Optical Design for a New Off-Axis 1.6 m Solar Telescope (NST) at Big Bear

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ABSTRACT

An optical design for a modern off-axis 1.6 m clear aperture solar telescope - the NST (New Solar Telescope) is presented. The NST will replace the 65 cm vacuum telescope at Big Bear Solar Observatory (BBSO) in 2006. A high-order Adaptive optics (AO) system will deliver light to the current and planned complement of BBSO instrumentation. The NST will fully utilize the optical and dynamical range advantages of its unobstructed (off-axis) pupil.

Keywords: Optical Design, Off-Axis Telescope, Adaptive Optics

1. INTRODUCTION

There are a few important reasons for upgrading existing 0.65 m vacuum solar telescope at Big Bear Solar Observatory (BBSO) with a modern larger size instrument. BBSO is an ideal site for high-resolution solar observations. It is situated in a mountain lake about 7,000 ft above the sea level. The Dome is located at the end of a 1000 ft long causeway with about two miles of open water to the west. Cool lake water with prevailing winds from the west provides a natural inversion and the ground-seeing problem is largely eliminated.[1, 2]

Some technological improvements (high-speed computers, real-time systems for analyzing and controlling position of telescope's optical elements) allow to develop and fully utilize advantages of off-axis telescopes, such as optical and dynamic range of unobstructed pupil with highest contrast and spatial resolution. The NST is a logical successor to 0.5 m SOLARC[3] and will benefit from a close working relationship with the National Solar Observatory (NSO) team that is currently designing the Advanced Technology Solar Telescope (ATST).[4]

In collaboration with NSO we are building two high-order adaptive optics (AO) system[5] - one for NSO and one for BBSO. The BBSO AO system,[6, 7] which is scheduled for its first light at BBSO in summer of 2003 will be used after some modernization for the NST beam. The AO system will provide diffraction limited images to an imaging (one for visible and one for near-infrared) magnetographs based on Fabry-Perot etalons.[8] These imaging magnetographs will also benefit from high-resolution NST setup.

Finally, the NST will be built at the existing Dome, replacing the 26" vacuum telescope and use its pedestal and all existing infrastructure, what makes the whole project relatively cheap and fast. First light for NST will be in late of 2005, with full operation in 2006. It will allow to extract the maximal science on solar dynamics and the origin of space weather from upcoming space missions, like SDO (Solar Dynamics Observatory, launch 2007), STEREO (Solar TErrestrial RElations Observatory, launch 2006) and SOLAR-B (launch 2006). Due to better spatial resolution of the NST (1.6 m aperture compare to 0.5 m for SOLAR-B) and unique IR capability of the NST, providing vector magnetograms and images to understand the magnetic evolution of CMEs (a major objective of the STEREO mission), the NST becomes a necessary and important element in a scientific chain of understanding many significant and dynamic solar phenomena.

The NST will achieve about 2.5 times better angular resolution of 0.08 arcsec (56 km on the solar surface) in the visible compare to 0.2 arcsec (140 km) for 26" telescope. NST will cover the wavelength range from 390 nm to a far-infrared (FIR). FIR instrumentation will be fed at a Nasmyth focal plane by a fully reflective optics with

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just three mirrors. Visible and near-infrared (NIR) set of instruments will be placed one floor below the NST on the optical tables, where both larger space and better observing conditions are present.

BBSO has an open data policy and NST will provide leading-edge capabilities to the NSF community. As a university-based facility, NST will make sustained, campaign-style high-resolution solar observations in a wide spectral range. Placed at an excellent observing site and equipped with high-order AO system, 1.6 m aperture off-axis NST will allow us to study spatial scales as small as 50-60 km in visible for testing flux models of fibers and tubes. Establishing the nature and dynamics of small-size activity elements is a key for understanding large-scale solar activity and the origins of space weather.

The NST project is a collaboration of BBSO/NJIT and the University of Hawaii (UH). We maintain collaborative discussions with the ATST group and GREGOR group.

