Vector Spectromagnetograph



1. Introduction

The Vector Spectromagnetograph (VSM) is responsible for taking high-quality magnetic field observations in the photosphere and the chromosphere by recording the Zeeman-induced polarization of spectral lines as well as a proxy of coronal structures.

The VSM operates in four different observing modes at three different wavelengths. The four observing modes are:

- 1. Stokes I, Q, U, and V profiles in the FeI 630.15 nm and 630.25 nm lines
- 2. Stokes I and V profiles in the FeI 630.15 nm and 630.25 nm lines
- 3. Stokes I and V profiles in the CaII 854.2 nm line
- 4. Stokes I in the HeI 1083.0 nm line and the near-by SiI line

The CaII 854.2 nm and the HeI 1083.0 nm lines were chosen to provide a continuing record of the current data set from the KPVT. To measure vector magnetic fields outside sunspots in the visible part of the spectrum, it is indispensable to observe at least two spectral lines with different Land³/₄ factors. The FeI 630.15 and 630.25 nm lines were chosen because they are the most appropriate lines to measure vector magnetic fields in quiet as well as active regions. Other often used lines such as the FeI lines around 525.0 nm are hampered by molecular blends in sunspots. Furthermore, the Advanced Stokes Polarimeter (ASP), an instrument that delivers precise vector field measurements, has used the FeI lines at 630.2 nm, and the analysis tools have already been developed for this line pair.

The major improvement over the currently produced data sets from the KPVT are the precise vector polarimetry, which allows the derivation of the true magnetic field vector as compared to the current longitudinal flux measurements.

2. Specifications

The following table (Table 1) shows the specifications for the VSM. Items in italic (bold face) indicate improvements (reductions) over the specifications listed in the proposal.

Parameter	Specification	Comment	
Angular			
Element	1.00 by 1.00 arcsec		
coverage	2048 by 2048 arcsec	Slightly larger than full disk	

format	2048 by 1	Proposal specified 2000 by 1		
geometric accuracy	better than 0.5 arcsec rms	After remapping		
instrumental mtf	measurable to ± 0.01			
total mtf	<0.1 at frequencies greater than Nyquist			
motion in RA	± 0.25 degrees	Added for flatfielding		
Temporal				
scan rate	0.05-5.0 s/arcsec	to provide fast or very accurate longitudinal magnetograms		
duty cycle				
timing accuracy	better than 1 s			
knowledge of start and end of integration at each slit position	better than 1ms	For comparison with other data and accurate remapping		
frequency	less than 20 minutes for full disk less than 2 minutes for active region	For accurate polarimetry		
full-disk longitudinal with reduced sensitivity	less than 2 minutes	To provide fast magnetograms with VSM instead of FDP		
Spectral				
spectral lines	630.1515, 630.2507 nm, 854.2089 nm, 1083.0 nm	Selected suitable spectral lines		
spectral resolution	200,000			
wavelength range	630.1515-0.05 nm to 630.2507+0.05 nm 854.2 +/- 0.1 nm 1083.0 +/- 0.5 nm	Were unable to design efficient instrument over full range of 600 to 1600 nm		
spectral lines	at least two simultaneously			
Polarimetry	···	·		

Туре	630.2 nm: I,Q,U,V 854.2 nm: I,V 1083.0 nm: I	Analysis of vector polarimetry in 854.2 nm not clear, traded wider spectral range in 1083.0 nm for polarimetry
sensitivity	0.0002 per pixel in 0.5 s	
relative accuracy	0.001	
Miscellaneous		
image motion stabilization	at about 100 Hz	To improve spatial resolution
cloud	detection at user- specified level	
real time seeing monitoring		For information only
interruption of scanning during and continuation after clouds		

Table 1: VSM Specifications

3. Concept

3.1 Challenges

The design of the VSM faced many challenges. In particular, the following requirements have made the design effort very demanding:

- compact instrument no longer than 2.5 m
- athermal optical design to keep instrument at ambient temperature
- high guiding accuracy of better than 0.5 arcsec rms
- low instrumental polarization of less than 1*10⁻³
- large wavelength range from 630 nm to 1090 nm with constant magnification
- high spectral resolution of about 200,000
- highest possible throughput
- high energy densities of up to 20 W/cm^2
- high data rate of up to 300 Mbyte/s

3.2 Overview

The following figure (Figure 1) shows an overview of the main components of the VSM. Note that only one of the two symmetrical reimaging systems is shown.

