

Optical System Design of the NVST Magnetograph Based on Lyot Filter (Postprint)

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Abstract

China's 1-meter New Vacuum Solar Telescope (NVST) can achieve high-resolution imaging observations superior to 0.2 arcseconds, but does not yet possess routine observation capabilities for high-resolution magnetic fields. Many magnetic structures and solar activities exist at small scales, necessitating high-resolution magnetic field measurements. The NVST site exhibits excellent seeing conditions; if the magnetograph is equipped with rapid modulation capability and combined with high-resolution statistical reconstruction techniques, it is expected to achieve sub-arcsecond resolution solar magnetic field measurements. The primary challenges for magnetic field measurement with the NVST include time-varying polarization introduced by the folded optical path, optical axis offset due to telescope attitude variations and wind loading, as well as turbulence effects, among other issues. To address the requirements for high-resolution solar magnetic field observations and the measurement challenges faced by the NVST, we have conducted a detailed analysis of the solar photospheric magnetic field measurement requirements for the NVST, established the basic parameters of the magnetograph, proposed requirements for the polarization analyzer, and designed a high-resolution observation scheme for the photospheric magnetic field. Finally, the optical path for the magnetograph was designed using ZEMAX optical design software, with results demonstrating that the optical design can satisfy the requirements for high-resolution imaging.

Full Text

Optical System Design of the Magnetograph for the 1 m New Vacuum Solar Telescope

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Abstract

The 1 m New Vacuum Solar Telescope (NVST) is capable of high-resolution imaging observations better than 0.2", but has not yet achieved routine high-resolution magnetic field measurements. Many magnetic structures and solar activities exist at small scales, requiring high-resolution magnetic field observations. The NVST site at Fuxian Lake offers excellent seeing conditions, and if the magnetograph possesses fast modulation capabilities combined with high-resolution statistical reconstruction techniques, sub-arcsecond resolution solar magnetic field measurements should be achievable. The primary challenges for magnetic field measurement with NVST include time-varying polarization introduced by the Coude optical path, optical axis shifts caused by telescope attitude changes and wind loading, and atmospheric turbulence effects. This paper analyzes in detail the requirements for high-resolution solar magnetic field observations and the specific measurement problems faced by NVST, formulates the basic parameters of the magnetograph, proposes requirements for the polarization analyzer, and designs a high-resolution observation scheme for photospheric magnetic fields. Finally, the optical path for the magnetograph is designed using ZEMAX optical design software, and the results demonstrate that the optical design meets the requirements for high-resolution imaging.

Keywords: solar magnetograph; Lyot filter; mounting in optical path; optical design

1. Requirements Analysis for NVST Photospheric Magnetic Field Measurement

1.1 Basic Parameters of the Magnetic Field Measurement Equipment

The fundamental parameters for photospheric magnetic field measurement include the magnetically sensitive spectral lines, field of view, effective aperture, polarization analyzer effective aperture, and acquisition frequency. In the visible band, numerous photospheric magnetically sensitive lines are available, with

Fe I 532.4 nm, Fe I 617.3 nm, and Fe I 630.2 nm being commonly used. The ASO-S/Full-disk MagnetoGraph (FMG) employs Fe I 532.4 nm for photospheric magnetic field measurements, while SDO/HMI uses Fe I 617.3 nm and Hinode/SOT uses Fe I 630.2 nm. To facilitate comparison and joint observations with space-based solar missions, NVST has selected these three lines as its primary magnetic field measurement lines, with the capability to switch between them by changing pre-filters and adjusting the filter.

The NVST magnetograph is intended for high-resolution magnetic field observations of the solar photosphere, requiring spatial resolution approaching the system's diffraction limit. With a 1 m aperture, NVST has a diffraction-limited resolution of 0.11 at 617.3 nm and 0.127 at 532.4 nm. The maximum field of view is 180 (40 mm). The available detector is a 2048×2048 sCMOS. To meet the diffraction-limited imaging requirements at 532.4 nm, the pixel resolution is determined to be 0.06 , corresponding to a field of view of 123×123 . At 617.3 nm, the pixel resolution is 0.12 , meeting the diffraction-limited imaging requirement and providing a field of view of 246×246 .

