SOLIS - A modern facility for synoptic solar observations

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ABSTRACT

SOLIS (Synoptic Optical Long-term Investigations of the Sun) is a suite of instruments that will modernize and greatly improve synoptic solar observations carried out by the National Solar Observatory. It will provide fundamental data necessary to understand the solar activity cycle, sudden energy releases in the solar atmosphere, and solar spectral irradiance changes. State-of-the-art instrumentation and data collection techniques will be employed to enhance both the quality and quantity of data. A high degree of automation and remote control will provide faster user access to data and flexible interaction with the data-collection process. The instruments include a vector spectromagnetograph that will measure the magnetic field strength and direction over the full solar disk in 15 minutes, a full disk patrol delivering digital images in various spectral lines at a high cadence, and a Sun-as-a-star precision spectrometer to measure changes in many spectral lines.

Keywords: Sun, instruments, synoptic, SOLIS, observations, vector-magnetograms

1. INTRODUCTION

SOLIS, the Synoptic Optical Long-term Investigations of the Sun, will provide unique, modern observations of the Sun on a continuous basis for several decades at a fraction of the operating costs of the existing equipment. SOLIS will replace NSO's aging synoptic observing facilities with a modern facility. New technologies enable much better observations to be made more efficiently and at lower operating cost. Nearly a thousand users currently use NSO synoptic data for research, forecasting, and technical purposes while tens of thousands browse the data for educational and other purposes. These users will be served much more effectively by a facility with real-time and archival data available over the Internet.

The SOLIS proposal submitted to the National Science Foundation in January 1996 has been funded at a level of $6M distributed over the next three years. The budget reduction of 12% from the originally requested amount has resulted in the removal of the Solar Coronal Imager from the proposed instrument suite. Nevertheless, the instrument is presented here because NSO hopes to secure funding from other sources to build this innovative instrument. The proposal and more information is available at `http://www.nso.noao.edu/solis`.

2. GENERAL CONSIDERATIONS

The scientific requirements lead to a need for four different kinds of observations: (i) high-accuracy, full-disk measurements of the vector magnetic field and velocity fields; (ii) frequent, full-disk and local-area measurements at selected wavelengths with optional polarimetric capability; (iii) a sensitive coronal emission-line imaging photometer; (iv) a high-accuracy, Sun-as-a-star spectrometer.

The instruments will be designed to be as simple as possible, consistent with meeting scientific goals. Low operations and maintenance costs and long lifetime are primary goals. Industry standard hardware and software will be used whenever possible.

Since intercomparison of images is a vital part of this program, the instruments will be designed to provide images with good geometric integrity. That is, it will be possible to register images to a fraction of a pixel rms in the absence of local seeing effects. Information will be obtained to allow for correction of refraction distortion. Instruments will have fast image motion stabilization and, where appropriate, the capability to select moments of good image quality.

Photometric measurements will be calibrated for linearity to better than 1% of the full dynamic range. Measurements of dark level and flat field will be made regularly. Charge transfer efficiency and other known CCD problems will be characterized and corrections applied as appropriate. Exposure-to-exposure stability will be better than 0.1%.

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Long-term gain sensitivity will be checked by reference to a well defined and repeatable average of sunlight. Spectral filters will be designed for long-term stability.

A problem with many previous synoptic measurements is a lack of basic accompanying information. This will be addressed by monitoring local weather conditions and instrumental parameters such as temperatures, voltages, currents, etc. Such monitoring will be a vital part of automating the instruments.

3. VECTOR SPECTROMAGNETOGRAPH (VSM)

Table 1. Specifications for the vector spectromagnetograph.

Parameter	Goal	Rationale
<u>ANGULAR</u>		
element	$1''$	To match average daytime seeing.
coverage	full disk	To observe features anywhere on the disk.
format	2000×1	To cover entire disk in one pass.
geometric accuracy	$<0.5''$ rms	To study proper motions and to co-align accurately with other data.
instrumental mtf	measurable to ± 0.01	To allow corrections for instrumental scattered light and blurring.
total mtf	<0.1 at $f \geq f_{\rm Nyquist}$	To avoid excessive angular aliasing.
<u>TEMPORAL</u>		
scan rate	0.5 s/arc s	To resolve changes of most solar phenomena at a scale of $2''$.
duty cycle	100%	To use light efficiently and minimize temporal aliasing.
accuracy	1 s	To correlate with other data.
frequency	$\leq$20 min (full disk)	To observe CME-related changes.
	$\leq$2 min (active region)	To observe flare-related changes.
<u>SPECTRAL</u>		
resolution	2×10^5	To resolve line profile shape.
range	600-1600 nm	To include good diagnostic spectral lines.
lines	$\geq$ 2 lines	To obtain accurate field strengths and filling factors.
<u>POLARIMETRY</u>		
type	I,Q,U,V	To deduce vector field.
sensitivity	2×10^{-4}/0.5 s	To achieve 1 Mx/cm^2 noise level.
relative accuracy	1×10^{-3}	To measure field direction accurately.

