Optical Design of the NASA-NSF extreme precision Doppler spectrograph concept WISDOM

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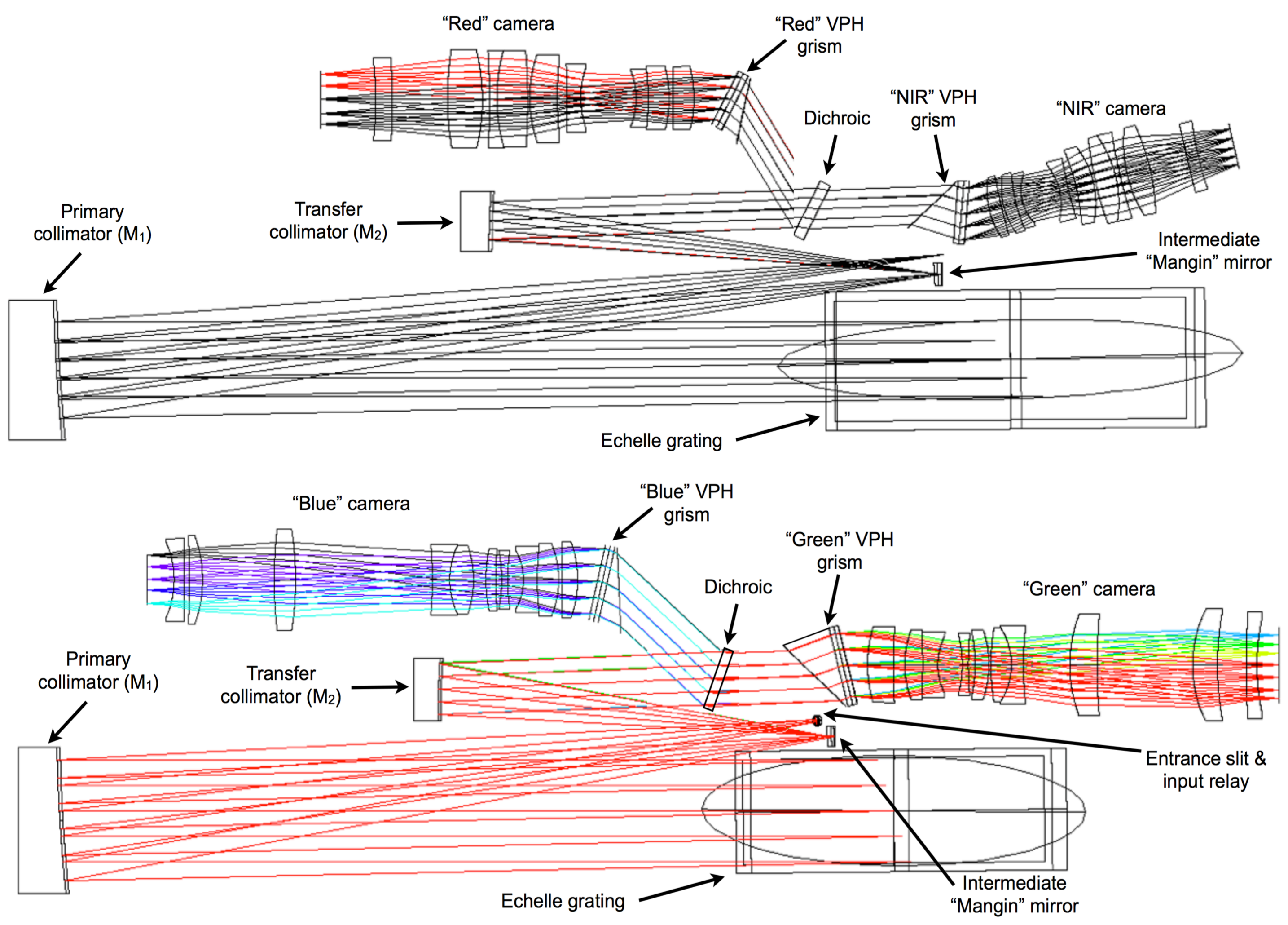
OVERVIEW

The WISDOM (**WI**YN **S**pectrograph for **DO**ppler **M**onitoring) instrument concept was developed at MIT as part of a NASA-NSF funded study to equip the 3.5m WIYN telescope with an extremely precise radial velocity spectrometer. (See talk/paper 9908-41 for more details.)

