

## **The Prime Focus Imaging Spectrograph: Design and Capabilities**

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**Abstract.** The Prime Focus Imaging Spectrograph (PFIS) will be the primary first-generation spectrograph for SALT. PFIS is a versatile instrument, specializing in high-throughput, low- and medium-resolution single- and multi-object spectroscopy and spectropolarimetry from 320 to 900 nm. This paper describes the optical and mechanical design of the instrument, highlighting its capabilities and expected performance.

### **1. Introduction**

The Prime Focus Imaging Spectrograph (PFIS) will reside at the primary focus, where it takes advantage of the direct access to the focal plane. The scientific niches that PFIS will exploit include: UV spectroscopy; long-slit and multi-slit high-throughput, medium-resolution spectroscopy; Fabry-Perot imaging spectroscopy; high-time-resolution spectroscopy; and spectropolarimetry. Ultraviolet spectroscopy is rare on large telescopes, and will be accomplished through the use of UV-reflecting coatings on SALT and high-throughput UV crystals in PFIS. A slit-mask mechanism at the SALT focal plane allows for long-slit and, taking advantage of the large SALT field, multi-slit observations. Dispersers include a complement of volume phase holographic (VPH) gratings, as well as a double etalon Fabry-Perot system. Additionally, PFIS will include polarimetric optics for spectropolarimetric observations, also very rare on large telescopes.

We present here the design philosophy and the resulting optical design and performance. The strict constraints on the PFIS system, including size, weight, and wavelength coverage resulted in a challenging design.

### **2. Optical Design**

#### **2.1. Design Goals**

There was a strong desire amongst members of the SALT consortium to have wavelength coverage to the atmospheric limit. Additionally, the capability for near-infrared observations was also desired. Given the space and weight constraints with having an instrument at prime focus, a single collimator is necessary with two cameras, one visible (320 nm – 900 nm) and one infrared (850 nm – 1.7  $\mu$ m). Only the visible camera has been designed, and it is described herein,

but its design was affected by the requirement of a viable upgrade infrared camera. Several factors drove the overall design philosophy. These are listed below.

- All transmissive optics for high efficiency and compactness. Gains in compactness are made by using transmission gratings and avoiding the wasted collimated beam space required with a reflective collimator. Also, a reflective camera would introduce vignetting after the polarizing beam-splitter, which greatly compromises polarimetric precision.
- Coverage 320 – 900 nm while maintaining a simultaneous IR beam (850 nm – 1.7  $\mu\text{m}$ ) upgrade path. This required the use of NaCl lenses, for good imaging and color correction of such a broad wavelength range.  $\text{CaF}_2$  and fused silica are the only other materials used in the design, for good ultraviolet throughput.
- 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

$$R = \frac{2 \tan \alpha d}{\phi D}$$

where  $\alpha$  is the grating tilt,  $\phi$  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<sup>1</sup>.

- Images  $\leq 0.30$  arcsec in the dispersion direction over the full wavelength range. The tightest imaging requirements are in spectroscopic mode with a reduced slit. 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. The specification is monochromatic: the design allows lateral color (about 1 arcsec currently), since it is assumed that broad-band imaging will be performed by the SALT scientific grade acquisition camera, SALTICAM (O'Donoghue et al. 2002).

## 2.2. Optical Layout

Figure 1 shows the optical layout of PFIS. The SALT SAC provides a flat, F/4.2, 8 arcminute diameter field of view focal plane. A mechanism attached to the PFIS structure will insert various long- and multi-slit masks into the beam at the focal plane. The field lens lies 10 mm behind the focal plane, after which there is a gap for the insertion of the  $1/2$  and/or  $1/4$  waveplates. For nonpolarimetric modes, a glass blank will be inserted to account for the optical path length of the waveplates. Following the waveplates is the main collimator assembly, which includes a NaCl triplet. A folding flat mirror redirects the beam  $90^\circ$  immediately before the final collimator doublet, after which is situated a Prontor shutter modified to a 150 mm aperture.

