The Visible Spectro-Polarimeter (ViSP) for the Advanced Technology Solar Telescope

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ABSTRACT

The Visible Spectro-Polarimeter (ViSP) is one of the first light instruments for the Advanced Technology Solar Telescope (ATST). It is an echelle spectrograph designed to measure three different regions of the solar spectrum in three separate focal planes simultaneously between 380 and 1600nm. It will use the polarimetric capabilities of the ATST to measure the full Stokes parameters across the line profiles. By measuring the polarization in magnetically sensitive spectral lines the magnetic field vector as a function of height in the solar atmosphere, along with the associated variation of the thermodynamic properties can be obtained. The ViSP will have a spatial resolution of 0.04 arc seconds over a 2 minute field of view (at 600nm). The minimum resolving power for all the focal planes is 180,000. The spectrograph supports up to 5 diffraction gratings and is fully automated to allow for rapid reconfiguration.

Keywords: ViSP, ATST, spectrograph, polarimeter, polarimetry

1. INTRODUCTION

Our understanding of solar magnetism depends on our ability to detect and interpret the polarization signatures of magnetic fields in solar spectral lines. Since the identification of sunspots as regions of strong magnetism by means of the observation of the Zeeman effect,[1] the number of physical mechanisms applied to the interpretation of solar spectral line profiles has increased significantly. The Hanle effect observed in linear polarization has been exploited to diagnose weak turbulent magnetic fields[2,3,4] and the magnetic structure of solar prominences.[5] A rich spectrum of linear polarization signatures observed near the solar limb (named the "second solar spectrum"[6]) is actively being investigated to constrain solar magnetic fields and improve our understanding of light-scattering physics. Observations of lines like those of Mn I, which display hyperfine structure, have been used to break the intrinsic degeneracy between magnetic flux and magnetic field which arises when using the Zeeman effect for weak magnetic fields.[7,8,9] Information about plasma kinetics during solar flares is encoded in the linear polarization of H lines through impact polarization.[10]

Because of the complexity of the physics involved in the formation of line polarization and of the plasma conditions on the Sun where these polarization signatures are produced, these studies profit highly from the simultaneous observations of different spectral lines. For example, the application of line-ratio techniques to multiple spectral lines has been shown to greatly enhance the diagnostic potential of Zeeman effect observations.[11] By probing different heights in the solar atmosphere observing multiple lines also constrains the magnetic field geometry in three dimensions. Improving infra-red detector technology has also made it possible to take advantage of the increased sensitivity of the Zeeman effect in the infra-red.[12,13]

The ATST's Visible Spectro-Polarimeter (ViSP) is an echelle spectrograph designed to provide precision measurements of the full state of polarization across spectral line profiles. Its goal is to measure three highly resolved spectra simultaneously at diverse wavelengths from 380nm to 1.6 microns by imaging three spectra onto different focal planes (cameras). The ViSP is also distinct from many spectrographs in that it seeks to obtain this information over a wide field-of-view (2 arc minutes) with an exceptionally high spatial resolution (half the diffraction limit of the ATST, or approximately 0.04 arc seconds at 600nm). This nearly 4,000:1 spatial dynamic range is unprecedented for solar spectrographs.

Not all science requires polarimetric information. Non-polarimetric observations are important because the time to form a map of a region can be dramatically reduced if no magnetic information about that region is required. Temperature and velocity fields can be obtained from spectral information alone. The ViSP can be run in a non-polarimetric mode

Ground-based and Airborne Instrumentation for Astronomy III, edited by Ian S. McLean, Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 7735, 77358C · © 2010
SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.857610

with no modifications. In such a mode the scan rate is limited by the camera speed and the desired spatial resolution. The spatial resolution is given by the slit velocity in arc-seconds/second divided by the camera frame rate.

