Design and Implementation of the Spatial Two-Dimensional Polarization Spectroscopy Observation Mode for the 1-m New Vacuum Solar Telescope at Fuxian Lake (Postprint)

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Abstract

As one of the observing terminals of the Fuxian Lake 1m New Vacuum Solar Telescope, the multi-band spectrometer must possess two observation modes—namely, spatial two-dimensional scanning observation and polarimetric spectral measurement—to achieve the scientific objective of diagnosing solar vector magnetic fields and their dynamic characteristics. This work focuses precisely on architecting and implementing these two observation modes. First, we clarify the basic requirements that the observation modes impose on three critical opto-mechanical components: the spatial scanning mechanism, polarimetric analyzer, and instrumental polarization calibration mechanism. Second, from the perspective of observational solar physics needs, we analyze the specific implementation methods for these requirements (continuous or stepwise), control precision (10^-2 or 10^-3), and signal-to-noise ratio improvement methods (multi-frame stacking or multi-group stacking), among other aspects. Finally, we organize and present flowcharts for various observation modes, integrate different observation modes into a unified acquisition control program, and deploy it for actual observation. We have respectively conducted multiple sets of two-dimensional spatial scanning observations of active regions and polarimetric spectral measurements of sunspots, achieving favorable results.

Full Text

Preamble

The Design and Implementation of Spatially Two-Dimensional Polarimetric Spectral Observation Modes for the Fuxian Lake 1-meter New Vacuum Solar Telescope

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Abstract

As one of the observing terminals of the Fuxian Lake 1-meter New Vacuum Solar Telescope (NVST), the multi-band spectrometer must support two primary observation modes: spatially two-dimensional scanning and polarimetric spectral measurement. These capabilities enable the scientific objectives of diagnosing solar vector magnetic fields and their dynamic characteristics. This work focuses on the architecture and implementation of these two observation modes. We first establish the fundamental requirements for three critical opto-mechanical components: the spatial scanning mechanism, polarimetric analyzer, and instrumental polarization calibration unit. From the perspective of practical solar physics needs, we analyze the specific implementation methods (continuous or stepwise), control precision requirements (10 ^{2} or 10 ^{3}), and signal-to-noise ratio enhancement techniques (multi-frame or multi-group stacking). Finally, we present flowcharts for various observation modes and integrate them into a unified acquisition control program. Field tests have been conducted with multiple sets of two-dimensional spatial scanning observations of active regions and polarimetric spectral measurements of sunspots, yielding satisfactory results.

Keywords: solar spectrum, polarimetric spectral measurement, spatial two-dimensional scanning, observation mode

0. Introduction

The terminal observing system of the 1-meter New Vacuum Solar Telescope (NVST) at Fuxian Lake primarily comprises the multi-channel high-resolution imaging system and the multi-band slit-grating spectrometer. The imaging system includes three narrowband channels (H-alpha 656.3 nm, He I 1083 nm, and Ca II 393.3 nm) and two broadband channels (G-band 430 nm and TiO 705.8 nm). The multi-band spectrometer covers two classical chromospheric lines (H-alpha 656.3 nm and Ca II 854.2 nm) and one photospheric line (Fe I 532.4 nm). Table 1 lists the basic parameters and routine working lines of the spectrometer. Notably, Fe I 532.4 nm has a Landé factor of 1.5, making it the primary wavelength for photospheric magnetic field measurements in China.

Figure 1 [Figure 1: see original paper] shows a side-view schematic of the two terminal systems. The imaging system and spectrometer are arranged orthogonally in space and have been precisely co-aligned to achieve a common focal point and field of view during installation and adjustment. The 45° mirror functions as a beam splitter, directing telescope light into both systems. Multiple

45° mirrors can be interchanged to meet different scientific requirements. For routine chromospheric spectral observations (H-alpha 656.3 nm or Ca II 854.2 nm), a full-band 1:9 beam splitter is used, transmitting 90% of photons into the spectrometer system to generate high signal-to-noise ratio (SNR) chromospheric spectra, while reflecting the remaining 10% into the imaging system—sufficient for obtaining high-SNR images in the broadband channels. In this mode, the imaging system serves as a slit-position monitoring system for the spectrometer. For photospheric polarimetric measurements, a bandpass beam splitter is employed, transmitting the Fe I 532.4 nm band to the spectrometer for polarimetric analysis while reflecting other bands such as H-alpha 656.3 nm and TiO 705.8 nm to the imaging system. This configuration enables simultaneous photospheric magnetic field measurements and acquisition of chromospheric and photospheric two-dimensional images of the target region.