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<sup>1</sup>Similar arguments apply to the Fabry-Perot system, where  $d/D$  is the parameter fixing the angular size of the “bullseye”, where the wavelength is constant to within the etalon resolution.

After the shutter is the disperser area, in which either a rotatable transmission grating or the double-etalon Fabry-Perot system may be inserted. To allow for the use of the gratings at varying angles, the camera will be mounted such that it is allowed to articulate around an axis that coincides with the grating rotation axis. The grating will maintain a Littrow configuration, thus the camera articulation angle is twice that of the grating rotation, with a maximum articulation of 100 degrees.

The current camera design has 9 elements in 4 groups. The first element has an aspheric shape on the front exposed surface. The original design required all spherical curves for ease of design; however, the addition of an asphere allowed for the removal of an entire NaCl triplet. The added risk and cost of the asphere was deemed acceptable in light of the reduction of the number of optical elements, particularly NaCl, and the number of air/glass interfaces.

To compensate for image error introduced by possible differences in filter thicknesses and uncompensated thermal effects, the camera will have an active focus system. Focusing will be accomplished by moving the singlet and the triplet in the camera together. Additionally, the camera will need to be refocused for each configuration, as the imaging was not optimized for all wavelengths simultaneously. However, a fixed focus position can be set for each configuration. Then final focus error due to filters/thermal effects can be removed.

The efficiency of the “fixed” optics (those in the beam for all observations) should be between 75% and 80% across the entire wavelength range, based on estimates of the anti-reflection and mirror coatings. The final throughput of the system will be defined by this efficiency, the efficiency of the disperser and/or polarization optics, detector quantum efficiency, and SALT telescope throughput, which includes the effects of the SALT and SAC mirror reflectivities as well as the track efficiency.

### 3. Volume Phase Holographic Gratings

PFIS will have a complement of five volume phase holographic (VPH) gratings and one transmission grating. The gratings were chosen to provide spectroscopic capability over the entire wavelength range of the detector and resolutions from  $R = 500$  to  $R = 5500$  with a standard slit width. The advantage of VPH gratings is the high diffractive efficiency, low polarization effects, and significantly reduced scattered light (as well as other benefits) as compared to standard surface-relief gratings (Barden et al. 2000). Also, VPH gratings can be tuned to shift the diffraction efficiency peak to a desired wavelength.

The five VPH gratings have groove densities of 900, 1300, 1800, 2300, and 3000 lines/mm. Additionally, a surface-relief transmission grating with 300 lines/mm is added, primarily as a survey grating for large wavelength coverage over a large field of view when used with multi-slit masks. This was chosen because of the lower peak efficiency at low groove densities and extremely large blaze shift and poor efficiency at large off-axis angles for VPH gratings.

Figure 2 shows the grating efficiency, resolving power and wavelength coverage for the PFIS VPH grating complement. The resolving power indicated is for a filled 1.25 arcsec slit, sized appropriately for the median zenith seeing of 0.9 arcsec at the SALT site. Higher resolutions may be achieved by using a