The surface magnetic field is generally not resolved owing to its intricate structure and intermittent spatial patterns on scales well below one arcsecond. Accurate magnetic field measurement using the Zeeman effect under these conditions requires accurate Stokes line profiles of more than one Zeeman-sensitive spectrum line. This enables effects due to spatial averaging to be isolated from the Zeeman effect, to some degree, when a model is used to interpret the observations. However, there is no substitute for high angular resolution when measuring a highly structured vector field, and ground-based measurements will always be hampered by atmospheric seeing. Errors are minimized by using highly Zeeman-sensitive line profiles, good models, and accurate polarimetry.

Since magnetic field information is encoded in subtle shape changes of spectrum line profiles observed in various states of polarization, high spectral fidelity and immunity from seeing noise are the primary concerns. This means that tiny spectral and polarization differences in line profiles have to be measured quickly, before seeing can obliterate these signals. Both the spectral recording and polarization modulation schemes have to be fast. There are many elegant and ingenious ways of doing this.

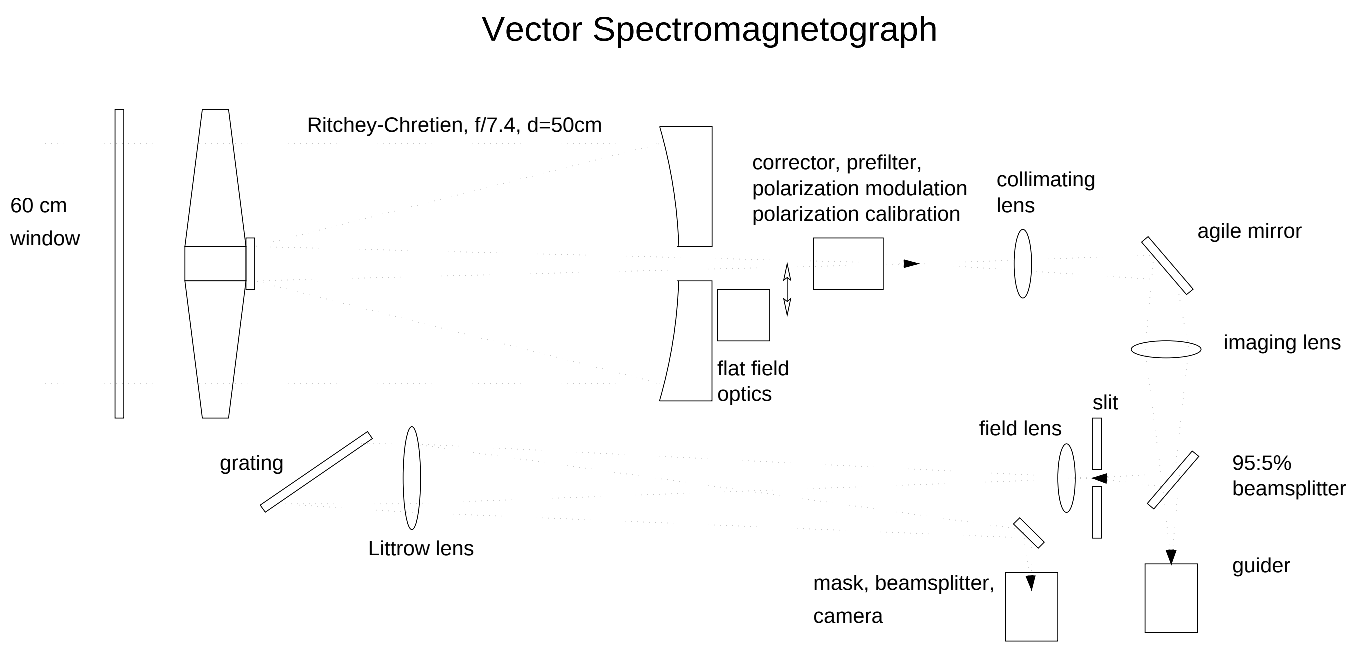

Figure 1. Conceptual layout of the vector spectromagnetograph.