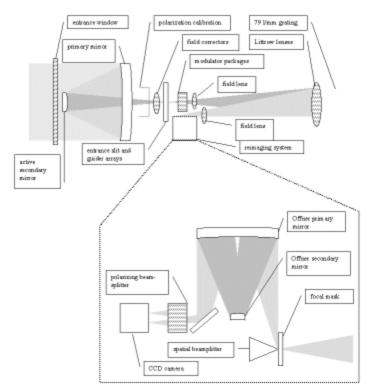


Figure 1: Overview of VSM Main Components

3.3 Telescope

An initial transmission budget for the complete optical system indicated that a 50-cm aperture telescope with a 10% obstruction is sufficient to achieve the required polarization sensitivity. Therefore, the aperture was fixed at effectively 50 cm. To match the CCD pixel size of 16 μ m per pixel (=1 arcsec) an f/6.6 is required.

The telescope does not need to be diffraction limited. It is a 50-cm quasi Ritchey-Chrétien with a two-lens field corrector to provide adequate image quality over the whole field of view, minimal geometric distortion, equal image size for all wavelengths, and a more or less telecentric beam to minimize field of view effects in the polarization modulators. We have tried Gregorian and Schmidt-Cassegrain optical setups, but we were unable to achieve optical performances close to what the quasi-RC approach provides.

The entrance window minimizes contamination of the optics and allows us to fill the whole instrument with helium to minimize internal seeing. It is slightly wedged and anti-reflection coated to minimize fringes. The window thickness is 6 mm to minimize its influence on the polarization measurements. For the same reason, fused silica was chosen over other materials (see the section on polarimetry). The window is also substantially oversized because aberrations and polarization effects are mostly concentrated at the window edge, outside the clear aperture in our case.

The primary mirror is made of ULE to minimize temperature-induced aberrations. It is coated with overcoated silver.

The secondary mirror is made of single crystal silicon. Regular glass-based mirrors with their low thermal conductivity would lead to large thermal gradients within the mirror substrate and therefore to intolerable optical aberrations. A fan system circulates the helium in such a way that the secondary mirror is cooled. Tests have shown that the temperature gradients within the secondary mirror and temperature variations do not lead to significant aberrations.

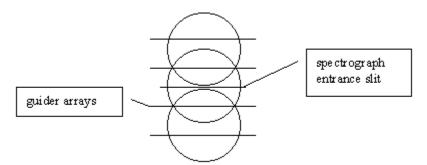
The secondary mirror will be active (tip/tilt) to remove image motion due to seeing and telescope shake and have a focusing mechanism to provide the best focus at all times.

Helium filling was chosen because it provides about the same amount of convective cooling while leading to about 10 times less seeing for a given temperature difference.

3.4 Entrance Slit and Guiding Arrays

The requirements of low instrumental polarization and high guiding accuracy has led to an innovative design of the entrance slit area. Four linear arrays are cofocal and parallel to the entrance slit and provide an accurate guiding signal to the secondary mirror tip/tilt system and the mount. Since the entrance slit and the guiding sensors are in the same focal plane, no differential guiding errors will occur as is so often the case when the guiding and the entrance slit are in different focal planes. And the absence of a beam-splitter to provide a separate focal plane for guiding reduces the amount of instrumental polarization at the location of the entrance slit.