2. NST REQUIREMENTS

A System Requirements Review (SRR) and Preliminary Design Review (PDR) for NST project are scheduled to be completed in 2003. Some of major topics to be reviewed are the system requirements, the major subsystems, the system design approach, the system requirements verification approach, the cost, schedule and personnel resources.

We summarized below in Table 1 some major science drivers for the NST. They allowed determination technical and optical requirements as a result of running a few so called "life cycles", including solved trade issues.

Table 1. Major Science Drivers for the NST.

A Science Driver	Its Main Features and Reasons
High resolution, high cadence studies of solar flares	A substantial improvement of both spatial resolution and cadence
Structure and Evolution of magnetic fields in flaring active regions	High precision polarimetry with Visible and IR vector magnetographs
Dynamics of kilogauss flux tubes	Precluding a Zeeman saturation with Fabry-Perot filters
Heating of the upper solar atmosphere	High sensitivity measurements of the quiet sun

Some of trade issues and optical requirements were solved as a best fit of optical design specifications to the existing Dome and telescope dimensions and limitations. For example, position of Secondary Mirror (SM), which determines both its size and reflected beam size was chosen as a compromise between image quality/tolerances and existing Declination axel dimensions. The effective focal length (related to the telescope f/number) was chosen as a compromise between image quality/tolerances and the best position for both Nasmyth and Gregory-coude focal planes. The position of Nasmyth focal plane is limited by telescope mount and Dome dimensions. It affects also position of Gregory-coude focal plane. Too short effective focal length would produce a Gregory-coude focal plane somewhere in beginning of the coude tube. As a result, it would require some large coude tube bearing assembly, as the beam after the focal plane is diverging. Any changes of telescope f/number also affect the level of modernization for existing AO design, which was developed to fit the 26" telescope with f/number = 52. Table 2 shows some of the NST and AO requirements.

There are a number of other solved trade issues not shown in the Table 2, such as a compromise between better position of PM from point of view telescope balancing, stability and polarization issues and telescope optical configuration. Say, it would be possible to reflect the beam from the SM directly to a coude mirror, having worse balancing and larger incoming beam angle. A schematic view of the 1.6 m off-axis NST is shown in Figure 1.

Table 2. Some of the NST and AO Requirements.

Optical configuration	Gregorian, off-axis
Aperture	1.6 m
Effective focal length	about 92 m
Telescope f/number	57.5
Parent f/number	about 0.73
Mount	Equatorial
Telescope Structure	Open with Fully Retractable Dome
Wavelengths	390 nm - 1600 nm (up to a far-infrared in a Nasmyth focal plane)
FOV	3 arcmin (up to 30 arcmin in prime focus for low-resolution nighttime observations
Optical Quality	about 0.1 arcsec over FOV
Polarizers size	less than 100 mm diameter
Adaptive Optics	0.3 to 0.5 Strehl within the isoplanatic angle
Telescope alignment	Three real-time subsystems for maintaining SM alignment

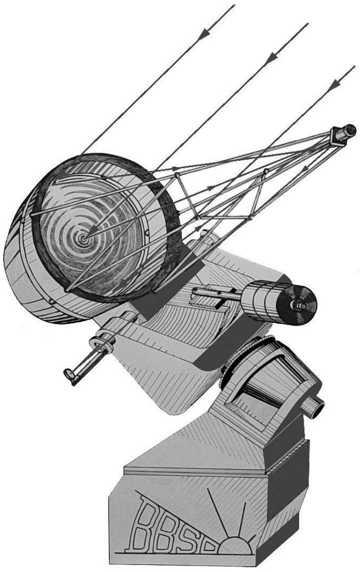

Figure 1. A schematic view of the 1.6 m off-axis NST. The primary mirror is as close to the Declination axis as possible with the existing space between fork's legs about 1.2 m. It makes the telescope balancing and mechanical stability better than for any other position of the PM. The optical path is indicated. The beam from the secondary mirror goes to a flat mirror and then to either the Nasmyth focal plane (far-IR instrumentation) or through a flip coude mirror to the Gregory-coude focal plane located on the polar axis and then to the Visible and near-IR instrumentation placed together with AO on the floor below.