Table 1 lists the specifications for the Vector Spectromagnetograph. The spectrum lines to be observed are primarily 630.25 and 630.15 nm for the vector magnetic field and 1083 nm for chromospheric structure and dynamics. Polarized spectroheliograms in other lines such as 854 nm will be possible. The modulator and calibration package consists of a bandpass filter to reject unwanted light, a polarization calibration section, and a polarization modulator. The latter will be a sandwich of two or three ferroelectric LC modulators. Note that there is no polarizer in the modulator package: Both complementary modulated beams go through the same path in the spectrograph. A calibration package consisting of fixed polarizers will be located in front of the modulator for calibration purposes. The basic idea for the spectrograph focal plane is to use a masked polarizing beam splitter just in front of the detector to produce two orthogonal, linearly polarized spectral images that have, until this point, gone through the same optical path. This is a scheme used successfully in the 1960's and early 1970's.

The Sarnoff VCCD1024H is a 300 frame per second, frame transfer, 1024^2 pixel CCD with a quantum efficiency of 75% at 630 nm. It has 18 micron square pixels with well depths of 240 Ke^-, on-chip double-correlated sampling, and a read noise of 46 e^- rms. Linearity is specified as better than 1%. The rapid speed is obtained by splitting the sensitive area into two halves and transferring each half to separate 512×1024 frame buffers. Each half has 16 readout channels running at up to 20 MHz. Two of these detectors could be used in the VSM, but a modified design would be better. Therefore we propose a similar, custom CCD with a different architecture better matched to our spectroscopic format of 2048×200. The continuum noise of a single Stokes parameter will approach 2×10^{-4}. This is about a factor of 2.5 better than the normal operating mode of the ASP and a factor of 5 better than the KPVT spectromagnetograph.

Assuming 0.067 efficiency per polarized spectrum, $1'' \times 1''$ samples, 2 pm pixels, and 3.3 ms exposures, we get 220,000 detected continuum photons from a 50 cm telescope with a 10% secondary obstruction. To match the CCD we have an image scale of 18 μm per arcsec implying a 3.7 m focal length or a speed of f/7.4. The entrance slit will be $2048'' \times 1''$ (37 mm by 18 μm). The spectrograph will be a Littrow arrangement with a size of up to a 1.4 m focal length triplet lens of 20 cm aperture. The telescope will be a 50-cm Ritchey-Chrétien with a two-lens corrector for astigmatism and field curvature. There will be a relatively thin entrance window with a coating designed to reflect light shortward of 600 and longward of 1100 nm.

The scan will be done in rapid steps instead of continuously in order to maintain nearly equal angular resolution both perpendicular and parallel to the slit. The agile fold mirror will be located after the primary telescope focus, at a pupil image, and it will be coated with a coating having less than one-degree retardation between *s*- and *p*-wave polarization states over a field angle of several degrees.

4. FULL DISK PATROL (FDP)

The Full-Disk Patrol (FDP) is intended to replace the current flare patrol, white-light patrol, daily sunspot drawing, daily spectroheliogram patrol, and high-degree helioseismometer programs in one automated facility. Table 2 lists its specifications. A digital solar full disk Hα imaging system will be superior to the present photographic and video flare patrol and permit an automatic flare detection capability for coordinated observatory-wide and community flare-reactive observing operations. The general tuning system proposed for the FDP will permit us to replace the present white-light patrol with true continuum observations. The daily sunspot drawing can be replaced by a threshold white-light image to give a more quantitative method for locating sunspots, with quantitative areal coverage and counting statistics as a valuable solar cycle diagnostic. The quality of K-line and Hα images obtained through the proposed FDP should exceed that of our daily spectroheliograms both in spatial and spectral resolution. High degree helioseismology measurements will be possible in both Doppler and intensity modes.

