shift, focal scale change, and image degradation. However, a scheme in which the first singlet and triplet were treated as a one group and the singlet between them as a second group gave good results. A schematic implementation of this scheme is shown in figure 7. Delrin, with a large thermal coefficient of expansion of 125×10⁻⁶/°C, is used to shift the groups passively. One delrin spacer moves the first singlet and triplet relative to the rest of the collimator, and a second moves the second singlet relative to this group.

The camera has no focal plane scale shift, appreciable image degradation, and a large focus shift with temperature. The passive thermal compensation system (figure 7) will shift the combination of the CaF₂ singlet and the NaCl triplet relative to the first camera group, and the camera housing will be aluminum, which aids in the compensation. This removes all of the camera focus shift, the remaining collimator focus shift, and improves imaging. The entire system has been re-optimized for the temperature range -5 - 20 °C.
In addition to the passive focus compensation, one must allow for an active focus adjustment. This must allow for an imperfect passive adjustment, for the different focus between the spectrograph configurations, and for residual differences in filter optical paths. Allowing 10% of the thermal travel (±65 μ), a configuration range of ±100 μ, and a filter thickness error of ±50 μ, we require ±235 μ for the active focus. This cannot be done in the collimator, since the visible and NIR beams need to be separately focused. The only collimator elements which are unique to a beam are the final doublets, and their focus sensitivity is much too low. This leaves the camera. It was found that focusing the CaF₂ singlet/ NaCl triplet group (the same group as the passive compensator) is best. Focusing the detector dewar would involve a heavy stage to cantilever the dewar with required stiffness. The singlet/triplet group has good focus sensitivity, and the end of the delrin spacer used for passive thermal compensation is conveniently available for a focus actuator. About ±250 μ motion of this group will suffice. The focus as a function of central wavelength for the five VPH gratings and for the Fabry-Perot is shown in figure 8.

5 Imaging Performance

Figure 9 shows the imaging performance of the system as designed, as a function of wavelength, for field angles 0 and 4 arcmin, and each of the five VPH gratings over the complete range of grating tilts. The temperature is 20 °C, at the warm limit of the nominal operating range. The panels on the left give the RMS image width at the detector of an infinitely thin slit oriented parallel to the spectrograph slit. The panels on the right give the RMS diameter of the spots for the same configurations. The bottom right panel shows the monochromatic imaging performance, appropriate to the Fabry-Perot mode of the instrument. The specification in the FPRD is shown as a thick red line. Note that the imaging is progressively better as the bandpass of the observation decreases, consistent with the dominant aberration of longitudinal color.
Figure 9. Design Imaging Performance
6 Coatings

For the fold flat, we propose to use the same LLNL multilayer coating that is to be used by the SALT SAC. This has roughly 95% reflectivity 320 - 900 nm. It is an extremely durable coating.

We propose to use three types of anti-reflection coatings for the refractive optics, depending on placement and exposure. Solgel is preferred. SolGel is a chemical coating producing a stack of 200Å pure silica spheres, having an effective index of refraction of 1.22. Used over a single layer of MgF₂ (n = 1.38), the single surface reflection can be less than 1% from 320 - 850 nm, degrading to no worse than 2% at 1.7μ. Durability concerns have held back the use of SolGel in astronomy, but efforts at DAO have developed them to the point that they are in use on several telescopes and are planned for use on Gemini. Figure 10 compares SolGel/ MgF₂ with MgF₂ and a conventional multilayer (the Spectrum Thin Films coating being considered by SALTICAM). The bottom panel shows the predicted transmission for the PFIS system using Solgel on all air-glass surfaces. A fallback, to be used on surfaces where it is determined that there is unacceptable risk of damage to the Solgel, will be to use MgF₂ on the surfaces common to the visible - NIR beams (possibly the field lens surface next to the focal plane, and the waveplate surfaces) and conventional multilayer coatings elsewhere, including the detector window).

7 Assembly Plan

7.1 Tolerances

The image quality budget allows a 10% increase of the image size due to uncompensated manufacturing errors and a 20% increase due to assembly errors. A preliminary tolerance analysis for manufacturing errors leads to the specifications in the following table:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Radii</td>
<td>±0.1%</td>
</tr>
<tr>
<td>Deviations</td>
<td>1/4 λ at 630 nm</td>
</tr>
<tr>
<td>Center thickness</td>
<td>±0.1 mm</td>
</tr>
<tr>
<td>Wedge</td>
<td>&lt; 30 arcsec</td>
</tr>
</tbody>
</table>
7.2 Element Manufacturing

The plan for fabrication is to obtain the optical blanks, figure the lenses, and coat the external surfaces in separate procurements. This will make it possible for the collimator and camera spherical surfaces, and the camera asphere to be figured in parallel by different manufacturers. Lick Observatory and Janos Technology responded to a preliminary Request for Proposal to procure blanks and figure a previous (all-spherical) design; figuring costs are approximately $160,000. The approximate delta for the asphere in the current design is $30,000, which is compensated for by the smaller number of surfaces. Blanks for the current design have been ROM costed at $120,000. The blank and figuring costs is therefore estimated at $280,000.

7.3 Opto-Mechanical

Internal surfaces in multiplets will be coupled with immersion oil. Lens holders for the NaCl triplets will be hermetically sealed; holders designed for the SOAR Goodman spectrograph NaCl triplets provide one of the starting designs.

The lens holders will be mounted in the aluminum camera and collimator housings. The camera and collimator tubes will be kept under a dry air purge to protect the coatings and the hygroscopic materials.

8 Risks

The following risks and mitigation plans have been identified

• Unacceptable cost growth. Descope the beam size and/ or the camera field of view.

• Insurmountable NaCl problems. Descope the wavelength coverage.

• Solgel coating problems. Replace coatings on surfaces common to the visible/ NIR beam with MgF₂. Replace other coatings with conventional multilayer coatings, descope the wavelength coverage if necessary.