The spectrograph employs an asymmetric white pupil optical design, where the instrument is split into two nearly identical "Short" (380 to 750nm) and "Long" (750 to 1300nm) wavelength channels. Each channel further splits into two by a dichroic near the white pupil, resulting in a total of 4 cameras (Blue/Green/Red/NIR). Each of these channels has an anamorphic VPH grism for cross-dispersion, and a fully dioptric, highly telecentric, all-spherical camera objective.



The spectral footprints cover 4k x 4k / 6k x 6k CCDs with 15μm pixels in the Blue/Red and Green wavelength channels, respectively, while a HgCdTe 1.7μm cutoff 4k x 4k detector with 10μm pixels is to be used in the long wavelength NIR channel.

The echelle grating and beam sizes are R3.75/125mm and R6/80mm in the short and long channels, respectively. Together with the 6-way pupil slicer and octagonal to rectangular fiber combining/coupling, this permits resolving powers over R=120k with a 1.2" diameter aperture that assures high throughput of 12%, including atmosphere/telescope/slit loss/fiber link/spectrograph/detectors. (See posters 9908-281 / 9912-183 for the fiber run / pupil slicer description.)

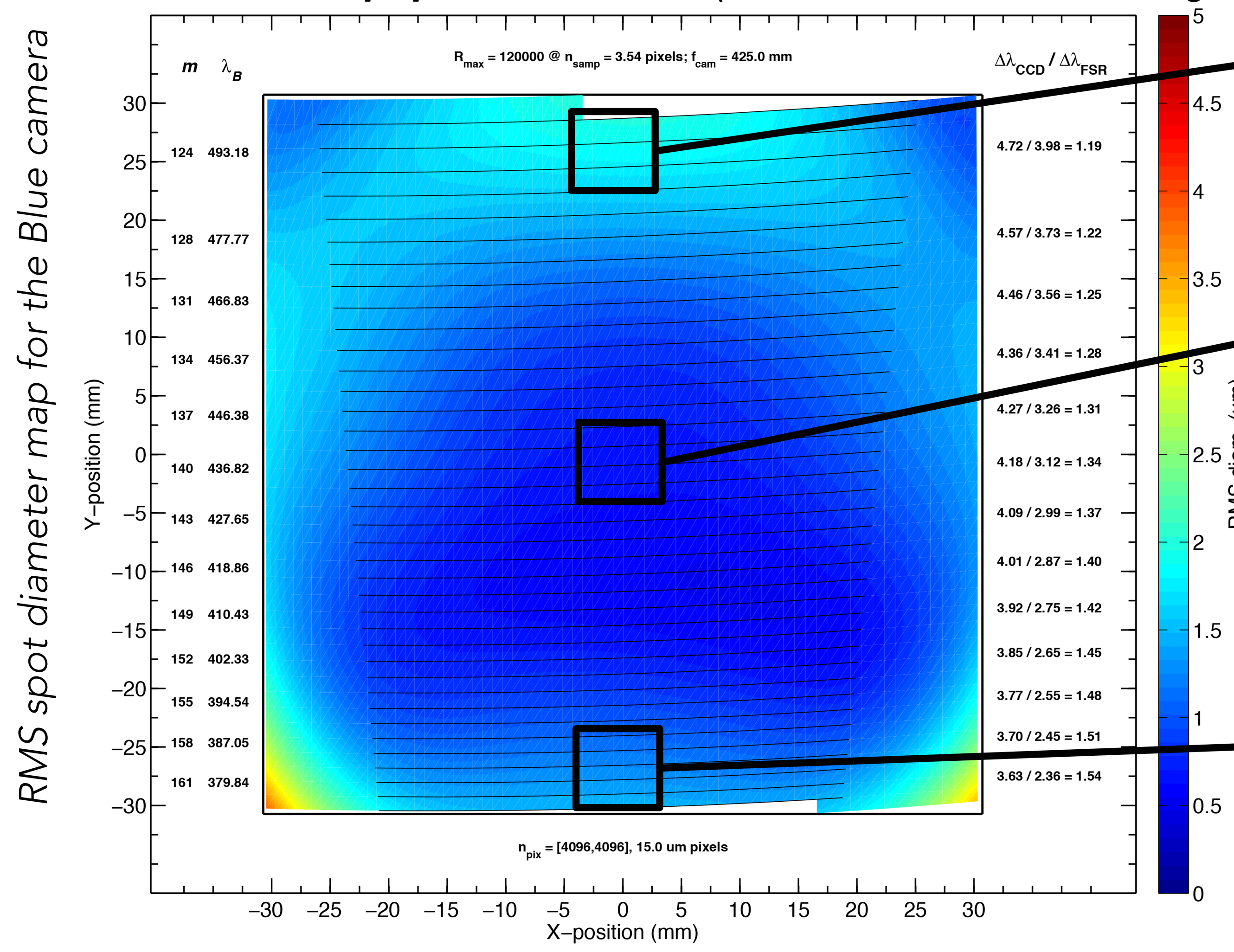
Table: Summary of the WISDOM spectrograph optical parameters