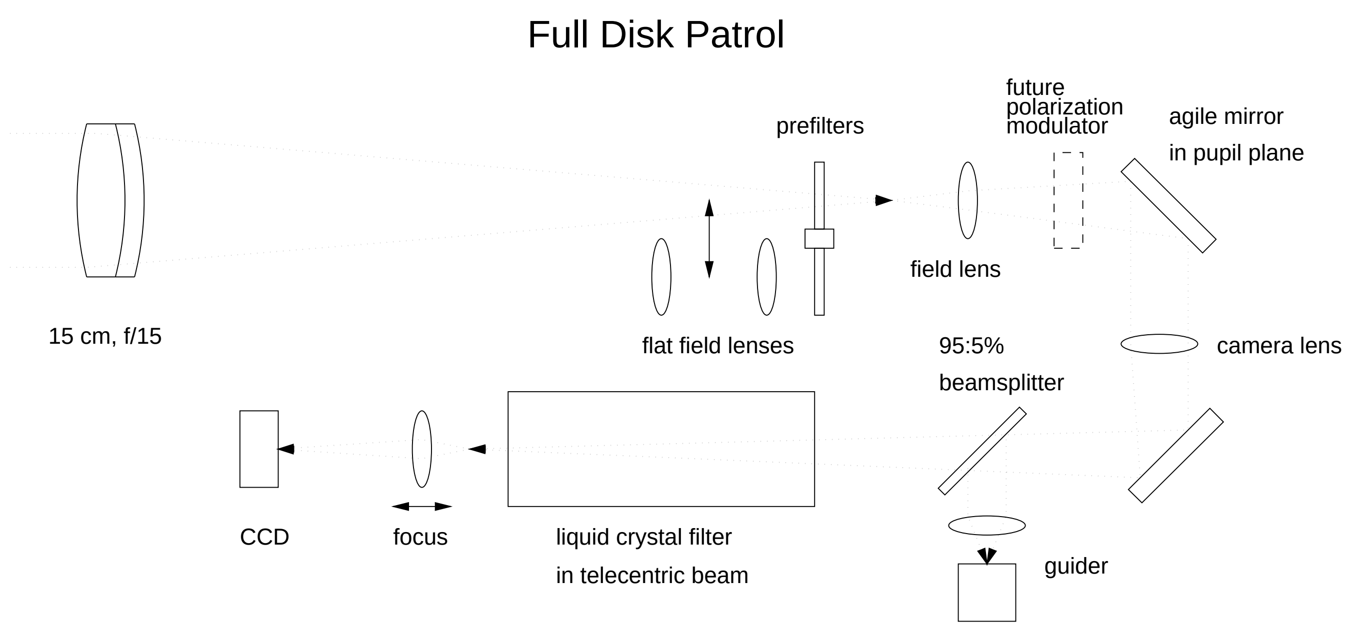

Figure 2. Conceptual layout of the Full Disk Patrol.

The FDP will provide spectral images at a continuum wavelength, in the cores and wings of 393, 656.3, and 1083 nm as well as a few other lines selected for particular purposes such as Zeeman sensitivity and insensitivity.

Table 2. Specifications for the full-disk patrol.

Parameter	Goal	Rationale
ANGULAR		
element	$1''$	To match average daytime seeing.
coverage	full disk	To observe features anywhere on the disk.
format	2000×2000	To cover entire disk in one exposure.
geometric accuracy	$<0.5''$ rms	To study proper motions and to co-align accurately with other data.
instrumental mtf	measurable to ± 0.01	To allow corrections for instrumental scattered light and blurring.
total mtf	<0.1 at $f \geq f_{\rm Nyquist}$	To avoid excessive angular aliasing.
TEMPORAL		
frequency	≤ 10 s	To resolve changes of most solar phenomena at a scale of $2''$ and the 5-min oscillation.
cycle	≤ 2 s	To switch between lines quickly.
accuracy	1 s	To correlate with other data.
SPECTRAL		
resolution	25000	To match line profile shapes.
range	380–1083 nm	To cover wide range of heights and phenomena.
POLARIMETRY		
type	wing I,Q,U,V	For morphological study of vector field.
sensitivity	2×10^{-4}/pixel	To achieve 1 Mx/cm^2 nominal noise level.

The detector will be a duplicate of the system developed for the Precision Solar Photometric Telescope project. It consists of a Thomson 2048^2 CCD with 15 μm square pixels, a well depth of about 150 ke$^-$, 4-quadrant readout at a total pixel rate of 16 M pixel/s, and a UV coating. This detector implies an image scale of $1''$ per pixel or an effective focal length of 3.09 m.