The ViSP is designed to be a fully-automated spectrograph capable of observing any triplet of lines from 380-1600nm with optical efficiencies of 30% or higher. A computer-controlled interface allows configuration of the spectrograph with little or no manual intervention. The ability to rapidly reconfigure the spectrograph makes it ideal for multiple observation campaigns within the same day or to address targets of opportunity (such as solar flares). Key to the success of the ViSP's mission is to obtain a spectral resolution of 180,000 or greater from 380-900nm while maintaining good polarimetric sensitivity for any triplet of lines desired by the campaign. To ensure high optical efficiency across the spectrum the spectrograph must be equipped with a variety of gratings selectable by an automated grating turret. For high-precision polarimetry the spectrograph must also employ 'dual-beam' configuration where two identical spectra (in orthogonal polarizations) are formed at each of the three focal planes. This combined with rapid polarization modulation and fast camera readout will enable the ViSP to obtain photon-noise limited polarimetry.

By combining a high level of automation with wavelength diversity, high optical efficiencies, high spectral resolution, and large fields of view, the ViSP is set to take full advantage of the ATST's unique capabilities at first light.

1.1 General Characteristics

The general characteristics of the spectrograph are listed below. These have been derived from input provided by the ATST Science Working Group. Note that the polarimetric sensitivity is actually a system-wide requirement for the ATST since the entire telescope's polarization properties must be calibrated to reach these goals.

Table 1: General Characteristics of the ViSP spectrograph

Parameter	Requirement	Comment
Wavelength range	380nm → 900nm	A 1600nm goal can be met (typically with a resolution less than 180,000)
Simultaneous wavelengths	3 focal planes	
Spatial resolution	2X telescope resolution	Approx. 0.04 arc seconds
Spatial field of view	2 arc min square	
Resolving Power	180,000 at 630nm	
Slit Scan Repeatability	+/- ½ a slit width	Slit is ~20μm wide
Slit Scan Accuracy	0.1 arc second	
Polarimetric Sensitivity	10^{-3} I_c in 10 second int. time while meeting other nom. requirements	An ATST observatory-level requirement
Polarimetric Accuracy	10^{-4} I_c	For measurements of arbitrary length. Mainly a calibration requirement
Context Imager Resolution	Same as spectrograph	The context imager images the light reflected from the slit for targeting and alignment
Context Imager Bandpass	4 continuum + 1 chromospheric line core	The context image is not science-grade. For targeting and alignment only.
Spectral Bandpass	1.1nm at 630nm	For each focal plane. 2nm+ will be possible.
Configuration time	At least 1 focal plane in 10 minutes	Should obtain alignment of all three focal planes in ~30 seconds
Slit move time	200ms for neighboring slit positions	Applies only to the polarimetric mode of the ViSP
Slit slew velocity	2 arc min. in 30 seconds	
Simultaneous operation with other ATST instruments	Must view same regions within 5 seconds	An ATST observatory-level requirement