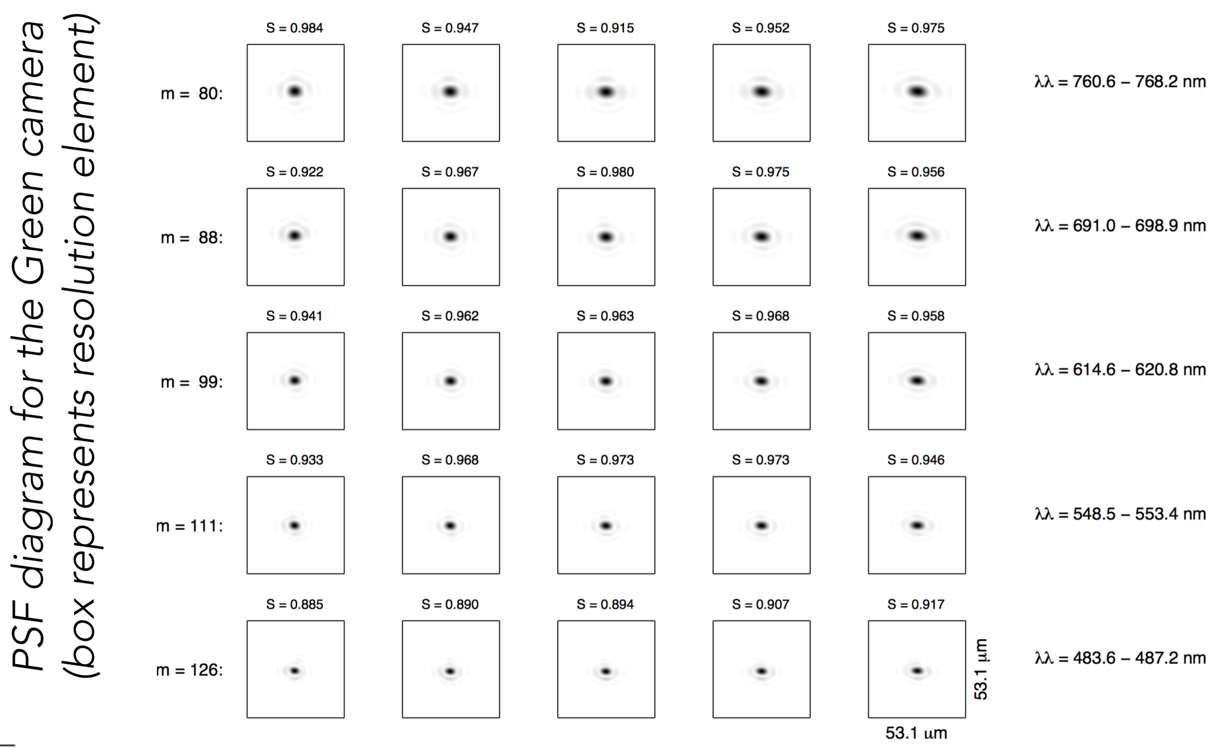
	Short wavelength channel (SWC)		Long wavelength channel (LWC)	
Channel:	"Blue"	"Green"	"Red"	"IR"
Wavelength range:	378.7–495.2 nm	483.4–769.2 nm	749.7–952.2 nm	934.2–1316.1 nm
Order numbers:	161–124, ($n = 38$)	126–80, ($n = 47$)	197–156, ($n = 42$)	158–113, ($n = 46$)
Resolving power:	$R = 120$k ($n = 3.54$ pixels)		$R = 120$k ($n = 3.50$ pixels)	
Beam size:	$B = 125$ mm		$B = 80$ mm	
Primary collimator:	$f_1 = 1000$ mm ($f/8$ OAP, $\theta = 6.5°$)		$f_1 = 1000$ mm ($f/12.5$ OAP, $\theta = 6.5°$)	
Echelle:				
Blaze angle:	$\theta_B = 75.1°$ ($R3.75$)		$\theta_B = 80.7°$ ($R6.11$)	
Line density:	$T = 31.6$ mm^{-1}		$T = 13.33$ mm^{-1}	
Ruled area:	130 × 400 mm		100 × 400 mm	
Mangin mirror:				
Glass, size:	S-FSL5, 25 × 120 mm		S-FSL5, 25 × 145 mm	
Thic., off-axis dist.:	$t = 8.7$ mm, $\Delta y \approx 21.5$ mm		$t = 8.7$ mm, $\Delta y \approx 21.5$ mm	
Secondary collimator:	$f_2 = 500$ mm, $k \approx -0.91$		$f_2 = 500$ mm, $k \approx -0.91$	
Cross-dispersing grisms:				
VPH line density:	1125 mm^{-1}	620 mm^{-1}	945 mm^{-1}	565 mm^{-1}
VPH AOI (cwl):	9.45°	7.35°	15.62°	12.19°
Prism glass:	S-BSL7	S-BSL7	S-BSL7	S-BSL7
Prism AOI	$\theta_i = 45.0°$	$\theta_i = 45.0°$	$\theta_i = 45.0°$	$\theta_i = 50.0°$
Prism apex angle:	$\alpha = 27.6°$	$\alpha = 27.8°$	$\alpha = 27.9°$	$\alpha = 30.6°$
Anamorphic factor:	$B_{out}/B_{in} = 1.25$	$B_{out}/B_{in} = 1.25$	$B_{out}/B_{in} = 1.08$	$B_{out}/B_{in} = 1.31$
Cameras:				
Focal length:	$f_{cam} = 425.1$ mm	$f_{cam} = 425.1$ mm	$f_{cam} = 258.2$ mm	$f_{cam} = 172.1$ mm
Focal ratio (X):	$f/D_x = 6.8$	$f/D_x = 6.8$	$f/D_x = 6.5$	$f/D_x = 4.3$
Focal ratio (Y):	$f/D_y = 5.5$	$f/D_y = 5.5$	$f/D_y = 6.0$	$f/D_y = 3.3$
Detector:				
Type:	CCD	CCD	CCD	H4RG
Format (approx.):	4096 × 4096	6144 × 6144	4096 × 4096	4096 × 4096
Pixel size:	15 μm	15 μm	15 μm	10 μm