The guider arrays will be read out at about 200 Hz. The location of the limbs will provide the solar disk position, the sharpness will provide a measure of focus position and seeing, and the light level indicates sky conditions. The guider electronics generates two encoder signals that can be used to determine a relative position in relation to a home position. The guider also generates two analog signals that describe the intensity of the image and the sharpness of the limb. The following figure (Figure 2) shows the conceptual layout of the guider and slit area with indications of the solar disk centered on the slit and at the extreme positions. The position of the guider arrays has been optimized to maximize the guiding accuracy.





The fast beam will lead to an energy density of about 20 W/cm² in the focal plane. Instead of trying to reflect the beam from the slit plate, we will absorb the energy there on a cooling plate made out of a copper-aluminum oxide composite that is often used for high-energy laser mirrors. This plate will absorb most of the energy that does not go on to the guider arrays or the spectrograph entrance slit. The guider arrays will be covered with reflective neutral density

filters to reduce the light to acceptable levels. The neutral density filter coating will be applied to glass filters that transmit a limited spectral range. This provides better image quality on the guider arrays as compared to the full spectrum.

3.5 Spectrograph

The entrance slit covers an area of 2048 by 1 arcsec (16μ m). There are four modulator packages behind the slit for the four different observing modes. A field lens focuses the telescope pupil close to the grating. The entrance slit is curved to compensate for a 26-pixel spectral line curvature. This curvature will be removed during data processing. The spectrograph is a Littrow arrangement with a doublet lens. Focussing of the spectrograph for different wavelengths is accomplished by longitudinal motion of the Littrow doublet. The grating is a Richardson Grating Laboratory Echelle with 79 grooves/mm, 63.5 degree blaze angle, a 204 by 408 mm ruled area, and a an efficiency of about 50%. Purely static mechanical structures will not be able to keep the grating stable enough. Therefore, there will be active positioning of the grating controlled by error signals generated by the CCD in the final focal plane.

3.6 Reimaging

Since we were not able to find CCD cameras that would cover the full length of the slit with 2048 pixels, there will be a focal beam-splitter in the spectrograph focal plane that splits the focal plane perpendicular to the spectral lines into two parts, each of which is 1024 arcsec long.

A system with a polarizing beam-splitter requires a mask in the focal plane that limits the area that falls onto the detectors. Otherwise, the two polarization states would overlap on the detectors. The fast f/6.6 beam does not allow us to have the focal mask and the polarizing beam-splitter close enough to the focus. Therefore, a reimaging system is required. The focal mask and the focal beam-splitter are put into the spectrograph focal plane, which is reimaged with an Offner system that provides achromatic one-to-one reimaging with good field properties. The polarizing beam-splitters are located just in front of the CCD cameras. They are described in more detail in the section on polarimetry.

3.7 CCD Cameras

To achieve a high signal-to-noise ratio (SNR) in a short time, the CCD cameras must be able to read out at a high frame rate. In addition, the modulation frequency, and therefore the read-out frequency, must be faster than typical correlation times of seeing. While the SNR considerations pushed for a frame rate of 300 Hz, this is also a good rate to minimize the influence of seeing.

Of course, the CCDs should have the highest possible quantum efficiency and a read-out noise that is significantly below the photon shot noise. Since the development of a single 2048 by 256 pixel CCD was deemed to be too risky, the VSM will use two 300 frame/s 1024 by 256 pixel frame transfer CCD cameras developed by PixelVision. They have a quantum efficiency of more than 80% at 630 nm, 16 μ m square pixels with well depths of 200,000 electrons, and a read noise of less than 35 e rms. Linearity is specified as better than 1%. The sensitive area is split into into two halves. Each is transferred in to separate 128 by 1024 frame buffers. Each half has 8 readout

channels running at 5 MHz. The observing scheme is based on making an unshuttered 3.3 ms exposure of the two orthogonally polarized spectra, transferring the exposure to a storage area in less than 0.15 ms, and reading out the two images during the next 3.3 ms exposure with 16 parallel channels at 14 bits. The state of the modulator will be switched during the transfer interval every 3.3 ms.