Spectral filtering will be done using a combination of narrow band ion-assisted deposition interference prefilters mounted on a wheel and a tunable birefringent filter. The wavelength range to be covered is 380 to 1083 nm. It is possible to obtain ion-assisted interference filters with 0.1% passbands, and 0.02% filters have been reported in the literature. The required final passband is roughly 1/25000 λ which can be reached with a five-stage series of Lyot filter elements in combination with the prefilters. The spectral passband at the K-line for the proposed Lyot system is narrow enough to resolve K-line spectral features, thus permitting the daily integrated-disk K-line spectral scan to be complemented with full images to provide full spatial as well as spectral diagnostics in their solar cycle variation. Tuning the filter will be done by liquid crystal variable retarders. They will serve as both the half-wave retarders needed in wide field elements and as the tuning stages of each element. Commercial filters of this sort are available from at least two vendors, albeit without such narrow passbands.

A small mirror will be located at a pupil image and mounted so that it can be rapidly tilted to compensate fast image motion. The error signal to do this will be derived from a duplicate of the Vector Spectromagnetograph guider. Focus and image scale adjustment will be done by a pair of movable lenses in front of the CCD.

5. SOLAR CORONAL IMAGER (SCI)

Solar emission lines from the corona are hard to observe because their intensity is often only a few percent or less of the scattered light from the solar disk, even at locations with very clean and transparent air (so-called coronal sites). Current synoptic observations of coronal emission lines are performed either during a restricted time of the year when the sky background is very low, during eclipses, or with sophisticated instruments that measure one point at a time and with a low spatial resolution of about $2'$.

The scientific specifications require a two-dimensional system that performs an accurate sky-background subtraction. Tunable filters are the obvious choice for these measurements since they allow fast chopping between the emission line and the sky background. Furthermore, tunable filters easily implement variations in the line position to obtain Doppler measurements. Table 3 lists the specifications for the Solar Coronal Imager.

The spectral filtering needs to cover all seven lines with a spectral resolution of about 0.1 nm. Liquid crystal retarders combined with a single birefringent element and narrow-band interference filters provide the necessary spectral resolution and tuning capabilities. A piezoelastic modulator will provide a rapid switching between the emission line and the sky background by selecting either of two passbands of the birefringent element. The chopping will occur at about 80 kHz. The rapid switching is required to take into account dust particles flying at high apparent speed.

The detector needs to be able to cope with the 80 kHz chopping between the coronal line and the continuum sky background. A two-dimensional detector that can perform this function is based on the approach taken for the Zürich Imaging Stokes Polarimeters (ZIMPOL) I and II. Every second row of the CCD is covered with an opaque mask. Charges are shifted back and forth between the free and the covered pixels in synchrony with the chopping. The CCD is only read out once it has reached close to its full well depth. Odd and even rows then correspond to coronal line plus sky background and sky background alone, respectively.

The super-polished mirror approach has the large advantage that there will be no focus variations over the complete wavelength range. On the other hand, a mirror system needs to be an off-axis system and requires correction after the prime focus to reduce the aberrations induced by the off-axis primary mirror. To achieve the required sensitivity, an aperture of 20 cm is needed. It will be an off-axis paraboloid at about f/7.5 to keep the instrument compact while controlling off-axis aberrations.

The occulting disk of a conventional coronagraph will be replaced by an inverse occulting, annular mirror. The light from the solar disk just passes through the center of this mirror while the coronal light is reflected. A set of a few mirrors in an exchange mechanism is required to obtain data close to the solar limb during the course of a year. A pop-up mirror mechanism near the primary focus will protect the optics following the primary mirror in the case of incorrect telescope pointing.

Table 3. Specifications for the solar coronal imager.