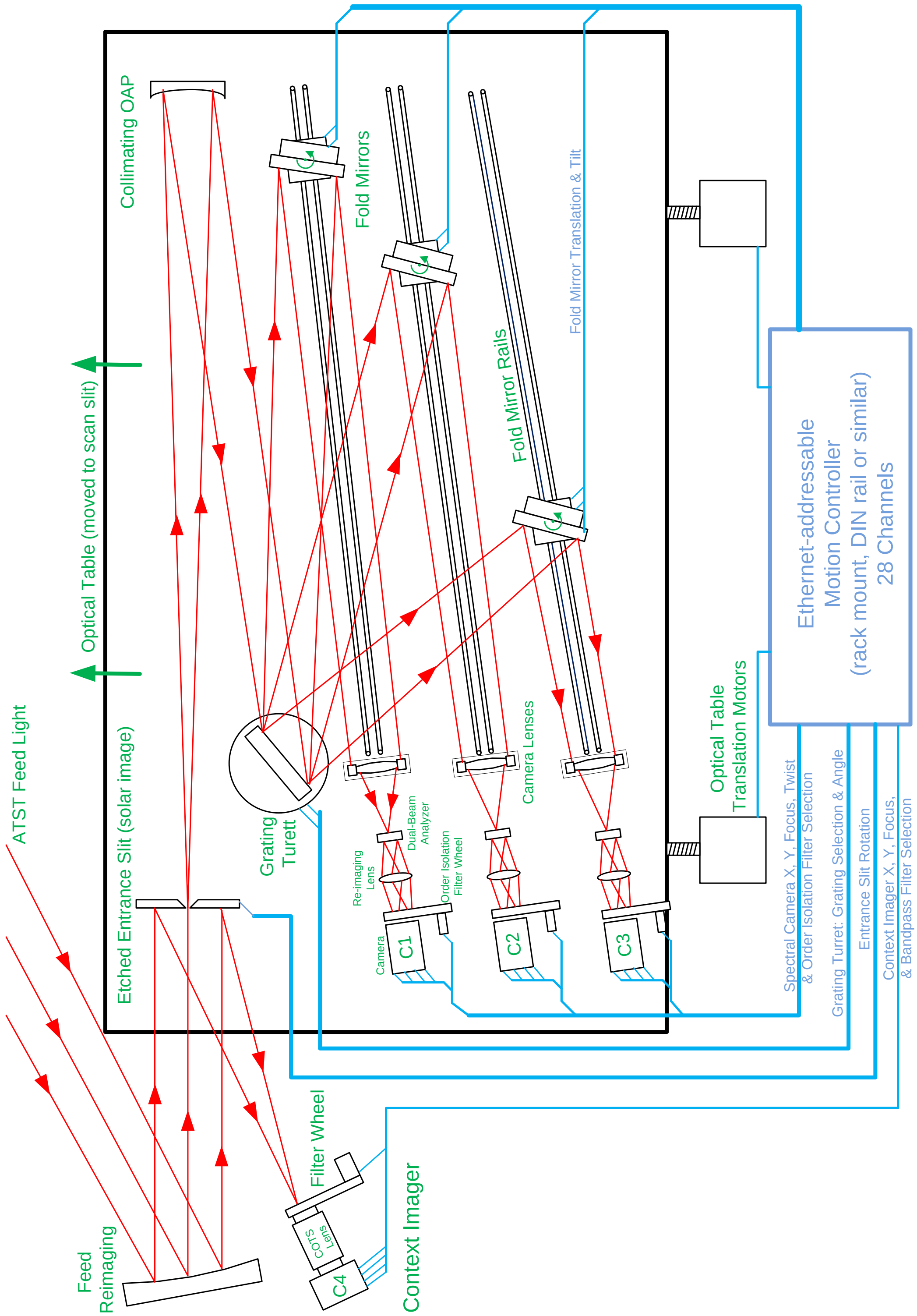

Figure 1: A functional block diagram of the instrument

1.2 Design

The requirement to observe three different wavelength ranges in the span from 380 to 1600nm requires a wide range of diffracted light angles (β) to be accessible. Figure 1 shows a functional block diagram of the ViSP instrument. It is located on the 16m diameter rotating coudé room of the ATST. After an adaptive optics system a collimated beam of light is directed to an off-axis parabolic mirror. That mirror forms an image of the field on the instrument's entrance slit with an f/ratio of 27. The entrance slit is etched in a vapor deposited aluminum coating on an optical-quality substrate. The light reflected from the slit is reimaged by a 'context imager' for use in target acquisition and alignment. The entrance slit is stationary with respect to the post-slit optics during operation. The field is scanned by moving the entire spectrograph table across the stationary image plane.

The light from the entrance slit passes to an off-axis parabolic collimator. The collimator focal length is 2m. The small width of the slit causes a significant amount of diffracted light, particularly if the slit is sized for a blue wavelength and a near-IR line is also being observed. For this reason the collimator is 10cm in aperture (f/20). For slit widths equal to the Airy diameter the loss due to diffraction is reduced to ~10% .