The parent f/number, which for fixed aperture and PM focal length depends only of PM de-center was chosen larger than it could be from point of view optical design, to fit the University of Arizona Mirror Lab requirement on a large (about 3 mm) asphericity of the PM off-axis parabola. This requirement allows representing the polishing technology of the NST PM as a proof-of-concept for figuring seven 8.4 m mirrors for twin 21 m telescopes. Fitting this asphericity requirement, our 1.7 m blank is a scaled model (1:5) for their future work.

3. TELESCOPE OPTICAL DESIGN

The NST is an off-axis Gregorian configuration (see Figure 2) with parabolic f/2.4 PM (M1), elliptical SM (M2), removable for night-time observations Heat-Stop mirror (HS) and two flat folding mirrors M3 and M4. We chose an off-axis Gregorian configuration because of the reduction of stray light, also taking into account advantages of HS mirror (see below). The stray light may be greatly reduced by installing an appropriate Lyot diafragm into the exit pupil, which is located behind the SM. Further, some image improvements are connected with better telescope's MTF (Modulation Transfer Function) for an off-axis design without any central obstruction. The NST off-axis design is also free of mechanical limitation on existing space (about 1.2 m) between the fork legs. It means that existing mount may be used for building the NST.

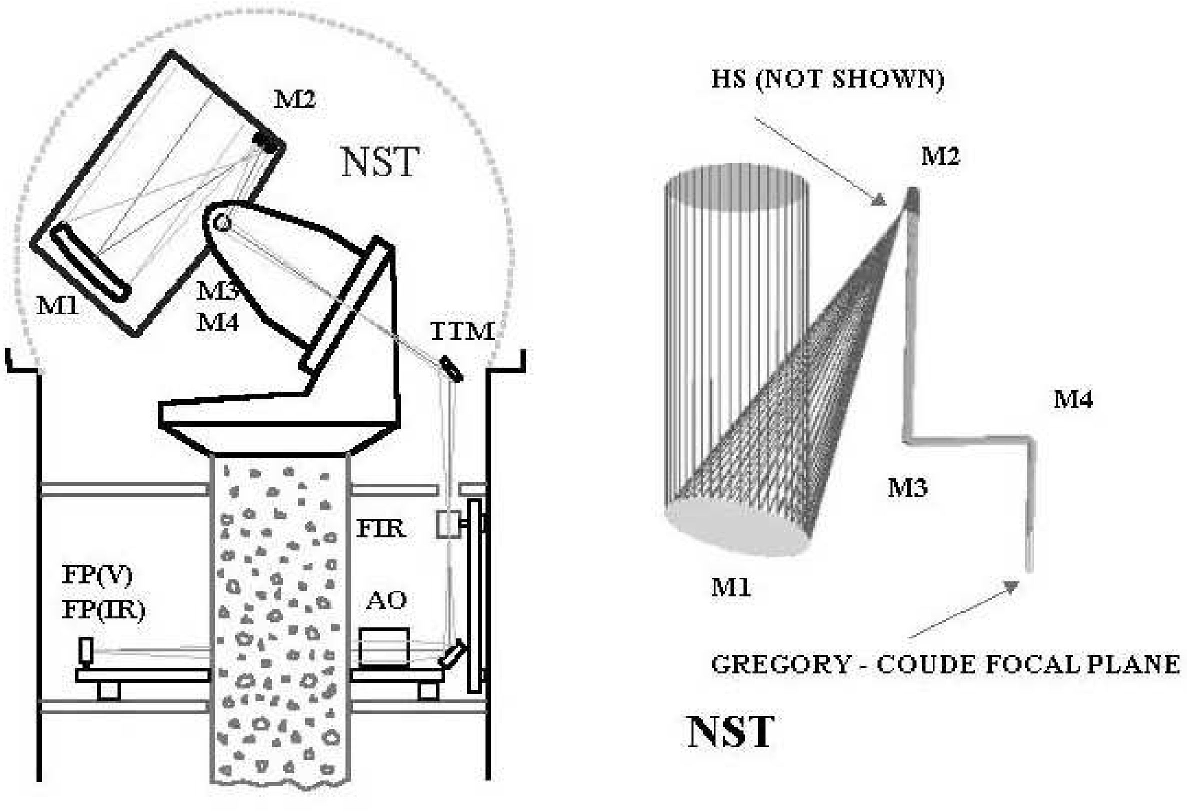

Figure 2. (Left) A schematic of the NST and its retractable Dome (not to scale). The main scientific instrumentation, including Visible and IR Fabry-Perot magnetographs, labeled FP(V) and FP(IR) as well as Adaptive Optics components, labeled AO are located on horizontal optical tables on the floor beneath the telescope. Far-IR (FIR) instrumentation may be placed on the Nasmyth focus or on the vertical optical table using just a Tip/Tilt mirror (TTM) for obtaining diffraction limited images. (Right) The optical layout of the NST with a true relative scale (a ZEMAX model). M1 is a parabolic primary mirror, Heat-stop mirror (not shown) is removable to use a prime focus for a wide-FOV night-time observations. M2 is an elliptical secondary mirror. M3 is a flat mirror for redirection the light along the Declination axis to either a flip coude mirror (M4) or to Nasmyth focal plane. The M3 may be a TTM if the FIR instrumentation is located on Nasmyth. Polarization optics will be set up between the M3 and M4 where the beam is close to parallel (f/number is 57.5).