Parameter	Goal	Rationale
ANGULAR		
format	1000×1000	To cover entire field at once.
geometric accuracy	$<1''$ rms	To study proper motions and to co-align accurately with other data.
instrumental mtf	measurable to ± 0.01	To allow corrections for instrumental scattered light and blurring.
scattered light	$< 1 \times 10^{-5}$	To be limited by the sky and not the telescope.
Low-Res Mode		
element	$4''$	To match typical daytime seeing for integration times of several minutes.
coverage	1.05 — $2\ R_{\odot}$	To observe features from 1.05 to 2 solar radii.
High-Res Mode		
element	$1''$	To obtain the highest possible resolution on selected areas (mainly prominences).
coverage	$5'$	To cover the typical size of coronal structures.
TEMPORAL		
time per line	1 minute	To resolve changes of most coronal phenomena at a scale of $4''$.
duty cycle	$> 50\%$	To use light efficiently.
accuracy	1 s	To correlate with other data.
SPECTRAL		
resolution	5000	To match coronal line profile width.
range	500–1100 nm	To observe all strong coronal lines in the visible.
stability	0.01 nm	To obtain accurate Doppler measurements.
SENSITIVITY		
intensity	$< 1 \times 10^{-7}\ B_{\odot}$	To measure weak coronal emission out to 2 solar radii.
background rejection	$> 1 \times 10^{3}$	To observe under most sky conditions at a good site.

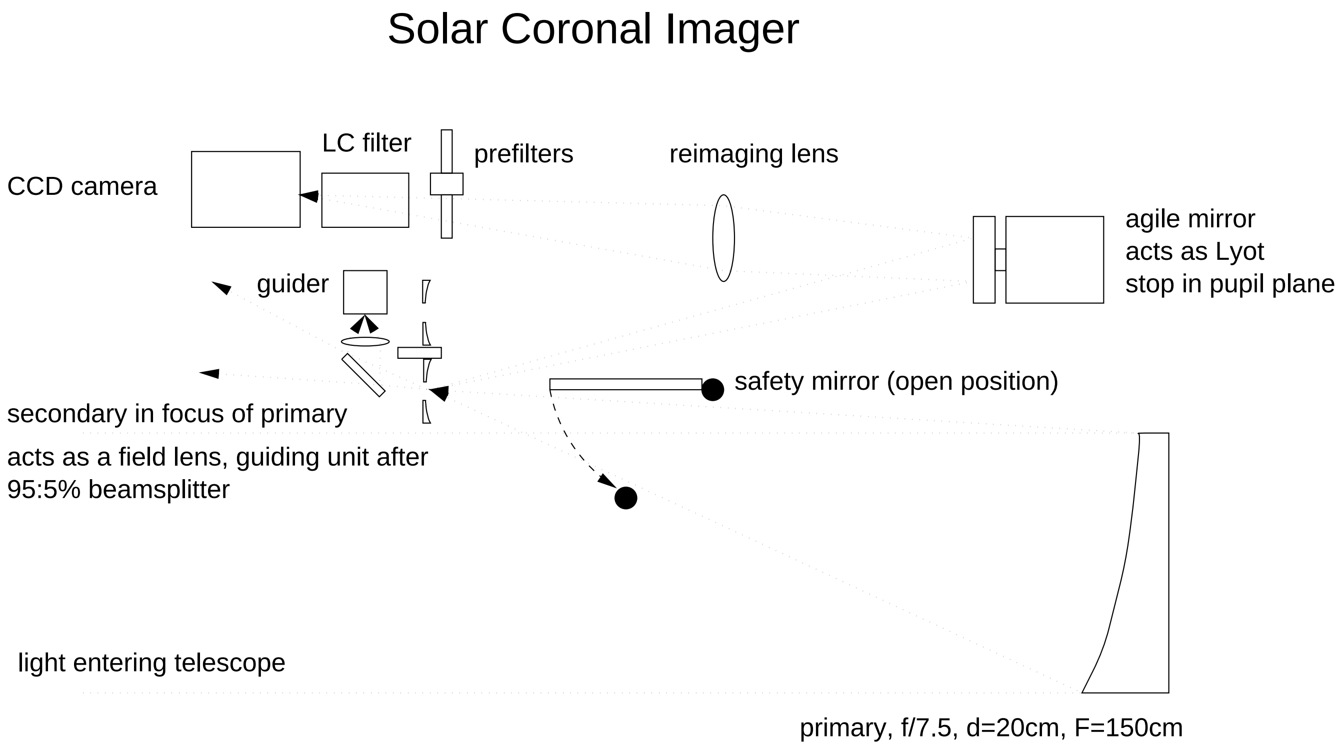

Figure 3. Conceptual layout of the Solar Coronal Imager.