Light from the collimator is directed to the grating turret. The grating turret is a vertical turret with up to five gratings stacked on top of each other with their ruled faces coplanar. Grating selection is accomplished by moving a vertical carriage holding the gratings (there is a hole through the optical table to allow this motion). The entire grating carriage is rotated to select an appropriate incident angle (α) for the grating and wavelengths desired. Each grating in the carriage is equipped with manual micrometers for adjustment of the four degrees of freedom not controlled by the turret. Initial alignment of the gratings is accomplished by moving the turret to 'zeroth' order and using a laser to adjust the beam angles.

The light diffracted from the grating is directed towards mirrors mounted on sliding rails. The angles of the mirrors can be adjusted with automated motions such that the reflected beam is directly above and parallel to the mirror rails. At the end of the rails are refractive camera lenses which form primary images of the spectra at a polarizing beam splitter. This beam splitter divides the light into two orthogonal polarizations which are aligned and anti-aligned with the rulings of the grating. The two beams of the splitter are diverted such that the two images of the spectra are formed next to each other on the same focal plane (camera). Figure 2 illustrates how this is done.

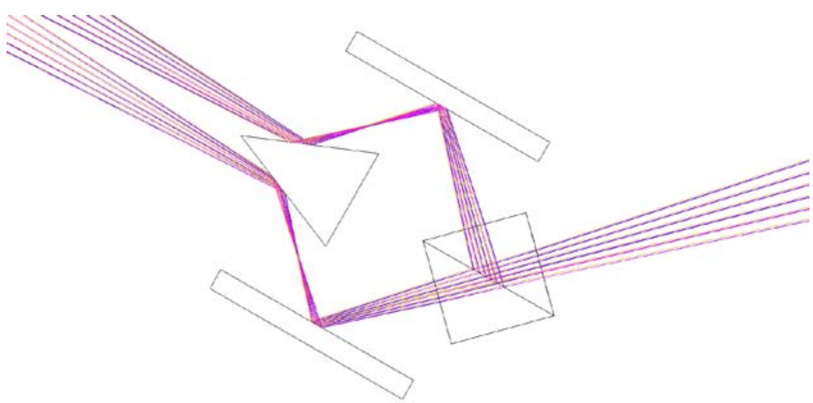

Figure 2: Detail of the polarization analyzer. The light enters from the right. A polarizing beam splitter divides the beam and two mirrors reflect the beams onto a reflecting prism that makes the two beams adjacent and parallel. One beam experiences three reflections and the other two, producing two mirror-image spectra. Relay lenses reimage the spectra onto the camera focal planes. This design creates two side-by-side spectra on a single focal plane.

Immediately before the focal plane of cameras are filter wheels. These hold filters for isolating the different orders of the gratings. The gratings in the ViSP are selected to have orders no higher than ~15. This forces the free spectral range of the gratings to be high enough so the wavelength span of the ViSP needs no more than ~15 isolation filters per camera. Because multiple gratings will use the same filters the bandpass of the filters needs to be sharp and square. The bandpass of the filters will not necessarily be centered on the diffraction grating orders. Note that the angle of diffraction (β) depends on both the wavelength and order. Because of this it is not possible, for example, to always direct blue light to camera 1 or red light to camera 3. Each arm of the spectrograph needs to be optimized for operation over the entire 380-1600nm spectral range. Because the cameras in the ViSP are nominally fixed (the instrument is in a clean room with limited access) the wavelength coverage becomes camera-limited. The practical wavelength range for the ViSP is expected to be 380-1100 nm.

1.3 Design Limitations

An etched entrance slit was adopted for the design because of the requirement to have better than 1 micron precision in its width over a 7cm height. It is also desirable to maintain a high quality of the light reflected from the slit. Although the slit can be changed with manual intervention in the coudé room (the instrument will have a library of slits) this limits the ability of the ViSP to address certain targets of opportunity or to support campaigns requiring rapid resizing of the slit. Though somewhat restrictive, there are no ViSP use cases which require a mechanically variable slit.