3.1. Primary Mirror

The NST primary mirror (PM) is an off-axis parabolic mirror with optical and mechanical specification shown in Table 3.

Table 3. Optical and Mechanical Specification for the NST PM.

A Parameter, Units	Specification
Circular Aperture, mm	1600
Blank Diameter, mm	1700
Blank Shape	Meniscus
Blank Thickness, mm	100
Diameter/Thickness Ratio	17
PM Weight, kg	575
PM focal length, mm	3850
PM Vertex Radius , mm	7700
PM f/number	2.4
PM de-center , mm	1840
PM Surface Quality (RMS) , nm	21
PM Surface Finishing , nm	1.0 – 1.5
PM Parent Diameter , mm	5282
PM Parent f/number	0.73

The PM blank is made from zerodur - low thermal expansion glass ceramic. The 100 mm thickness was chosen as a compromise between PM thermal inertia and its mechanical flexibility, actually, the number (and price) of actuators for compensating a gravity sag and thermal distortions. A preliminary FEA model with 36 actuators shows (Figure 3) axial RMS surface errors about 5 nm.

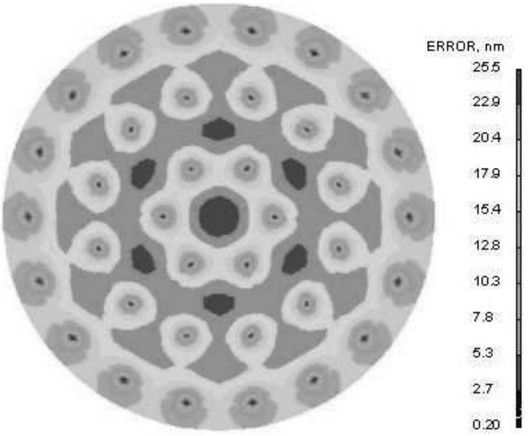

Figure 3. A result of FEA modeling for the NST PM surface errors for a system with 36 axial actuators. After removing artificial pimples created by a FEA model from numerical analysis, the maximal errors (PTV) amplitude is about 26 nm, with RMS error about 5 nm.

The goal of the PM active support is to decrease a combined error on the PM surface to an amount, which allows the level of combined wave-front aberrations (including all other mirrors) correspondent to a diffraction limited image quality in the Gregory-coude focal plane, taking into account that combined RMS surface error of other three telescope mirrors is expected to be less than 39 nm due to their small sizes and large thickness (mean diameter/thickness ratio is about 3).

3.2. Heat Stop Mirror

The Heat-Stop Mirror (HS) is an important advantage of the Gregory optical configuration for some scientific tasks where a small portion of solar disk, like an Active Region is studied. In this case all unwanted light may be rejected by a HS, substantially decreasing amount of solar irradiation which heats the SM and other subsequent optics. Off-axis design has an additional (to an on-axis scheme) advantage for HS mirror (we do not mention here the absence of central obstruction because usually HS mirror is in a shadow of SM). This advantage is a possibility to reflect the unwanted light in a transversal plane to the incoming beam (to a PM) and outgoing beam (from a SM) plane.