3.8 Data Acquisition

Each of the 32 channels from the two CCD cameras delivers its data via fiber optical links to an image acquisition system. This system will add up frames in buffers according to the states of the polarization modulators. For the 630.2 nm vector mode, there will be four buffers, the longitudinal modes will have two, and the 1083.0 nm mode will have single buffer. At least 8 frames need to be summed to reduce the initial 300 Mbytes/s to less than 40 Mbytes/s. At this reduced data rate, the accumulated data can be sent directly to the data storage system.

4. Science Capabilities

The VSM provides the following core science data products:

- 1. photospheric full-disk vector-magnetograms using the FeI 630.15 and 630.25 nm lines (field strength, azimuth, inclination, flux, Doppler velocity, continuum intensity)
- 2. chromospheric full-disk magnetograms using the CaII 854.2 nm line (line-of-sight magnetic flux, Doppler velocity, line core intensity)
- 3. full-disk HeI 1083.0 nm line characteristics (equivalent width, continuum intensity, Doppler velocity, line depth, line asymmetry, Doppler width, Si line width, Si line depth, Si Doppler velocity)
- 4. photospheric full-disk longitudinal magnetograms using the FeI 630.15 and 630.25 nm lines (line-of-sight magnetic flux)

Data products 1) to 3) are produced three times a day while data product 4) will be produced once a day. Users may observe the same or subsets of these products such as vector-magnetograms of active regions at high cadence or HeI 1083.0 nm equivalent width measurements of selected areas.

5. Mechanisms

The VSM contains many mechanisms that need to be controlled. Table 5.2 gives an overview over all mechanisms used by the VSM except for the mount axes. Most of the mechanisms are considered passive because they are moved only between observations. The secondary tip/tilt and the grating tip/tilt mechanisms are considered to be active mechanisms because they move throughout an observation. In the following we describe every mechanism and its functionality. Table 5.2: Current list of mechanisms in the VSM

5.1 Declination Axis

5.1.1 Position

The position of the declination axis and the tip angle of the secondary mirror determine the position of the entrance slit on the solar disk. The position of the declination axis is controlled in such a way that the average tip angle of the secondary mirror is zero.

5.1.2 Scan Rate

To achieve the scanning in declination, the declination axis is moving at a constant scan rate while the fast tip/tilt mechanism of the secondary mirror moves in such a way that the slit makes a stop/go motion. The number of integrations determines the scan rate.

5.2 Right Ascension Axis

The RA axis can be in two states: either it is tracking the right ascension of solar disk center or it is in a flat-field mode where the solar disk drifts in the RA direction to provide a good flat-field for the VSM.

5.3 Window Cover

The window cover is a two-position mechanism located in front of the telescope entrance window. The window cover can either be in an open or closed position. Whenever the telescope is pointing at the sun, and weather permits, the cover should be open, even if no observations are currently performed. This assures that the entrance window is not undergoing rapid changes in its response to environmental factors such as heating due to sunlight and cooling due to wind.

In general, the window cover is opened when the SOLIS facility unstows and closed when the facility stows at the end of the day or for bad weather.

5.4 Secondary Mirror

5.4.1 Focus Position

The axial position of the secondary mirror is the only mechanism that can be used to focus the telescope. Focussing is required whenever the wavelength changes and due to temperature changes of the structure connecting the secondary and the primary and the temperature of the optics itself. There will be look-up tables that tabulate the position for the three wavelengths and the correction term for the temperature. There will be a focussing procedure where the secondary mirror is moved axially and the guider system evaluates the image sharpness at each focus position to determine the optimum secondary mirror position for a given configuration.

5.4.2 Fast Guiding Parameters

The tip/tilt secondary mechanism provides two degrees of freedom for the secondary mirror. The mechanism allows the image to move rapidly in both declination and right ascension to correct for seeing and tracking errors. The tip/tilt mechanism is active throughout an integration, unlike most other mechanisms. The tip/tilt system can be in two states. Either it responds to error signals from the guider system or it is not moving and stays in its nominal home position.