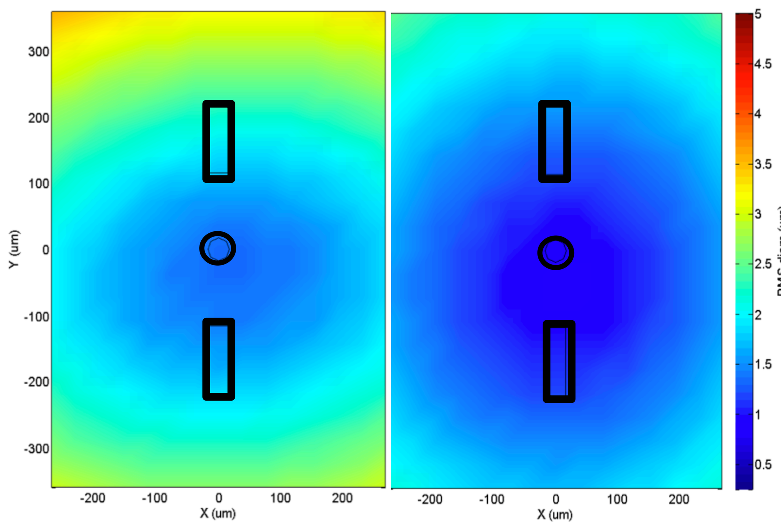
NOTABLE DESIGN ELEMENTS

The white pupil relay includes a ***Mangin mirror*** very close to the intermediate focus to correct the Petzval curvature o white pupil relay before it is swept into a cylinder by the cross-dispersers. This design decision allows that each dioptric ***cameras can be fully optimized and tested independently of the rest of the spectrograph***. Ghosts of the Mangin mirror are mitigated by the wedging/tilt of the surfaces.

