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Postprint: Measurement and Analysis of Field-of-View Frequency Drift in the NVST High-Resolution Narrow-Band Imaging System

Authors: Wang Liangkai^{1,2}, Xu Zhi^{1}, Jin Zhenyu^{1}, Chen Yuchao^{1,2}, Xu Jun^{1}

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Abstract

The imaging system of the 1m New Vacuum Solar Telescope comprises three narrow-band imaging channels: H , Ca II, and He I, all employing a Lyot filter system for monochromatic imaging. Using observed images from the H channel as an example, we investigate the cause of non-uniform spatial brightness distribution in solar images during off-band observations at line center and line wing positions. This non-uniformity, distinct from stray light, exhibits spatial distribution patterns and varying degrees that depend on the specific observation wavelength. Analysis of multiple observational datasets reveals that the fundamental cause of this brightness non-uniformity is the field-of-view effect of the filter, whereby the operating wavelength in peripheral field regions undergoes a frequency shift relative to the central region. The magnitude and spatial distribution characteristics of this frequency shift are closely correlated with optical path alignment. Through comparative analysis of frequency shift conditions before and after the optical path adjustment in March 2017, we conclude that within the current 2.2' field of view of the H imaging channel, the maximum field-of-view frequency shift is 0.05 Å, which remains smaller than the transmission bandwidth and occurs only at the lower-left edge of the field of view.

Full Text

Preamble

Measurement and Analysis of Field-of-View Wavelength Drift in the High-Resolution Narrowband Imaging System at NVST

Wang Liangkai[12], Xu Zhi[1], Jin Zhenyu[1], Chen Yuchao[12], Xu Jun[1]
(1. Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011,

China;
2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract

The imaging system of the 1-meter New Vacuum Solar Telescope (NVST) includes three narrowband channels—H , Ca II, and He I—all of which employ Lyot filter systems for monochromatic observations. Using measured images from the H channel as an example, this paper investigates the cause of spatially non-uniform brightness distributions in solar images observed at various wavelength offsets from line center to wing. This non-uniformity differs from stray light, as its spatial pattern and degree of variation change with the observation wavelength point. Analysis of multiple sets of measured data indicates that the fundamental cause of this brightness unevenness is the field-of-view (FOV) effect of the filter: the working wavelength at the edge of the FOV experiences a frequency drift relative to the central region. The magnitude and spatial characteristics of this drift are closely related to optical alignment. By comparing the frequency drift before and after an optical realignment in March 2017, we conclude that within the current 2.2 FOV of the H channel, the maximum FOV drift is 0.05 Å, which is smaller than the filter' s passband and appears only at the lower-left edge of the FOV.

Keywords: Lyot filter field-of-view effect; frequency drift; H observations

Introduction

The 1-meter New Vacuum Solar Telescope (NVST) at Fuxian Lake is the largest ground-based solar telescope in China[1] and has obtained a large amount of long-duration, sub-arcsecond solar imaging data[2]. The current imaging observation system includes two broadband channels (TiO and G-band) for photospheric observations and three narrowband channels (H , Ca II, and He I) for chromospheric observations. As is well known, the chromosphere contains many important active phenomena such as prominences, plages, and flares. However, the chromosphere' s radiative energy across the entire visible band is only one ten-thousandth that of the photosphere, making chromospheric structures difficult to detect[3]. Consequently, narrowband filter devices such as Fabry-Pérot filters[4] or Lyot filters[5] are typically used to obtain monochromatic images at specific wavelengths. Nevertheless, single-wavelength monochromatic images contain limited physical information and cannot directly distinguish whether observed intensity variations arise from radiative changes or Doppler velocities. Therefore, monochromatic imaging usually requires observations at multiple wavelength points between the line center and wings, which facilitates studies of the dynamic characteristics of solar structures. Currently, all three narrowband imaging channels at the 1-meter solar telescope use Lyot filters developed by the Nanjing Institute of Astronomical Optics & Technology, with adjustable central wavelengths to meet the requirement for sequential multi-wavelength ob-

servations. Table 1 lists the central wavelengths, tuning ranges, and passband parameters for the three narrowband channels.