The NVST magnetograph filter will utilize a domestically developed Lyot filter with mature technology and excellent stability. The core optical component of the Lyot filter is Iceland crystal, with optical-grade Iceland crystal available in effective apertures exceeding 40 mm, thus the effective aperture is set at 40 mm. The filter bandwidth is ± 0.01 nm, with a wavelength scanning range of ± 0.3 nm. The polarization analyzer must be installed after the filter, so its effective aperture cannot be smaller than 40 mm.

The classical atmospheric coherence time is 10 ms. To enable high-resolution magnetic field measurements using high-resolution reconstruction techniques, the exposure time must be shorter than the coherence time, typically around 10 ms. At a single wavelength point, the magnetograph's low transmission results in a modulation time of 20–30 ms per polarization state. The ideal acquisition rate would be 100 ms for all polarization states, yielding 10 frames of polarization images per second. To address atmospheric transmission fluctuations, the polarization analyzer requires modulation speeds for all polarization states to be less than 100 ms.

1.2 Time-Varying Instrumental Polarization and Polarization Analyzer Requirements All NVST instruments are installed at the f/42 Coude focus, where a rotating instrument platform eliminates image field rotation. The Coude optical system introduces significant time-varying instrumental polarization. The polarization response matrix X describes the instrument's polarization characteristics, defined as $S = X \cdot S$, where S and S are the Stokes vectors of the incident and emergent light from the telescope, respectively. Through polarization calibration of NVST, the polarization response matrix shows substantial crosstalk between I and Q, U, V components, and this instrumental polarization is time-varying, changing with season and time.

To eliminate crosstalk effects, we must measure all Stokes components and combine them with the polarization calibration model during data processing. The Huairou Solar Magnetic Field Telescope employs a KD*P polarization analyzer with high-speed modulation capability between two polarization states, but requires mechanical switching of waveplates for Q, U, and V observations, which cannot meet NVST's requirements. The liquid crystal variable retarder (LCVR) scheme offers fast modulation among all polarization states with mature technology and is therefore a viable option.

A plane mirror M3 between the instrument platform and Coude optical system changes the optical path from vertical to horizontal. The relative rotation between the instrument platform and Coude optical system introduces time-varying instrumental polarization not included in the telescope's polarization model. A feasible solution is to design a polarization-compensating element in the magnetograph optical system. This mirror can also function as a fast steering mirror to correct optical axis deviations caused by tracking errors and wind disturbances.

2. High-Resolution Observation Scheme for Photospheric Magnetic Field

Leveraging the excellent atmospheric seeing at the Fuxian Lake Solar Observatory, high-resolution magnetic field observations with the NVST magnetograph will primarily employ high-resolution statistical reconstruction techniques. Once the observation and data processing pipeline are stabilized, we can attempt magnetic field measurements using NVST's existing adaptive optics system. The high-resolution magnetic field measurement approach involves simultaneous observations with both broadband and magnetic measurement channels, using the broadband channel for high-resolution reconstruction and applying these results to reconstruct the magnetic measurement channel data.

High-resolution reconstruction techniques statistically combine multiple short-exposure images, requiring sufficient signal-to-noise ratio in each frame. The narrowband filter's half-width must reach at least 0.01 nm. The NVST magnetograph uses a birefringent filter with transmission approaching 40%, resulting in weak light intensity signals at the polarization spectral measurement channel detector, which reduces high-resolution reconstruction accuracy. Therefore, a beam-splitting prism is placed before the polarization analyzer to divert part of the light to a synchronous channel for simultaneous imaging with the polarization spectral measurement channel.

Broadband images, having high signal-to-noise ratio, can be used not only for synchronous reconstruction but also to measure and correct atmospheric transmission fluctuations and the anisoplanatic effects of turbulent atmosphere. The instantaneous optical transfer function (OTF) can be obtained from reconstructed broadband images and used to deconvolve the simultaneously recorded

narrowband images. The phase-diversity method is an effective technique for calculating the atmospheric point spread function (PSF) and is one of the high-resolution reconstruction methods employed by the telescope. This method relies on defocused and focused images captured in the synchronous channel to calculate the atmospheric PSF. A telecentric optical path ensures that defocused and focused images have the same scale, avoiding errors introduced by magnification changes.