The HS is located at the primary focus. For night-time observations in the primer focus with a wide FOV, the HS may be removed from its position, allow placing a camera in the primer focus. In our NST design the HS has a central cone, which allows to transmit about 3 arcmin FOV to subsequent optics. All other portion of light is reflected by front surface of the HS with reflectivity better than 55%. One of possible designs of HS includes a flat plate (or slightly convex) front surface mirror. The internal body of HS has a number of channels for circulation a cooling agent. Cooling agent's temperature will be controlled by a thermal system (see below) with about 10-15 C difference with the ambient temperature to maintain the HS temperature equal to the ambient. This condition will prevent thermal air turbulence from HS mirror.

3.3. Secondary Mirror

The Secondary Mirror (SM) specification is shown in Table 4.

Table 4. Optical and Mechanical Specification for the NST SM.

A Parameter, Units	Specification
Aperture, mm	127.4
Blank Diameter, mm	435 (for two SMs)
Blank Shape	Meniscus
Blank Thickness, mm	45
SM Diameter, mm	139
Diameter/Thickness Ratio for SM	3
SM Weight, kg	1.75
SM conic number	-0.84577
SM foci, mm	300 and 7168
SM Vertex Radius , mm	575.9
SM de-center , mm	143
SM Surface Quality (RMS) , nm	21
SM Surface Finishing , nm	1.0 – 1.5
SM Parent Diameter , mm	413.2

The SM will be a part of a real-time control system for detecting its misalignment compare to the best aligned position and for maintaining its alignment inside a range of determined tolerances. The tolerances for position of SM are: ± 5 arcsec for SM tilts, ± 0.01 mm for SM decentering and ± 0.02 mm for SM shifting.

The size (and position) of the SM in NST optical design was chosen as a result of a few side compromise between mechanical issues of existing telescope mount, image quality in the Gregory-coude focal plane and tolerances. Say, for the same telescope f/number increasing a distance from the primer focus to the SM on about 17% will improve the merit function on about 9%, but the SM Parent diameter will be changed from 413.2 mm to 481.5 mm, or be about 17% larger. It will also increase the reflected beam size.

The SM real-time control system allows to have quite soft tolerances on the NST's Optical Support Structure (OSS). It means that an OSS may be made from common use and cheap materials without any special requirements on their CTE (Coefficient of Thermal Expansion).

3.4. Polarization

The NST will utilize both the Visible-light Imaging vector Magnetograph (VIM) and the Infra-Red Imaging vector Magnetograph (IRIM). These Magnetographs will use some polarizing optics. The polarizing optics is installed between M3 and M4 (Figure 2, right) where the beam has diameter about 93 mm and is close to parallel. This place is also convenient from point of view using the polarizing optics for both coude optical path and Nasmyth instrumentation. Besides, it is easily reachable place on the telescope mount.

Each of two science channels on the second floor (Visible and IR) may require some additional polarizing optics to compensate some instrumental polarization related with a number of fold mirrors.

3.5. Thermal Systems

There will be four high-precision thermal systems for the four mirrors (M1, HS, M2 and M3 and a few more simplified for a number of other mirrors. The goal of a thermal system is to control the temperature difference between the mirror surface and ambient air on a level of about 1 K. Absorbed power and heat flux for a number of mirrors are shown in Table 5.