6. INTEGRATED SUNLIGHT SPECTROMETER (ISS)

High resolution, precision solar spectroscopy is difficult. To date the best results have come from large FTS and double-pass grating spectrometers using single element detectors. Wavelength information is built up by scanning in time. The most challenging measurement is to get accurate line bisectors. The major problems are scattered light, poor spatial integration, and contamination of the wavelength scanned information by atmospheric fluctuations. Long-term stability is a major issue.

High spectral resolution is required, not only to resolve the solar spectrum line profiles, but also to at least partially resolve telluric line profiles that blend with several of the solar lines. A wide range of lines is needed to encompass the full range of diagnostic power offered to us by the visible solar spectrum. More than one line with particular characteristics should be observed to guard against the possibility that any single line is anomalous in some way. Table 4 lists the specifications for the Integrated Sunlight Spectrometer.

The McPherson Co. makes a two-meter focal length, f/14 double-pass spectrograph with resolution better than 0.5 pm that is the leading choice as the basis of the Integrated Sunlight Spectrometer. They also provide fiber-optic feed optical interfaces. Custom modification would include an intermediate shutter mechanism. The grating will be rotatable to select spectrum lines and for calibration purposes, but it will not be rocked to scan the spectrum line being measured.

The detector will be either a EG&G Reticon RA0564J, 512 by 64, 27 μm pixel spectroscopic format CCD, or a similar Hamamatsu device. It has a dynamic range in excess of 10000 per read. It will be mounted on a translation stage that moves it along the dispersion direction in a precisely controlled and repeatable way. The purpose of this is to permit calibration of the response of all of the pixels relative to each other. In addition, an observation will be done at least twice at slightly different grating angles to allow calibration of the spectral response of the spectrometer's focal plane.

The key problem is to scramble 350–1100 nm sunlight efficiently. Sunlight will be fed to the fixed spectrometer by means of a 600 μm UV-transmitting fiber optic cable system. Since fibers effectively scramble position on their

Table 4. Specifications for the integrated sunlight spectrometer.

Parameter	Goal	Rationale
<u>ANGULAR</u>		
coverage	full disk	To capture light from entire disk.
non-uniformity	$\leq$0.001	To evenly weight all parts of the disk.
tracking	$<2''$ rms	To keep noise low.
scattered light	$< 1 \times 10^{-3}$	To avoid sky spectrum contamination.
<u>TEMPORAL</u>		
time per line	$\leq$1 minute	To resolve and correct for 5-min oscillation.
accuracy	1 s	To correlate with other data.
<u>SPECTRAL</u>		
resolution	$\geq$300000	To resolve solar line profiles.
range	380–1100 nm	To cover wide range of diagnostic lines.
stability	$\leq 1 \times 10^{-6}$	To obtain accurate line profiles.
<u>INTENSITY</u>		
sensitivity	$< 1 \times 10^{-3}$	To obtain accurate line profiles.
non-linearity	$< 1 \times 10^{-3}$	To obtain accurate line profiles.
uniformity	$< 1 \times 10^{-4}$	To obtain accurate relative line profiles.

input face and input skew angle, but not input radial angle, a small optical system will focus a 400μm diameter image of the Sun on the input face of the fiber. This will have an effective focal length of 40 mm and an 8-mm aperture to match the f/5 fiber. The output beam from the fiber will then consist of sunlight scrambled in both angle and position so that any output angle from any position on the exit face will be well integrated. This light will proceed into a monochromator which will isolate the desired wavelength band, pass light through the entrance slit and uniformly fill the pupil stop in front of the grating.

7. SCHEDULING, DATA DISTRIBUTION, AND ARCHIVING

This proposal incorporates modern concepts of telescope scheduling. This new facility will be operating in a solar astronomy environment that includes other solar facilities, both national and international, and on Earth and in space. The ability to link ground and space observations and coordinate simultaneous observations between these varied facilities will essentially create a larger, virtual solar observatory. This introduces a revolutionary new science capability to solar physics. We plan to help realize the potential for truly simultaneous, multi-wavelength coverage by many solar facilities in planning for the operation and scheduling of this next-generation facility.

The scheduling process will be driven by assigning time to science programs rather than by assigning a predetermined set of days to a solar physicist. The Telescope Allocation Committee will be charged with assigning priorities to the science programs. The highest priority science programs will then be entered into the scheduling routine and carried out at the appropriate time based on conditions, activity, instrumentation, etc.