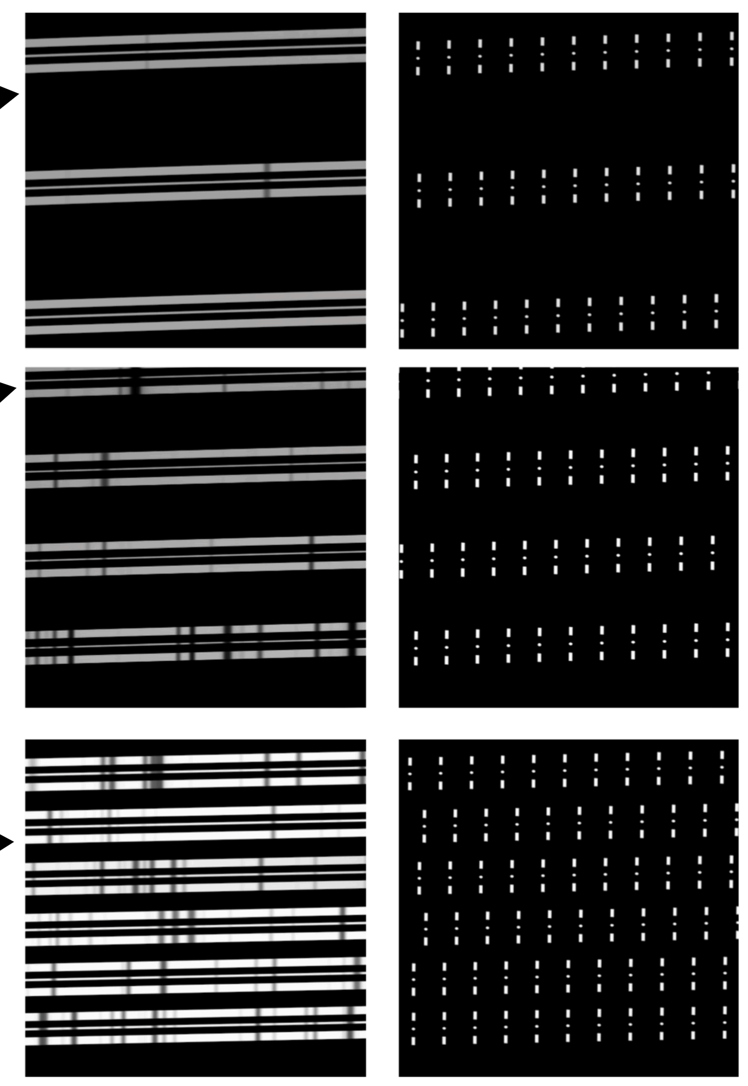
The cameras deliver ***very high and uniform image quality*** (diffraction limited), with a design philosophy and tolerancing that ensures it remains true for the *as-built* cameras as well, across all wavelengths. By design optimization we also ***eliminated sensitivity of spot centroid locations to variations in the pupil illumination***. *(See more below, bottom right.)*







The Mangin mirror allows for a longer slit, with more uniform image quality along the slit. If a flat fold is used with a cylindrical lens, the image quality, averaged over the entire echellogram (color coded), is better for a fiber at the center of the slit (left panel). With the Mangin mirror (right) a longer slit or more fibers (rectangles) produce the same image quality as the slit center.



Using the EchMod package (Barnes, 2012) we simulated the spectra for a solar type star, a ThAr and an etalon calibrator. *The anamorphic cross dispersers, the splitting into multiple channels, the careful balancing of wavelength split points result in a* ***very generous inter-order spacing*** even at the densest part of the echellogram. The 6 fibers of the pupil slicer are grouped into two sets of 3 and coupled into two rectangular fibers, forming the top and bottom trace of the slit, while a single fiber between them serve as a simultaneous calibrator. Note the ***absence of slit tilt across the entire echellogram***, that is also a feature per design and it allows for binning in cross dispersion without degrading spectral resolution.

The WISDOM instrument employs a non-circular fiber feed and optical double scrambler to stabilize the pupil illumination within the spectrograph. Similarly to recent PRV instrument designs (G-CLEF, CARMENES, etc.) the cameras themselves have been optimized to eliminate systematic RV errors that arise due to small changes in pupil illumination not eliminated by the scrambling within the fiber link. However, we found that ***while it is possible to prescribe an ideal optical system insensitive to variations in the pupil illumination, but a realistic "as-built" system can easily loose that precious property***. Selecting equally performing (e.g. based on the usual RMS spot size criteria) model realizations from a pool of Monte-Carlo simulated realistic cameras we have shown that systematic RV offsets at the m/s level can occur for as small as 1% pupil illumination variation, even when using relatively tight manufacturing/alignment tolerances.

The ***optical layout was carefully developed*** so the instrument can be ***packaged into a compact***, cylindrical vacuum vessel for environmental control. The high level of symmetry allows for ***a vertical, planar optical bench***, that is well balanced. The multiple detectors and mirrored symmetry allow for identification of instrumental RV erros.