To facilitate image registration between the two channels, the synchronous and polarization spectral measurement channels must have identical image specifications, requiring identical fields of view and resolution. This necessitates using the same detector for both channels and designing the imaging paths as telecentric. A field calibration unit is placed at the field stop for calibration, with image clarity adjusted by repositioning the detector. During observations, both channels maintain focus through the telecentric design, preventing image scale changes due to defocusing.

3. Optical System Design of the NVST Magnetograph

The optical design process begins with Gaussian optics to determine beam apertures and assign light-gathering power to each optical group. Since the filter and polarization analyzer have already been manufactured, their apertures are fixed, and vignetting must be avoided. Gaussian design can preliminarily determine the apertures of optical elements, focal lengths of each group, and the overall structure.

The NVST field of view is limited by the field stop at the prime focus, producing an image height of 39.3 mm. A collimator lens L1 with focal length 420 mm produces a beam diameter of 10 mm at the pupil, where a folding mirror is placed. The Lyot filter's thickest stage is positioned after the pupil. The beam passes through the filter and is then imaged by an imaging lens L2 with focal length 550 mm, yielding an image height of 19.5 mm. The synchronous channel has an F-number of 22.8.

After obtaining the basic optical system structure from Gaussian design, ZEMAX optical design software is used to correct aberrations. Designing the entire system at once reduces optimization speed, so a stepwise approach is adopted. Based on the Gaussian design's power distribution, a double-telecentric initial structure is constructed by scaling doublet components from the ZEMAX patent library. Both conventional optimization and hammer optimization are employed to achieve structures meeting aberration requirements. Multiple configurations are built to simultaneously optimize the polarization spectral measurement channel and the entire system's total focal length. The image quality at both focal planes must meet design requirements, as detectors are placed at each. Although multiple configurations increase system complexity and reduce optimization speed, the final design achieves diffraction-limited performance in

both channels.

4. Design Results and Analysis

The design results show that the magnetograph optical path achieves diffraction-limited performance in both channels. Figure 3 presents the modulation transfer function (MTF) and spot diagrams for the polarization spectral measurement channel (left column) and synchronous channel (right column). The MTF approaches the diffraction limit and demonstrates good consistency between channels. The spot diagrams show that the spot sizes for both channels do not exceed the Airy disk diameter of 17.17 m .

Figure 4 shows the wavefront aberrations for both channels. The polarization spectral measurement channel has a peak-to-valley (PV) wavefront aberration of 0.163λ and root-mean-square (RMS) value of 0.0244λ at the edge field of view, and 0.1516λ PV and 0.0119λ RMS at the center field. The synchronous channel has 0.163λ PV and 0.0244λ RMS at the edge field. All values meet the diffraction limit criterion of $< \lambda/14$ RMS.

Distortion between the synchronous and polarization spectral measurement channels is a critical factor affecting synchronous reconstruction. Both channels' distortions are controlled within extremely small ranges. Since the polarization spectral measurement channel follows the synchronous channel, the latter contributes to the former's aberrations. This requires the two channels to have opposite distortion signs to control the polarization spectral measurement channel's distortion within 0.05%. The synchronous channel's relative distortion is controlled to a maximum of 0.0053%, while the polarization spectral measurement channel's minimum distortion is -0.021%. At 1/2 image height, the synchronous channel measures 9.767 mm and the polarization spectral measurement channel measures 9.758 mm.

5. Conclusion

The magnetograph is a crucial instrument for achieving high-resolution magnetic field measurements with ground-based solar telescopes. Extensive research has been conducted on high-resolution magnetic field measurements for NVST. The successful development and trial observation of the liquid crystal Lyot filter enables the magnetograph with fast modulation capability, allowing polarization information to be measured within atmospheric coherence time. This represents a significant step toward achieving high-resolution magnetic field observations with NVST.

Based on problems identified in preliminary experiments, this paper establishes optical design objectives for the magnetograph's synchronous reconstruction system according to image processing requirements. The design considers the

requirements for ground-based magnetographs, incorporates NVST's structural characteristics and data processing needs, and achieves diffraction-limited imaging with controlled distortion.

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Note: Figure translations are in progress. See original paper for figures.

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