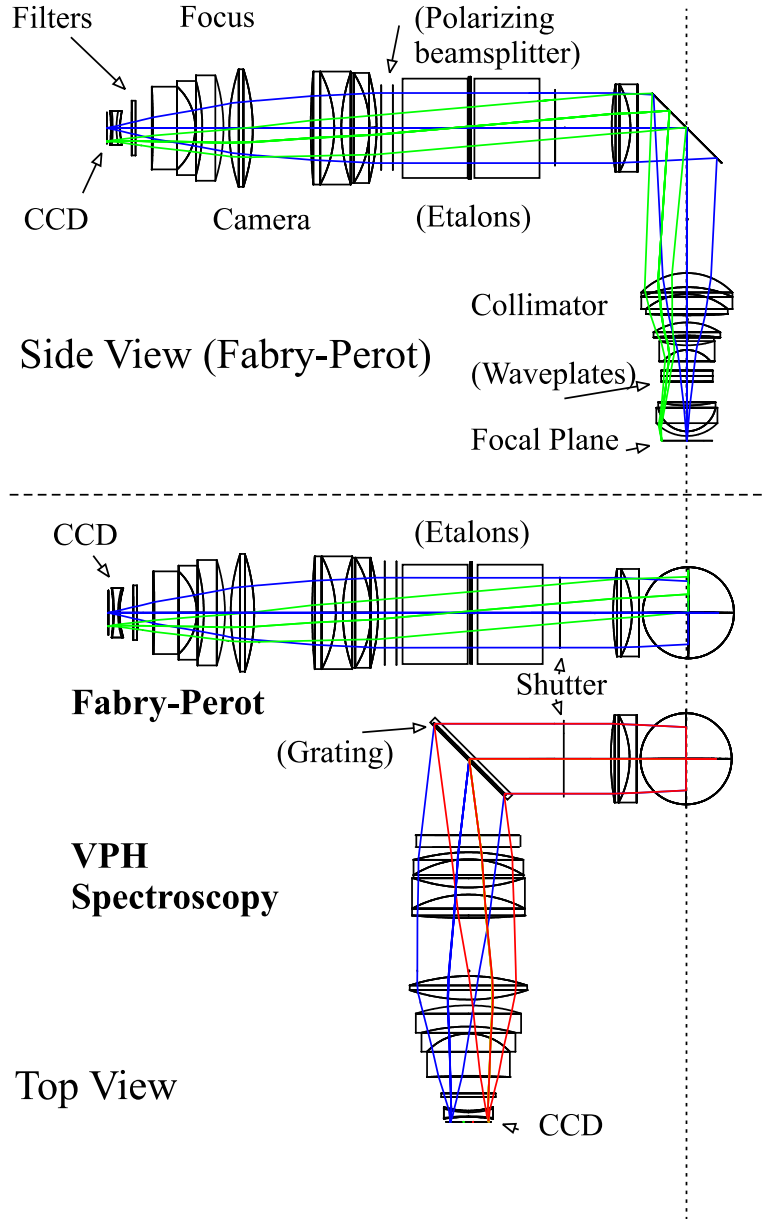


Figure 1. SALT/PFIS Optical layout. Above: Side view of optics layout in unarticulated (imaging) mode. On-axis and maximum off-axis (4 arcmin) rays are shown. Below: Top view, showing unarticulated (on-axis and 4 arcmin off-axis rays shown) and articulated (spectroscopy – two wavelengths shown) modes. Note that the articulation angle will vary for the various gratings and central wavelengths desired, tuning for the most efficient throughput. The maximum articulation angle is 100 degrees.