A larger issue is that of the camera lenses. In the current design the camera lens focal length is determined by simply matching the slit height to the height of the camera focal plane. Unfortunately this also fixes the spectral sampling (the sampling changes depending on the grating, wavelength, and order). It is possible that the spectral sampling thus achieved may not be sufficient to obtain the requisite resolving power, especially in the blue portion of the spectrum. One can get adequate resolving power by changing the camera lenses but this sacrifices the ViSP's field of view. Resolving this trade is difficult in a general-use spectrograph. The current design does not include the ability to change camera lenses. Adding the capability to change camera lenses is a possible upgrade path for the instrument.

Although automation adds a huge amount of versatility it also limits the user to configurations obtainable by the mechanisms. It is possible with this design that two lines separated by slightly more than a focal plane bandwidth may not be separable without vignetting (causing loss of efficiency and resolution). Smaller telescopes have enjoyed the freedom to implement dichroic beam splitters or other 'creative' spectrograph layouts to gain access to closely-spaced spectral lines. The operational modes of the ATST will not allow free access to configure the coudé instruments. That said the instrument meets all of the requirements set forth by the Science Working Group committee.

2. SPECTROGRAPH OPTIMIZATION

There are a very large number of parameters which describe the ViSP spectrograph. The problem of defining the optical configuration of a wavelength-diverse spectrograph such as the ViSP resides mainly in the huge set of science-derived instrument requirements. In principle one would like to be able to meet all the science requirements simultaneously for each beam of the instrument. In practice this is not possible and therefore one must prioritize requirements. A reasonable starting point is to identify optimal constraints for the various dimensions of the instrument. This is important since the size of the optics is a strong cost driver. As in all optimization problems it is necessary to start with an initial guess then iterate as required. We start with the collimator aperture and then build other constraints as outlined below. Ultimately Monte Carlo techniques are used to sample the parameters space, particularly with regard to the grating parameters. Grating optimization requires consideration of specific wavelengths of interest for solar science. We considered both stock gratings and custom gratings in the optimization. Stock gratings offer proven performance and attractive cost while custom gratings allow much greater flexibility. The ViSP will likely include both in its turret.

The ViSP collimator will have an aperture with a maximum width in the direction of the spectrograph dispersion of 10cm. This allows the use of standard-size gratings of 30cm width with an inclination up to about 70°. A thorough analysis of the Newport-RGL list of stock gratings has shown that very few gratings have the right properties to provide simultaneously the required resolving power and wavelength diversity at sufficiently low orders of dispersion. Limiting the order is required to limit the number of order-isolation filters needed for the operation of the spectrograph. One of the results of this study is that a collimator beam width of 10cm is sufficient to meet the requirements.

To access as many lines as possible it is important to keep the *minimum* angle between the different beams ($\Delta\beta$) as small as possible. Constraining the focal length of the collimator to be 190cm or larger produces a lower limit on $\Delta\beta$ of about 3°. Small $\Delta\beta$s also allow the spectrograph to approach the optimal Littrow configuration. The maximum $\Delta\beta$ is limited by mechanical considerations and the reduced optical efficiencies of the gratings when used far from the 'blaze condition' (where the angle of incidence is equal to the angle of reflection for the ruling facets). We consider a 'fan' of angles for β about 40° wide (so that the allowed range for α-β is between 3° and 40°).