Table 1 Parameters of three narrow-band filters

At present, the 1-meter solar telescope primarily conducts routine solar chromospheric observations in the H channel. To ensure stable filter performance, operators must regularly monitor the filter' s characteristics, particularly checking for changes in the central wavelength and the symmetry of the wavelength scanning profile; detailed methods are described in reference[6]. However, reference[6] integrates intensity values spatially across the entire FOV to obtain the intensity at a given wavelength, ignoring the issue of intensity distribution within the FOV. Figure 1 [Figure 1: see original paper] shows a series of H observations of a quiet solar region at offset values of −0.06 nm, −0.02 nm, 0 nm, +0.02 nm, and +0.06 nm. The images exhibit large-scale brightness non-uniformity unrelated to solar structures, most notably the bright-dark patterns in the upper-left and upper-right regions, whose brightness also varies with the offset value.

Figure 1 Examples of H channel observations at different offset wavelengths, from left to right: −0.06 nm, −0.02 nm, 0 nm, +0.02 nm, +0.06 nm [Figure 1: see original paper]

The causes of brightness non-uniformity within the FOV are numerous, including stray light, optical vignetting, and detector non-uniformity. However, since the brightness unevenness shown in Figure 1 is wavelength-sensitive, the phenomenon is more likely attributable to the filter' s field-of-view effect. The so-called FOV effect refers to the shift in the filter' s passband center wavelength when incident light is not strictly perpendicular to the filter, with the shift magnitude depending on the angle of incidence[5].

1.1 Acquisition Method

The wavelength scanning procedure is as follows: the scanning range covers −0.1 nm to +0.1 nm with a step size (single-step wavelength interval) of 0.01 nm, and 10–20 frames are collected at each step. A complete wavelength scan thus comprises data from one line center and 20 different offset points. Second, careful attention is paid to target selection and smoothing. As seen in Figure 1, in addition to large-scale brightness non-uniformity, small-scale chromospheric structures are present within the FOV. To avoid the influence of solar structures on the results, data are collected in quiet regions near the solar disk center, and multiple sets of results are combined.

1.2 Preliminary Data Processing

To investigate the spatially non-uniform brightness distribution, the FOV is divided into 3×3 sub-blocks (as indicated by the red dashed lines in Figure 1), and the scanning profile characteristics in each of these nine sub-blocks are

examined. For clear presentation of the profiles, Figure 2 [Figure 2: see original paper] displays only the scanning profiles for the central region and the four corner regions. To eliminate brightness variations caused by factors such as vignetting and stray light (for example, the upper-left region in Figure 1 appears consistently dark at all offset points, where vignetting is the dominant factor), all profiles are normalized to the intensity of the central region at the line wing (−0.1 nm). The analysis reveals: (1) the scanning profiles from different sub-blocks do not coincide, exhibiting relative frequency drifts; and (2) relative to the central region' s profile, all corner region profiles are blue-shifted.

Figure 2 Comparison between the profiles from the central area and four corner areas [Figure 2: see original paper]

To more intuitively demonstrate the relative magnitude of the frequency drift, we further analyze the relative intensity between the corner regions and the central region by taking the ratio of each corner' s intensity to that of the central region, as shown in Figure 3 [Figure 3: see original paper]. The figure indicates: (1) all four ratio curves exhibit a pattern of being lower on the left (blue wing) and higher on the right (red wing). For the H absorption line profile, this clearly confirms that the corner region profiles are relatively blue-shifted. This manifests in the observational data as relatively weaker intensity in the blue wing and stronger intensity in the red wing in these regions. (2) The position where the ratio curve deviates farthest from unity appears in the upper-right corner (the transition from dark to bright in this region is also clearly visible in Figure 1; although the upper-left region also shows ratio curves deviating significantly from unity and appears consistently dark in Figure 1, careful examination reveals its relative brightness still varies with wavelength). The position closest to unity appears in the lower-left corner. In other words, the relative frequency drift magnitudes differ across the four corner regions and are not centrally symmetric.

Figure 3 Intensity ratio of four corner areas to central area [Figure 3: see original paper]

2. Two-Dimensional Measurement and Analysis of FOV Frequency Drift

To investigate the formation mechanism of FOV frequency drift, it is necessary to quantitatively calculate the drift magnitude in each region relative to the central region. The center-of-gravity method is used to compute the central wavelength of the scanning profile for each sub-block, and the difference in central wavelengths characterizes the relative drift magnitude. Two points should be noted: (1) although the profiles exhibit frequency drift, their basic shapes remain unchanged (unaffected by solar dynamic structures), so even if the H profile has systematic asymmetry, it only affects the absolute drift magnitude, not the calculation of "relative" drift; (2) only the profile within the ±0.05 nm range is used for the center-of-gravity calculation to minimize the impact of

systematic profile asymmetry. For the 3×3 sub-block case, the frequency drift of each block relative to the center is shown in Table 2 .