5.5 Calibration Mechanisms

The calibration mechanism uses three motors to control the position of the calibration optics. The optical elements can be positioned before an observation to perform one of a number of calibration observations.

5.5.1 Position

The polarization calibration mechanism has four positions: empty, closed, 630.2 nm, and 854.2 nm. The empty position transmits light for regular observations and the closed position is used to measure dark current. The 854.2 nm position contains a fixed assembly consisting of an interference filter, a polarizer, and a quarter-wave plate at 45 degrees with respect to the polarizer, all optimized for 854.2 nm. The 630.2 nm position contains two rotating mechanisms described below.

5.5.2 Angles of 630.2 nm Polarizer and Quarter-Wave Plate

The polarization calibration for the vector polarimetry in 630.2 nm is performed by two rotating mechanisms. The first holds an interference filter and a polarizer while the second one contains a quarter-wave plate. Both assemblies can be rotated independently of each other. For polarization calibrations, they will be moved to about 16 different combinations to determine all the unknown polarization parameters. For each combination, several frames are added to obtain calibrations with adequate signal-to-noise ratios.

5.6 Modulator Changer

The modulator mechanism provides a combination of interference filters for order separation, ferro-electric liquid crystal (FLC) switchable retarders and quarter-wave retarders for each of the three polarization observing modes, namely 630.2 nm vector and 630.2 nm longitudinal as well as 854.2 nm longitudinal. For 1083.0 nm an interference filter followed by a piece of glass (to compensate for the optical path length difference introduced by the modulators) is inserted. The modulator mechanism moves to one of the four positions before an integration starts.

5.7 Littrow Lens

The Littrow lens is a simple mechanism that moves the doublet to focus the spectrograph for changes in wavelength. The Littrow lens moves to a calibrated position for each of the observable wavelength. It also adjusts this position slightly for changes in ambient temperature through a look-up table.

5.8 Grating

The grating mechanism is a two-axis mechanism that provides movement in spatial and spectral directions. The coarse grating position is selected before the observation by the requested wavelength. Data from the detector is processed by the VSM detector controller to determine a finer adjustment in both axes for camera alignment errors due to flexure and temperature.

5.8.1 Rotation axis

The major movement in this axis done to tune the grating to the correct position for the three wavelengths. Fine adjustments will be made during the course of an observation to keep the spectral lines in a fixed position during the course of an observation. At 630.2 nm and 1083.0 nm we expect to monitor the position of the telluric lines while for 854.2 we will use the wide CaII line itself. Note that the average position of any solar spectral line is not much influence by the solar rotation because the slit is parallel to the declination axis.

5.8.2 Tilt Axis

Since purely static mechanical assemblies are not able to keep the grating tilt angle stable enough to avoid motion of the spectra in the spatial direction on the CCD cameras, the tilt axis can be controlled with a piezo. Demanding that the position of the two solar limbs is symmetric with respect to the optical axis generates the error signal.

5.9 Focal Plane Mask

The polarimetry at 630.2 nm and 854.2 nm requires that a field mask is placed in the focus to limit the spatial extent of the images to avoid overlap of the two images produced by the polarizing beamsplitter. Since no polarimetry is performed at 1083.0 nm and a large spectral range is advantageous for the data analysis, the mask needs to be removed for observations at that wavelength. The focal mask is a two-position. The mask moves to its half-size position for 630.2 nm and 854.2 nm, and to its full-size position for 1083.0 nm. The mask moves only between observations and when required for a new configuration.

5.10 Polarizing Beam-Splitter

For optimum performance, each wavelength has its own polarizing beam-splitter in front of the camera (630.2 nm, 854.2 nm), and a glass block for 1083.0 nm. Whenever the wavelength is changed, the appropriate beam-splitter needs to be inserted. The beam splitter mechanism selects the correct beam splitter for an observing wavelength by moving to one of three positions. The mechanism moves only between observations and when required by a new configuration.

6. Observation Types

The VSM can record data in various modes, also called observation types. The following sections give a brief overview of the different types.