Table 5. Absorbed power and heat flux for the NST mirrors

A Mirror	Diameter (size), mm	Incident Power, W	Absorbed Power, W	Heat Flux, W/m^2
M1 (PM)	1700	3063	306	134.8
HS	250	2757	1227	25000
M2 (SM)	139	30	3	198
M3 (NM)	120	27	2.7	239
M4 (CM)	100	24.3	2.4	306
M5 (TTM)	45 x 70	21.9	2.2	698
M6 (CLM)	110	19.7	2.0	210
M7 (DM)	80	17.7	1.8	358
M8 (FM)	70	15.9	1.6	415

Calculations of the Absorbed Power for PM, SM, Nasmyth Mirror (NM), Coude Mirror (CM), Tip/Tilt Mirror (TTM), Collimator Mirror (CLM), Deformable Mirror (DM), and Fold Mirror (FM) were done with assumption that each of these mirrors reflects 90% of the incident power and absorbs 10%. For HS mirror we assumed it will reflect as a minimum 55% of incident power and absorb 45% of the power. The circular hole (about 200 arcsec diameter) in the HS will transmit to the SM a portion of incident power in a ratio of 200^2 / 1920^2. The Heat flux was determined as absorbed power divided by the area of the mirror.

Thermal systems will utilize about 50 temperature sensors to detect thermal variations on the mirrors and inside the Dome. Controlled temperature and clean air will be used in air-knives to produce close to laminar air flows above the mirrors. Small mirrors may be edge-cooled by a water or air.

3.6. Optical Support Structure

The main constructive mechanical component of the Optical Support Structure (OSS) is a metal hollow round-shaped box (Figure 4), which bears the PM cell assembly from one side and the SM support structure from another side. This hollow box is fixed to the existing telescope mount box, which supports now the 26” vacuum telescope, two refractors and counterweights.

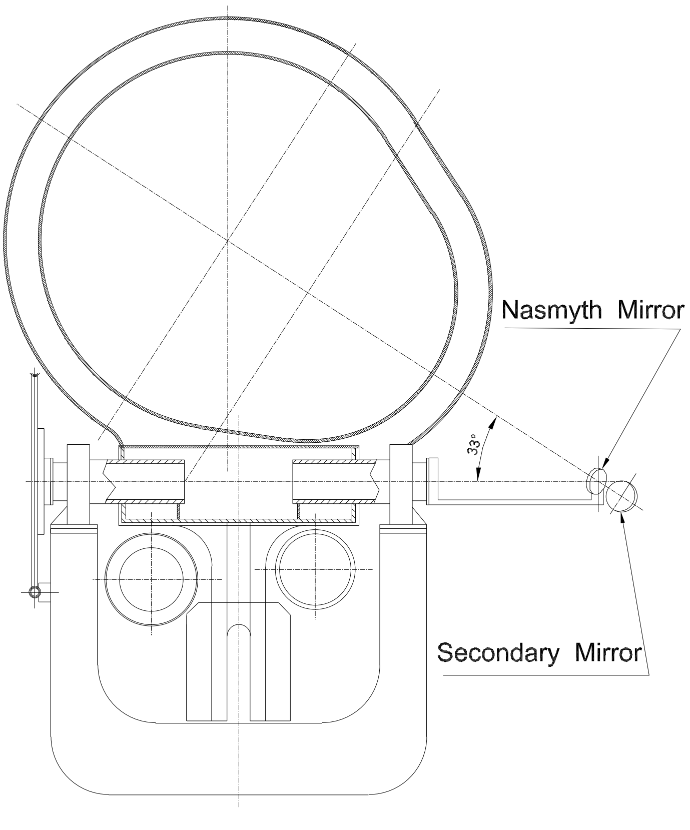

Figure 4. It shows in a projection on the polar axis plane the existing telescope mount after some modernization together with a mechanical interface, which bears both the PM cell (not shown) and SM structure (not shown). Two existing refractors are shown below the DEC axel.

4. ADAPTIVE OPTICS

The NST will be installed at an excellent daytime site, at BBSO, where some steady periods with the Fried parameter in visible is 20 cm (from ATST site survey telescope). Nevertheless, to address many of the outstanding problems in solar physics, especially those requiring high spatial resolution studies of the sun, the NST will utilize a high-order AO system. Currently NSF-MRI has funded the construction and implementation of two high-order AO systems - one for BBSO and second for the Dunn Solar Telescope (NSO) - the AO-76 Project. The BBSO AO system will be upgraded to work with the NST. The upgraded AO system will use some new optical components, new alignment procedure. On the second stage of the NST project we expect to upgrade the Deformable Mirror (DM) to a larger size as well as Visible and IR Fabry-Perot filters.