Table 2 Frequency drifts of different areas (Unit: nm)

The results show that edge regions exhibit a consistent blue-shift relative to the central region, with varying degrees of shift among different regions. The maximum value is -0.01 nm, appearing in the upper-right corner, which agrees well with the results in Figure 3 and partially validates the correctness of the center-of-gravity method.

The 3×3 sub-block description of the drift spatial distribution is rather coarse, so the sub-blocks are further subdivided. Figure 4 [Figure 4: see original paper] shows the relative frequency drift when the FOV is divided into 9×9, 15×15, and 25×25 sub-blocks. In all three cases, the central wavelength of the geometric center sub-block is used as the reference.

Figure 4 reveals that the spatial distribution of frequency drift is nearly circular, with its symmetry center located in a region slightly left of and below the center, rather than at the FOV center. This spatial distribution trend is independent of the segmentation level, although higher segmentation resolution does reveal the influence of solar structures on the results. Therefore, only the 9×9 segmentation case is discussed below.

Figure 4 Frequency drifts at different segmentation levels. Top panels show drift magnitudes in each region; bottom panels show corresponding spatial distributions [Figure 4: see original paper]

Based on these results, we conclude that the symmetry center' s offset from the FOV center is caused by non-ideal optical conditions, which can be improved by adjusting the detector' s spatial position.

3. Analysis of FOV Frequency Drift Causes

The wide-field units used in practical Lyot filters are shown in Figure 5 [Figure 5: see original paper][7], where P represents the polarizer, the two crystal plates C have mutually perpendicular optical axes, and an achromatic half-wave plate is inserted between them with its axis at 45° to both crystal axes. Neglecting effects such as crystal axis alignment errors, the quantitative relationship for the FOV effect in an ideal wide-field filter is as follows[5]:

Figure 5 Wide-field birefringent element of Lyot filter [Figure 5: see original paper]

$$\frac{\delta\lambda}{\lambda} = \frac{n_e - n_o}{2n_e n_o} \sin^2\theta$$

where θ is the angle of incidence on the filter, λ is the passband center wavelength, $\delta\lambda$ is the center wavelength shift, and n_o and n_e are the ordinary and

extraordinary principal refractive indices of the crystal, respectively. Clearly, as long as the light deviates from perpendicular incidence, $\delta\lambda$ is non-zero and frequency drift occurs. The above formula is only approximate; the actual transmittance of a Lyot filter also varies with the azimuth angle of the incident ray. Reference[8] notes that compared with the effect of ray inclination, the variation caused by azimuth angle changes is more than two orders of magnitude smaller and can be neglected. Of course, if the crystal axes in the Lyot filter' s wide-field unit have alignment errors, this can also cause frequency drift and further highlight the relationship between transmittance and incident ray azimuth[7]; here we assume that alignment errors are small and do not significantly affect transmittance.

In the actual observation system, the H channel filter is located in a collimated beam (after the collimator and before the imaging mirror), as shown in Figure 6 [Figure 6: see original paper]. Precise optical alignment can ensure that rays from the FOV center (i.e., along line o-o) are parallel to the system axis and perpendicularly incident on the filter. However, rays from the edge of the FOV, such as those from point A, become parallel light at an angle θ to the optical axis after passing through the collimator, meaning the incidence angle on the filter is not zero. Consequently, the passband center wavelength for this ray shifts by $\delta\lambda$. Since the crystal used in the H Lyot filter is calcite ($n_e < n_o$), $\delta\lambda$ is positive, meaning the transmittance curve always experiences a redshift regardless of whether θ is positive or negative. When this redshifted transmittance curve acts on the H absorption profile, it manifests as a blueshift of the absorption profile, which is why the scanning profiles in edge regions are always blueshifted relative to the central region.

Figure 6 Schematic diagram of H channel optical path [Figure 6: see original paper]

Based on this, the phenomenon of the zero-drift point not being at the FOV center may be caused by two factors: (1) the system optical axis does not pass through the detector center. If the detector moves perpendicular to the optical axis, the zero-drift position will inevitably deviate from the detector center; (2) the detector position is correct, but the filter axis is tilted relative to the system axis (as shown by the red dashed box in Figure 6). In this case, it is not the central point of the FOV (point O) but rather a ray from another point in the FOV (e.g., point A) that is parallel to the filter axis. For this ray, the transmittance remains unchanged, so the zero-drift point appears at a location offset from the FOV center (point A), and the maximum FOV drift increases, as seen in the upper-right corner of Figure 4.