6.1 Scanning

The VSM can scan in the four modes mentioned above: 630.2 nm vector, 630.2 nm longitudinal, 854.2 nm, and 1083.0 nm. The entrance slit is stepped over the solar disk while data is recorded at each slit position using four, two, or no modulation states.

6.2 Dark-Current Calibration

The calibration mechanism blocks the beam while data is recorded.

6.3 Flat-Fielding

There will be two different flat field modes. While removing small-scale flat-field features is reasonably easy to do by averaging the spectra over an area scanned across the sun, the large-scale features in the flatfield are not easy to obtain. By splitting up the flat-field procedure into two different procedures, we should be able to derive a good flatfield for all spatial scales. Flatfields are done separately for the four observing modes.

6.3.1 Drift-Scan Flat-Field

An excellent flatfield can be obtained by moving the slit in right ascension only. If there would be no spectrograph slit curvature, this would ensure that every point along the slit sees (on average) exactly the same intensity distribution. This is the same procedure as is currently used successfully at the KPVT. Tests at that telescope have shown that the spectrograph slit curvature does not lead to a substantial degradation of the flatfield. To obtain this type of flatfield, the VSM must have control over the RA axis, which prevents the other instruments from taking data.

6.3.2 Scanning Flat-Field

To obtain a flat-field calibration that is good at least on the small scales, we will scan a small area near disk center while accumulating frames. This average spectrum should provide a good flatfield for the small spatial scales. This technique has been used successfully by many people to accurately calibrate intensity spectra.

6.4 Polarization Calibration

The three different observing modes that rely on polarimetry each have their own associated polarization calibration. Either the 630.2 nm or the 854.2 nm units are moved into the beam. In the case of the 630.2-nm vector calibration, the polarizer and the waveplate are rotated with respect to each other and with respect to the entrance slit while data are recorded at each rotational position.

6.5 Focusing

To empirically determine the correct focus position, the secondary mirror is moved while the sharpness information from the guider is recorded. From this data, the optimum position of the secondary mirror with respect to the image sharpness can be determined.

7. Observing Parameters

A user of the VSM has several parameters to play with. The following sections outline these parameters as they are currently envisioned and that are unique to the VSM.

7.1 Observing Mode

There are four possible choices: 630.2 nm vector, 630.2 longitudinal, 854.2 nm, and 1083.0 nm.

7.2 Number of Scans

A user can request the number of scans to be performed within a given area and one of the four modes.

7.3 Start Time of First Scan

The start time of the first scan can be requested. This time may also be given as a time interval to give the scheduler more flexibility in scheduling observations from different users.

7.4 Start Times of Subsequent Scans

If the number of start times is more than one, the start times of subsequent scans can be requested relative to the previous scan. Subsequent scans are either started as soon as the previous scan is finished or at a fixed time interval between two adjacent scans.

7.5 Scan Area

The area to be scanned can be limited either in geocentric or heliocentric coordinates. Since we are scanning in geocentric north-south direction, heliographic coordinates need to be converted into an equivalent rectangle in geocentric coordinates that completely include the rectangle in heliographic coordinates. It would be nice to have an interactive region-of-interest selection capability using a recent magnetogram, H α or similar full-disk.

7.6 Number of Frame Groups Per Spatial Step

This number determines the number of groups of frames that are accumulated at each spatial position of the spectrograph slit. The 630.2 nm vector mode has four frames per group, the two longitudinal modes have 2 frames per group, and the HeI 1083.0 nm mode has one frame per group. At least 8 frames must be accumulated. The number of frame groups determines the scan rate in declination.

7.7 Maximum Wait Time for Clouds

Since a VSM observation may take up to an hour or so for a single scan, it should be possible to stop a scan due to clouds and then resume it after the clouds have passed. The user should be able to set a maximum wait time. If the wait time for clear skies is longer than the requested maximum wait time, the observation is stopped completely.

7.8 Data Reduction

The user should have the possibility to limit the data products from the given set of possible data products (discussed below) and request either a quick-look reduction and/or a final, accurate reduction.