The main components of the BBSO AO system - Tip/Tilt Mirror (TTM) channel and Wave-Front (WF) channel are described[6] in details for the AO-76 Project. These components together with visible and IR science channels will be installed for the NST on the same optical tables as they are now.

There is a vertical optical table installed in the coude room as a place for some optical components between the Telescope and science channels. This vertical table may be used for installing two additional deformable mirrors to obtain a Multi-Conjugate AO.

4.1. Scientific Channels

There are a few on-going instrumentation projects at BBSO. They will benefit from high-contrast and high-resolution images taken with 1.6 m aperture. Both the Visible (V) light and Infrared (IR) vector magnetographs[8] will be able to make much more accurate measurements of evolving magnetic fields in flare-producing active regions. They will use correspondent Fabry-Perot filters to provide the spectral line profile and the full Stokes vector. For the first stage of the NST project we will use 70 mm diameter Fabry-Perots.

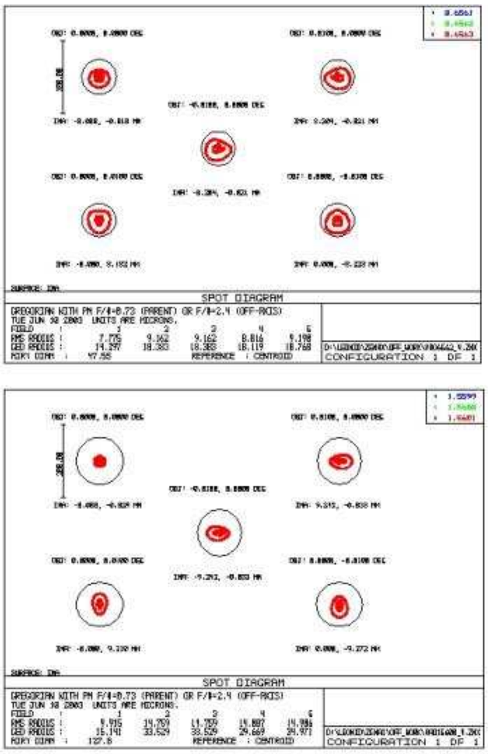

Figure 5. Spot diagrams show diffraction limited image quality for H α (top) and a 15600 Å spectral lines (bottom) in both V and IR science channels. The FOV is 80 arcsec and f/numbers are about 29.7 and 33.6 accordingly.

As the optical configurations for V and IR are based on telecentric designs, it requires some reduced FOV (about 80 arcsec) for chosen telecentric beam f/number about 110. Upgrading the science channels for working with 3 arcmin FOV will require purchasing larger Fabry-Perot filters (about 150 mm clear aperture). Optical specification for V and IR Magnetographs is shown in Table 6.

Real-Time Image Reconstruction (RTIR) algorithm does not require a special optical equipment and will be used for post-facto images processing to achieve diffraction limited observations.[9] The RTIR will use the speckle masking imaging technique in a combination with a parallel computer built of 32 1.8 GHz AMD Athlon processors. It will allow near real-time image reconstruction with a cadence of approximately 1 min. A time for image processing using a single CPU is usually a few hours for a middle size images.

Table 6. Optical Specification for V and IR Fabry-Perot (F-P) based Magnetographs.

A Parameter, Units	Visible	IR
F-P Circular Aperture, mm	70	70
FSR, Å	4.0	5.5
Spectral Window, m Å	72	133
Optical Configuration	Telecentric	Telecentric
F/number at F-P location	105	121
Beam diameter at F-P location (FOV=80"), mm	69	69
Prefilter diameter , mm	50	37

Speckle masking imaging works with a sequence of short-exposure images to "freeze" the wave front aberrations. This way the object information may be separated from the atmospheric turbulence. Adaptive Optics will not replace the RTIR as it improves images in a single isoplanatic patch. RTIR will not replace the AO as AO allows to collect high-quality images with a cadence of 0.1 - 0.25 sec. High-contrast images are also necessary for effective image reconstruction. Working together they will provide a new window for studying solar dynamics and evolution of the photosphere structures.

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