In practical operation, beyond the selection of the 45° beam splitter, the three most critical components in the optical path are the spatial scanning mechanism (field scanner), polarimetric analyzer (polarimeter), and instrumental polarization calibration unit. The field scanner, positioned before the beam splitter, enables two-dimensional spatial spectral observations by moving the solar image relative to the spectrometer slit. The polarimeter, located after the beam splitter and before the slit, modulates the four Stokes parameters (I, Q, U, V) into signals of different frequencies or phases. The calibration unit, placed near the telescope’ s F2 focus, is only inserted into the optical path during calibration to generate standard polarization signals for characterizing the telescope’ s instrumental polarization.

Currently, the NVST’ s spectral observation modes include routine spectral mode, polarimetric spectral mode, and polarimetric calibration mode. The routine and polarimetric modes must integrate with the scanning mechanism for two-dimensional spatial scanning observations. To meet these requirements, the three mechanisms and the backend detector must operate in an orderly and rapid alternating sequence. Furthermore, to facilitate observer operation and minimize human error, all observation modes should be integrated into a comprehensive framework, posing significant challenges for the design and implementation of the overall observation system.

1. Analysis of Key Mechanism Control Requirements

All observation modes of the NVST spectrometer are primarily realized through control of the field scanner, polarimeter, and calibration unit. We therefore begin by establishing the scientific requirements for each component’s operation.

1.1 Requirements for Spatial Scanning Mode

The field scanner consists of two sets of K-mirrors and an electrically controlled vertical translation stage. The translation stage, manufactured by Beijing Zolix with an external grating scale, achieves a closed-loop resolution of 1 μm, repeat positioning accuracy of 2 µm, and reset accuracy error of 4%. During initial development and alignment, two fundamental scanning requirements were met: fixed scanning direction (perpendicular to the slit) and repeatable targeting of observation objects.

However, field tests revealed that more critical requirements concern the scanning process itself—specifically, the scanning mode. The translation stage' s motion enables two scanning patterns (Figure 2 [Figure 2: see original paper]): (1) **Continuous scanning mode** (Figure 2a), where the stage moves uniformly from start to end position; and (2) **Step-by-step scanning mode** (Figure 2b), where the stage moves a fixed distance, pauses, receives the next command, moves the same distance again, and repeats until reaching the target position.

Continuous scanning requires no communication with the polarimeter or detector—only an appropriate scanning speed must be selected. However, from the detector' s acquisition perspective alone, continuous scanning misses portions of the scanned area. For a typical CCD, data acquisition comprises exposure time and readout time, during which the scanning mechanism continues moving, leaving the traversed region unobserved. Consequently, the final acquired region is discontinuous.

Beyond detector acquisition, two additional issues cannot be ignored: (1) NVST ultimately aims to achieve two-dimensional polarimetric spectral observations, which require polarimetric modulation at each spatial position with an absolutely stationary slit, making continuous scanning completely unsuitable. (2) NVST currently lacks an image stabilization system. Under the influence of telescope tracking accuracy, wind, or seeing, the solar image jitters randomly at approximately 1 Hz with amplitudes exceeding 1 arcsecond. In this situation, the actual scanned field deviates significantly from the preset field, resulting in low effective spatial sampling.

Based on this analysis, NVST' s scanning mechanism adopts step-by-step scanning for scientific observations, waiting for completion of polarimetric measurements or detector acquisition before moving to the next position.

Even with step-by-step scanning, field tests showed that solar image jitter still compromised spatial sampling. In routine spectral scanning (without polarimeter motion), the step size is typically set to the slit width (the red narrow band in Figure 2, representing spatial sampling width). NVST commonly uses a 100 µm slit width, corresponding to 0.45 arcseconds on the solar disk. However, due to image jitter, the scanned region is not sampled at equal intervals by the slit, producing the pattern shown in Figure 3 Figure 3: see original paper: some areas are oversampled while others remain completely unobserved (indicated by black lines).

To address this, we implemented an N-frame/step acquisition scheme at each position. This slightly reduces temporal resolution but offers two advantages: (1) During multi-frame acquisition, high-frequency solar image jitter can improve the slit' s spatial sampling rate by increasing the probability that the slit occupies the desired position in at least one frame. (2) Observers can flexibly adjust N based on image jitter amplitude, specific scientific objectives, and seeing conditions. Figures 3(b), (c), and (d) demonstrate how increasing N dramatically improves spatial sampling rate and resolution.

1.2 Control Precision Requirements for Polarimetric Observation Mechanisms

The NVST polarimetric observation system comprises the polarimeter and calibration unit, both sharing a similar structure: polarizer, waveplate, and rotation stage. Both rotation stages use ultrasonic piezoelectric turntables from Physik Instrumente (PI).