8. Photon Budget

The following table (Table 3) provides the photon budget for the current optical configuration and the currently known or estimated transmission and reflectivity values. It is clear from this estimate that the product of the camera read-out rate and the full-well depth of the CCD limits the signal-to-noise ratio for polarimetry. The expected noise is very close to the one listed in the specifications.

Quantity	Wavelength (nm)			Units	Comment
	630.2	854.2	1083		
Solar flux in continuum	175	101	63.2	erg/cm ² /A	from Allen
Photon energy	3.15E-12	2.33E-12	1.83E-12	erg/photon	
Atmospheric transmission	0.86	0.95	0.97		approx. 7000ft
Primary diameter	50	50	50	cm	effective diameter
Central obscuration diameter	15.6	15.6	15.6	cm	this is the stop
Effective aperture	1772.361	1772.361	1772.361	cm ²	
Surface	Transmission/reflectivity				
Entrance window	0.965	0.961	0.954		fused silica and MgF ₂
Primary mirror	0.980	0.970	0.980		protected silver
Secondary mirror	0.980	0.970	0.980		protected silver
Corrector lens 1	0.990	0.990	0.960		
Corrector lens 2	0.990	0.990	0.960		
Interference filter	0.800	0.850	0.850		Barr quote
Modulator	0.884	0.940	0.990		no surface losses
Field lens	0.980	0.980	0.980		
Folding mirror	0.980	0.970	0.980		
Littrow lens 1	0.980	0.980	0.980		
Littrow lens 2	0.980	0.980	0.980		
Grating	0.570	0.550	0.540		Richardson measured
Littrow lens 2	0.980	0.980	0.980		
Littrow lens 1	0.980	0.980	0.980		
Folding mirror	0.980	0.970	0.980		
Field lens	0.980	0.980	0.980		
Field corrector	0.980	0.980	0.980		

Beamsplitter	0.980	0.970	0.980		protected silver
Offner primary mirror	0.980	0.970	0.980		protected silver
Offner secondary mirror	0.980	0.970	0.980		protected silver
Offner primary mirror	0.980	0.970	0.980		protected silver
Folding mirror	0.980	0.970	0.980		protected silver
Cylindrical lens	0.980	0.980	0.980		
Calcite beamsplitter	0.950	0.950	0.950		
Total transmission	0.256794	0.25432	0.269219		unpolarized
CCD quantum efficiency	0.8	0.65	0.02	e-/photon	PixelVision specification
Spatial sample size	3.45E-07	3.45E-07	3.45E-07	solar fraction	1" by 1" sample size
Spectral sample size	2.30E-02	3.00E-02	3.40E-02	А	
Photoelectric flux	1.38E+08	1.25E+08	3.75E+06	e-/s	per pixel and second
Polarization channels	2	2	1		-
CCD readout rate	3.00E+02	3.00E+02	3.00E+02	Hz	
CCD full well capacity	2.00E+05	2.00E+05	2.00E+05	e-	PixelVision specification
Maximum detection	1.20E+08	1.20E+08	6.00E+07	e-/s	
Detected flux	1.20E+08	1.20E+08	3.75E+06	e-/s	
Stokes Q modulation efficiency	0.58				
Stokes V modulation efficiency	0.50	1.00			
Stokes I noise in 0.5s	1.29E-04	1.29E-04	7.30E-04		
Stokes Q,U noise in 0.5s	2.24E-04				
Stokes V noise in 0.5s	2.58E-04	1.29E-04			

 Table 3: Photon Budget

9. Future Upgrades

A future upgrade, when suitable detectors become available, will be the FeI line pair 1564.8 nm and 1565.3 nm. Use of these lines will more than halve the field strength at which the true field strength rather than equivalent flux is deduced. While the current optical design will transmit at those wavelengths, the design has not been optimized for those wavelengths. Additional work

would need to be done to determine how suitable the current optical setup is for these near-infrared lines.