Next, we discuss whether the observed drift magnitude for the H channel' s nearly 2 FOV conforms to the quantitative relationship between drift magnitude and filter incidence angle described above. First, a two-dimensional surface fit is performed on the 9×9 sub-block drift data to locate the symmetry center of the fitted surface. Then, the spatial distance of each of the 81 sub-blocks from this center is calculated (spatial distance = pixel size $\times$ number of pixels)

and converted to the ray' s incidence angle (incidence angle spatial distance / imaging lens focal length). The star points in Figure 7 [Figure 7: see original paper] show the relationship between incidence angle and drift magnitude for the 81 sub-blocks, compared with the theoretical curve.

Figure 7 Measured frequency drift values, fitting curve, and theoretical curve [Figure 7: see original paper]

Figure 7 shows that: (1) the basic trend of the measured values (star points) is consistent with the theoretical values (black solid line), further confirming that the brightness non-uniformity observed in the FOV indeed reflects the filter' s FOV effect; (2) the measured frequency drift is slightly larger than the theoretical prediction. Our interpretation is that the theoretical calculation is based on ideal optical conditions, whereas the actual system includes non-ideal factors such as filter imperfections, optical components not being strictly coaxial, and the detector target not being precisely located at the imaging lens' s focal plane; (3) due to the presence of solar structures, the measured data exhibit some scatter, but multiple observation sets yield consistent fitted curves (red dashed line); (4) the difference between measured and theoretical values increases with field angle.

4. Significance of Studying FOV Frequency Drift

The degree of frequency drift within the FOV and its spatial distribution characteristics can effectively reflect the working state of the optical system. For example, the H channel of the 1-meter solar telescope underwent an optical realignment around March 2017. Comparing the drift magnitude and spatial distribution characteristics before and after this adjustment, as shown in Figure 8 [Figure 8: see original paper], reveals that the post-adjustment data (June 2017, blue dot-dashed line) follow the theoretical prediction more closely than the pre-adjustment data (December 2016, red dashed line). Figure 8(c) shows the post-adjustment results after replacing the detector, which reduced the observation FOV (relative size indicated by the red dashed box in Figure 8(b)). In this smaller FOV, the maximum drift magnitude decreased to 0.005 nm and appeared only at the lower-left edge, compared with the previous 0.01 nm, and the spatial distribution became more uniform.

Figure 8 (a) Comparison of theoretical curve with two measured results at different times, (b) Result from December 2016, (c) Result from June 2017 [Figure 8: see original paper]

This study of FOV frequency drift demonstrates that both the H channel and other Lyot filter systems suffer from FOV drift issues. Therefore, the scanning profile and wavelength calibration procedures for the 1-meter solar telescope system can be improved by modifying the original full-FOV averaging approach to a sub-block analysis, selecting an optimal sub-block as the reference position to reduce averaging effects and provide more detailed and accurate results. Additionally, the current flat-field processing procedure[9] for the 1-meter solar

telescope does not distinguish between spatial intensity non-uniformity caused by optical vignetting and stray light versus that caused by the filter' s FOV effect. The availability of FOV drift data can provide a valuable reference for future flat-field processing.

5. Summary and Discussion

In summary, analysis of H channel wavelength scanning data reveals that the direct cause of brightness non-uniformity within the observational images is the relative frequency drift between the central region and other regions of the FOV, with the fundamental cause being the filter' s FOV effect. Through further adjustment of the telescope and imaging system optics, the maximum drift magnitude within the current 2.2 FOV is approximately 0.005 nm, which is smaller than the filter' s passband. The maximum drift appears only at the lower-left edge of the FOV, thus having minimal impact on observational data, particularly Doppler velocity measurements.

Further analysis reveals that the residual between measured and theoretical drift values as a function of incidence angle exhibits the pattern shown in Figure 9 [Figure 9: see original paper], where the results have been mean-filtered.

Figure 9 Residual error of frequency drift after mean filtering [Figure 9: see original paper]

Figure 9 shows that the residual exhibits a regular undulation, with its oscillation period decreasing as the incidence angle increases. Due to the limited amount of data currently available and the high time cost of continuous large-volume acquisition as well as issues with solar intensity variations, we cannot yet determine its cause. Future work could address this issue by investigating the accuracy of symmetry center position calculations and examining whether the drift distribution depends on azimuth angle, thereby providing a reasonable explanation.

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