Provision for adding or removing programs will be provided and accomplished over the Internet using a well-defined scheduling algorithm that permits multiple different observing requests and synoptic programs to be run concurrently. Within every observing minute a number of different experiments may be executed following a scheduling algorithm that has well defined rules for resolving conflicts without observer intervention. Several models for the scheduling software are available. Data from different experiments will be output to different output devices, helical scan tape, CDs, or hard disk.

Along with automated operation of the facilities, the data will also be automatically processed, distributed and archived under computer control. As the data is obtained, it will be immediately placed in a real-time stream

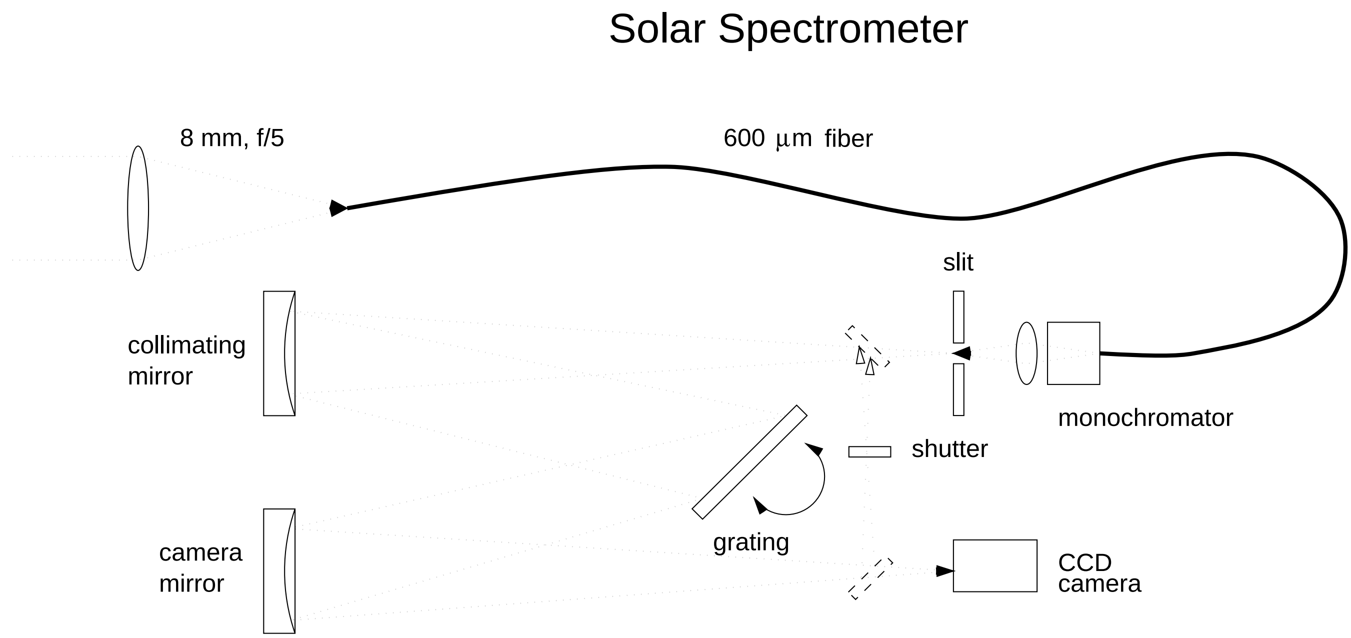

Figure 4. Conceptual layout of the Integrated Sunlight Spectrometer.

accessible at all times as compressed images over the Internet. A buffer will hold near-real time full-resolution data covering the last 10-100 images depending on the temporal frequency of the data. A pipeline scheduling agent will search for new data. When new data is found, the pipeline will automatically perform quality assessment and process it using a standard set of algorithms. After the processing finishes, a suite of selected data products will be transferred over the Internet without the need for operator intervention to scientific and government agencies that require the data.

A full set of both raw and processed data will be inserted into the NSO Digital Library. The product descriptors will be inserted into a relational database system accessible over the Internet via various World-Wide Web Browsers and anonymous FTP. The data should progress from instrument to archive in the amount of time held by the near real-time buffer. Thus, the entire data set obtained by the facility, from the beginning of operations up to the present moment, will always be available for use by the international solar physics community, mission agencies, and the general public.

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