Notably, the calibration unit resides inside the telescope’ s vacuum tube, far from other terminal equipment. We therefore adopted a serial-to-Ethernet conversion strategy: the calibration unit’ s motor controllers connect via multiple switches to the acquisition computer through a local area network, solving cabling challenges (Figure 4 [Figure 4: see original paper]). Tests revealed that network communication introduces an average command delay of less than 20 ms, with no observed impact on instrument performance. The polarimeter, located on the terminal platform, has its turntable controller connected directly to the acquisition computer via RS232.

During operation, the polarimeter requires a stationary polarizer while the waveplate rotates in fixed 22.5° increments for 8-step modulation, with data acquisition occurring only after each rotation completes. Initial control specifications allowed generous tolerances, considering 0.04% angular positioning error (approximately 0.01°) sufficient. Modulation was performed in both 0°-180° and 180°-360° ranges, with the hope of improving SNR through combination.

However, field tests revealed that angular positioning errors caused significant measurement inaccuracies. In the left half of Figure 5 [Figure 5: see original paper] (before x=40), the waveplate completes an 8-step 0°-180° rotation (with polarimeter positioning accuracy of 0.002±0.001°). The intensity variations across these 8 states constitute the modulation process, with linear combinations used for final demodulation of polarimetric signals. Since polarimetric signals are extremely weak (typically 1% of intensity signals), N (=5) frames are acquired at each state to improve SNR. Apart from atmospheric transparency variations, these N frames should show no intensity fluctuations. In practice, however, a 0.01° positioning error causes intensity variations exceeding 10%. When N is small (N=1 or 3 in special cases), averaging is insufficient, directly affecting demodulation accuracy. Therefore, rotation stage positioning accuracy must be improved to 0.002±0.001° (the highest available precision) to eliminate these fluctuations and ensure polarimetric accuracy.

Second, after completing 0°-180° rotation, could the waveplate continue through 180°-360° to return to zero, thereby improving precision? As shown in Figure 5, position 1 corresponds to 22.5° rotation, while position 1’ corresponds to

22.5°+180°. Positions 1-8 represent the first 180° measurement, and 1’ -8’ the second. Ideally, intensities at position a and a+180° should be identical, but this is not the case. While some positions (e.g., 4 and 4’) show minimal differences, others (1 vs. 1’ , 5 vs. 5’ , 7 vs. 7’) exhibit significant discrepancies. These differences produce response matrix variations of at least 10^{2} between 0°-180° and 180°-360° measurements, reaching up to 1.3%. To avoid additional errors from this asymmetry, NVST’ s polarimeter waveplate currently rotates only within 0°-180°, returning to the optical zero point after each 8-step modulation cycle, adding approximately 500 ms of overhead.

1.3 Multi-frame Superposition Mode for Polarimetric Observations

NVST currently employs single-beam polarimetry, requiring the fastest possible modulation to minimize atmospheric turbulence effects. The standard approach acquires one frame per angle (N=1) for a complete modulation cycle, then stacks multiple groups of results—demodulate first, then superpose. The number of stacked groups represents a trade-off between temporal resolution and SNR.

However, field tests revealed this approach severely reduces temporal resolution. At each modulation position, total time equals waveplate rotation time plus data acquisition time, with the former dominating. For a single-frame spectral exposure of 80 ms, an 8-step modulation cycle requires approximately 4 seconds. To achieve a polarimetric signal continuum RMS of ~10^{3} · I_c (meeting the “scientific objective requirement”), about 20 modulation groups must be stacked, totaling 80 seconds.

We therefore adjusted the observation mode: during polarimetric observations, acquire sufficient frames at each modulation state first, superpose them to obtain high-SNR modulation signals, then perform demodulation—superpose first, then demodulate. Using the same example with N=20 per step and unchanged exposure time, total observation time reduces to 23 seconds. Table 2 shows the measured relationship between continuum RMS and N.

Table 2 demonstrates that for two-dimensional spatial scanning polarimetry (110 steps at 0.5” /step, covering ~1 arcminute), achieving 3.0×10^{3} · I_c SNR requires 23 seconds per step, totaling 42 minutes. Reducing SNR to 5.6×10^{3} · I_c shortens the total time to 18 minutes.

2. Field Test Results

After clarifying and implementing the above requirements, we conducted numerous scientific observations of “two-dimensional spatial spectral scanning” and “polarimetric spectral measurement.” Below we describe the basic workflows and discuss issues encountered and resolved during field tests.

2.1 Two-Dimensional Spatial Spectral Scanning Observations

Figure 6 [Figure 6: see original paper] illustrates the basic workflow for spectral scanning. This mode targets non-magnetically sensitive chromospheric lines (H-alpha 656.3 nm and Ca II 854.2 nm). In implementation, it operates as a special case of polarimetric spectral observation with the polarimeter in a fixed state (acting only as an attenuator), requiring only scanner and detector control. The scanner employs the step-by-step motion described in Section 1.1.