A science requirement of the ViSP is that it must deliver spatially resolved datasets at twice the diffraction limit of the 4m ATST aperture. It is also required to have a 120 arc second FOV. This means the height/width ratio for the slit is on the order of 4000:1. Limiting the slit to a height of less than 10cm then implies slits which are only 10s of microns wide. The current baseline design for the ViSP is to implement a library of photo-etched slits on optical quality mirror surfaces. Considering the required spectral range of operation for the ViSP we propose a set of 3 slits. These would match the diffraction-limit resolution of the telescope at 450, 650, and 850 nm (0.023, 0.034 and 0.044 arc seconds, respectively). Narrow slits exaggerates the light loss due to diffraction and reduce overall flux. This can become an issue for meeting the target temporal resolution for polarimetry. This is especially true in the blue end of the solar spectrum. For this reason we require the following:

Table 2: The performance of a stock Newport RGL grating for various solar spectral lines

Newport 53-*-451E: 316 lines/mm, 63° blaze			
α = 68.114°, $\alpha-\beta \in$[4.35, 36.87], average efficiency = 0.459			
λ (nm)	order	$\alpha-\beta$ (degrees)	efficiency
393.3	14	13.819	0.502
396.8	14	12.269	0.553
453.6	12	15.729	0.447
455.4	12	15.084	0.477
460.7	12	13.124	0.551
486.1	11	18.494	0.351
517.3	11	7.631	0.508
518.4	11	7.183	0.498
525.0	11	4.351	0.432
553.8	10	12.820	0.577
587.6	9	20.108	0.342
589.0	9	19.766	0.355
589.6	9	19.619	0.361
617.3	9	12.253	0.535
630.2	9	8.304	0.485
656.3	8	21.127	0.334
676.8	8	16.575	0.527
769.9	7	17.300	0.554
849.8	6	25.012	0.337
854.2	6	24.354	0.360
866.2	6	22.521	0.449
874.1	6	21.280	0.599
1083.0	5	16.558	0.560
1526.0	3	36.867	0.497
1565.0	3	34.355	0.489

The slit must be wide enough such to limit the losses due to diffraction to less than 10% at the wavelengths of 450, 650 and 850 nm. This imposes a lower limit for the f/# of about 25 for the feed optics of ViSP (an effective primary focal length of 100m). In order to converge on an optimal f/# for the feed and collimator focal length we need to impose requirements on the resolving power of the spectrograph.

The resolving power over the required spectral range of the ViSP (380-900nm) must be higher than 180,000. Considering the importance of the chromospheric line He I 1083nm for polarimetric solar studies it is desirable that the resolving power requirement be extended to include this line as well. We have identified the best stock grating from Newport RGL based on the highest average grating efficiency over the spectral range of interest while maintaining the resolving power requirement. In the Monte Carlo simulation the spectral range is sampled by 25 standard solar lines between 380 and 1600 nm. The specifications and performance of the Newport RGL 53-*-451E grating are listed in Table 2 above. Note that the efficiencies in the calculations are based on a scalar calculation. Actual optical efficiency strongly depends on polarization and requires a vector-field calculation. Commercial software such at PCGrate from IIG, Inc. can calculate the vector-field efficiencies, however it is difficult to incorporate into the Monte Carlo. The average efficiency of the vector calculations generally agree with the scalar values.

At 1083nm this grating provides a resolving power of 168,000 ($\Delta\lambda$ of 6.4pm) when used with the narrowest library slit and 158,000 ($\Delta\lambda$ of 6.9pm) when used with the widest slit. Both these figures are largely adequate for most polarimetric science based on He I 1083nm. As a result we adjusted the geometry of the spectrograph as follows: 1) The focal length of the collimator was increased to 2.0m. This leaves some extra allowance in the minimum separation of the beams decreasing the risk of vignetting for beams as close as 3°. 2) The f/# of the feed optics was increased to 27 (108m effective focal length) in order to limit the diffraction losses at the collimator entrance to under 10%. With these modifications and assuming conservative values for the efficiency losses due to optics, grating, and cameras it is possible to reach a target polarimetric sensitivity $<10^{-3}\ I_c$ with a 5 second integration time. This can be maintained over a spectral range between approximately 450 and 1100 nm when using the intermediate (650nm) slit or above approximately 500nm when using a wavelength-scaled slit.

NCAR and ATST are supported by the National Science Foundation.

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