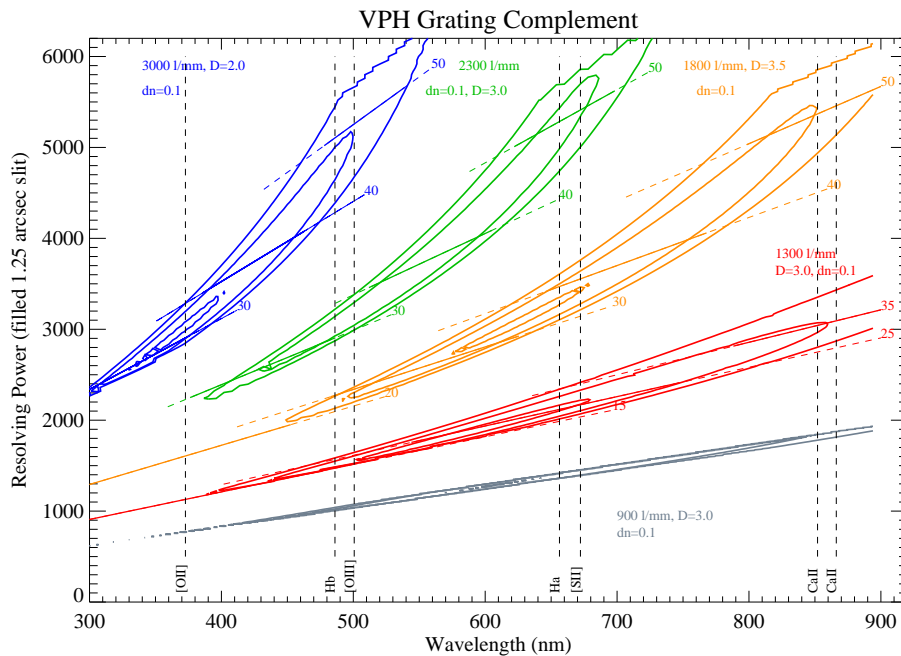


Figure 2. Grating efficiency, resolving power, and wavelength coverage for the PFIS VPH grating complement. Contours shown are the 90, 70 and 50% efficiency levels.

narrower slit, at the expense of throughput. Both the resolving power and the wavelength coverage are dependent on the grating rotation angle.

#### 4. Fabry-Perot etalons

PFIS will implement a double etalon Fabry-Perot (FP) system, the first on a large telescope, with resolutions from 500 to 12,500 over a full octave in wavelength. On a telescope the size of SALT, this provides a high dispersion, high spatial resolution diffuse-object capability with a net efficiency that exceeds slit spectroscopy by more than an order of magnitude, because the detector pixels are more efficiently multiplexed.

The system will have three spectral resolution modes: low ( $R = 500 - 1000$ , tunable), mid ( $R = 2500$ ), and high ( $R = 12,500$ ). Low resolution mode will use a single etalon, with an interference filter to select the desired interference order (corresponding to wavelength). The mid- and high-resolution modes will use two etalons in series, with the low-resolution etalon and its filter selecting the desired order of the mid- or high-resolution etalon, respectively. Only two of the three etalons will be installed at any time.

The spectral range of the FP system will be 430 nm to 860 nm. A potential future enhancement will be to add blue etalons and filters. Approximately 30 interference filters ( $R = 50$ ) will be required to isolate the FP orders over the entire spectral range. Fifteen of these will be installed in a removable magazine.

## 5. Polarimetric optics

Polarimetric observations will utilize a “wide-field” design, in which a polarizing beamsplitter in the collimated beam takes the central half of the field and splits it into two orthogonally polarized fields, the “ordinary” (O) and “extraordinary” (E) 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 is an array of calcite Wollaston prisms, inserted in the collimated beam just before the camera. This ensures there is no vignetting of the split beam, which would compromise the polarimetric precision. Also, by placing the beamsplitter after the dispersers, both the O and E beams have the same wavelength gradient in FP mode.

The modulator comprises two rotating superachromatic mosaic waveplates, a 100 mm  $\frac{1}{2}$  and a 60 mm  $\frac{1}{4}$  waveplate, near the beam waist in the collimator. This placement keeps it ahead of any optical elements with polarization sensitivity, like the fold mirror and the dispersers.

## 6. Detector

The detector is a mosaic of three Marconi/EEV 42-82 (2048x4096 15  $\mu\text{m}$  pixels) chips, for a total of 6144x4096 pixels (95x61 mm). For the F/2.2 camera, the pixels are 0.13 arcsec, so that the seeing disk is critically sampled for 2x2 binning, and a 0.5 arcsec slit is critically sampled for unbinned readout. The measured quantum efficiency of the three chips peak above 80%. They vary in UV sensitivity (ranging from 50% at worst to 80% at best at 350 nm) and thus will be placed appropriately in the mosaic to ensure maximum efficiency across the spectrum.

## 7. Summary

The Prime Focus Imaging Spectrograph, the primary first-generation instrument for the Southern African Large Telescope, will be a versatile spectrograph with several modes of operation. These modes and some science programs that will be performed to verify the commissioning of the instrument are described elsewhere in this volume (Nordsieck 2004). The optical and mechanical design of the spectrograph, as described above, allow for a compact, low mass, high-throughput instrument that will be well suited to the observing and operational constraints of SALT.

## References

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