While Section 1.1 proposed using N-frame/step acquisition to improve spatial resolution, field tests revealed that utilizing the quasi-simultaneous imaging system as a slit monitor enables real-time, precise slit positioning, further enhancing scanning resolution. Currently, the imaging and spectrometer systems use completely different detectors with distinct acquisition modes. Table 3 compares their performance parameters.

Without additional external triggering, we achieved quasi-simultaneous acquisition by adjusting the acquisition rates of both systems while maintaining reasonable data volumes. The spectrometer uses three PCO4000 CCDs connected to a single acquisition computer whose bandwidth and CPU cores fully support simultaneous acquisition and control of three detectors. With 2×2 pixel binning, single-frame spectral acquisition takes ~100 ms (60 ms exposure + 40 ms readout), yielding ~10 frames/s. Single-channel spectral data rate is approximately 50 MB/s.

For chromospheric spectral observations, we typically use the TiO channel of the high-resolution system for slit monitoring. This channel employs an Andor Neo CMOS camera. In routine high-resolution observations using 1×1 binning and "non-burst-mode," 200 frames are acquired in 30 seconds, but this creates temporal sampling gaps—concentrated acquisition for ~18 seconds followed by ~12 seconds of storage. For slit monitoring, we switched to burst-mode for continuous acquisition and 4×4 binning to control data volume while achieving 15 frames/s.

Through this parameter matching, we achieved quasi-simultaneous dual-system acquisition. This method was used for scanning observations of two active regions, producing high spatial resolution two-dimensional spectral scans (spectral mosaics shown in Figure 3).

2.2 Polarimetric Spectral Field Measurements

Figure 7 [Figure 7: see original paper] shows the polarimetric observation workflow, which includes both scientific observation and instrumental calibration. Calibration observations are a special type of polarimetric measurement performed with the calibration unit inserted into the beam. Each calibration takes ~1 minute to determine the telescope' s polarization state. Since the telescope' s polarization varies significantly with time, continuous or intermittent (30-minute interval) calibration is required. During calibration, the telescope points to a quiet region at disk center without activating the scanner. NVST’ s polarimetric calibration has achieved excellent results, substantially correcting cross-talk between polarimetric signals (Figure 8 [Figure 8: see original paper]).

After calibration, the unit is removed for scientific observation, which may involve spatial scanning or fixed-point measurements. For brevity, the scanning workflow is not detailed in the flowchart. The basic two-dimensional polarimetric scanning process is: the scanner moves stepwise; at each position, the polarimeter performs stepwise modulation; at each modulation state, the detector acquires N frames; after completing all 8 modulation states, the scanner moves to the next position, repeating until all preset steps are finished.

3. Summary and Discussion

The primary observation modes for NVST spectral observations have been designed, optimized, integrated, and commissioned for routine operations. Observers can execute complex two-dimensional polarimetric spectral observations through a unified control interface or perform individual observations including routine two-dimensional spectral scanning (including fixed-point), fixed-point polarimetric measurement, and polarimetric calibration. The “NVST Spectral Observation Procedure” has been completed (see Appendix).

This discussion focuses not on engineering challenges during design, but on analyzing how observation modes satisfy scientific objectives and how the motion patterns, precision, and logical sequences of electromechanical components were determined.

Additionally, spectral and imaging observations can operate quasi-synchronously, with the imaging system serving as a slit monitor to improve spectral scanning spatial resolution—an important step toward NVST’ s dual-high (high spatial and high spectral resolution) observation mode. However, strict synchronization between different NVST systems or channels has not yet been implemented, requiring consideration of hardware external trigger modes.

Finally, we discuss two issues in polarimetric spectral observations: (1) NVST currently uses stepwise modulation, limiting spatial resolution in two-dimensional observations. Recent experiments have begun exploring continuous modulation mode, where camera exposure begins at the waveplate’ s 0° position and ends as the waveplate rotates through equal angles. Implementation focuses on synchronizing these processes and quantifying measurement errors from synchronization inaccuracies. (2) NVST employs single-beam polarimetry. Since orthogonal polarization states cannot be acquired simultaneously, atmospheric seeing causes Stokes I to cross-talk into Q, U, and V, reducing polarimetric precision. The next step is to develop a dual-beam scheme using a polarizing beam splitter instead of the polarimeter’ s polarizer, simultaneously obtaining orthogonal polarization signals at different CCD positions. Subtracting these signals eliminates I-to-Q/U/V cross-talk, improving polarimetric precision compared to single-beam systems.

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Appendix I: NVST Spectral Observation Procedure

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