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**Method for Creating Reference Data of SMART/SDDI
toward Sun-as-a-star Analysis of Solar Active Regions**



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Abstract

In conducting Sun-as-a-star analyses of active regions and filaments, it is crucial to accurately construct the reference spectra used for generating differenced Sun-as-a-star spectra. This technical report aims to create reference spectral data from full-disk $H\alpha$ spectral images observed by the SMART/SDDI at Hida Observatory, Kyoto University. By accounting for center-to-limb variation, effect of flat field, and solar rotation, we successfully constructed reference spectral data from a single-time snapshot of spectral image data. Using these reference spectral data, it becomes possible to quantitatively evaluate how much the solar brightness changes due to the appearance of active regions or filaments. We present some examples obtained using reference data constructed with the method proposed in this technical report.

1 Introduction

Sun-as-a-star analyses of solar data are useful for understanding spatially unresolved stellar observations. In such analyses, solar data are spatially integrated to be directly compared with stellar data. In particular, Sun-as-a-star analyses of $H\alpha$ spectra provide various information of active phenomena, such as solar flares and filament/prominence eruptions. Recent studies have shown that dynamics of solar flares and filament/prominence eruptions can be confirmed even in the spatially integrated $H\alpha$ spectra (e.g., [Otsu et al. 2022](#)). The variations of solar brightness caused by solar active phenomena are typically much smaller than the overall solar brightness. For instance, during solar flares, the variation in the $H\alpha$ line is typically on the order of 10^{-4} relative to the full-disk integrated continuum near the $H\alpha$ line. To extract signals related to solar active phenomena from Sun-as-a-star data, it is therefore necessary to subtract a reference dataset from the target observation. In previous studies of explosive phenomena such as solar flares, pre-event or post-event data were used as the reference for this subtraction ([Namekata et al. 2022a,b](#); [Otsu et al. 2022](#); [Otsu & Asai 2024](#); [Otsu et al. 2024](#)).

Recently, we have begun performing Sun-as-a-star analyses of non-flaring solar active regions to facilitate comparisons between solar and stellar active regions. The most straightforward choice for reference data in such analyses is the quiescent level corresponding to data taken when no active regions are present. However, this reference data must be carefully selected, since the results of Sun-as-a-star analyses are sensitive to variations which

is unrelated to target phenomena, as discussed in the following sections.

In this technical report, we propose a method for creating reference data for Sun-as-a-star analyses of active regions. The structure of this technical report is as follows: Section 2 introduces SMART/SDDI, which provides the $H\alpha$ data used in our analysis. Section 3 describes the method for creating reference data for Sun-as-a-star analyses. In Section 4, we present two examples of analyses using the proposed method and compare the results with those obtained using alternative reference data sets. Finally, Section 5 summarizes this report and outlines directions for future works.

2 SMART/SDDI

The Solar Dynamics Doppler Imager (e.g., [Ichimoto et al. 2017](#)) is installed on the Solar Magnetic Activity Research Telescope (SMART; [Ueno et al. 2004](#)) at Hida Observatory, Kyoto University. SDDI takes solar images at the wavelengths ranging from $H\alpha - 9.0 \text{ \AA}$ to $H\alpha + 9.0 \text{ \AA}$, with a pixel size and a temporal cadence of 1.23 arcsec and 12 sec, respectively. Since SDDI can measure line-of-sight velocities of chromospheric-temperature plasma up to approximately 400 km s^{-1} , it has been widely used in previous studies to analyze pre-eruption motions of filaments, erupting filaments, and small-scale eruptions ([Seki et al. 2017, 2019a,b, 2021](#); [Kotani et al. 2023](#); [Cabezas et al. 2024](#)). More recently, SDDI has been extensively used for Sun-as-a-star analyses of transient phenomena, such as solar flares and filament/prominence eruptions ([Namekata et al. 2022a,b](#); [Otsu et al. 2022](#);

Otsu & Asai 2024; Otsu et al. 2024). However, Sun-as-a-star analyses of solar activities that exhibit long-term temporal variations, such as the evolution of active regions, have not yet been conducted using SDDI. The reference data of SDDI proposed in this technical report will enable such analyses in the future.

3 Method

The aim of this technical report is to provide the reference data of SDDI that can be used for Sun-as-a-star analyses of active regions. To achieve this, we consider three key components as follows:

- (1) center-to-limb variation;
- (2) effect of flat field;
- (3) solar rotation.

In the following subsections, we explain why each of the above components must be taken into account and how they are incorporated into the reference dataset. In this technical report, we use the $H\alpha$ data acquired by SDDI at 01:05 UT on 2024 May 3, as an example. Figure 1 shows the original (level 1) $H\alpha$ center image obtained by SDDI at that time. The orange dashed and skyblue dotted square regions indicate the target areas used in Section 4.

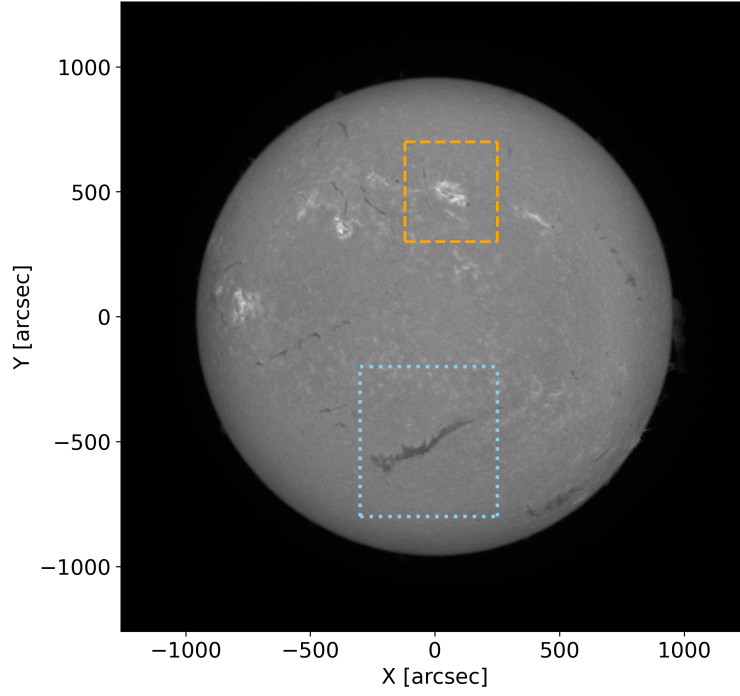


Figure 1. A solar image at the $H\alpha$ line center taken by SMART/SDDI at 01:05 UT on 2024 May 3. Top and right are the celestial north and the western direction, respectively. The orange dashed and skyblue dotted regions indicate areas including NOAA 13663 and a quiescent filament in the southern hemisphere, respectively. These regions are used in Section 4.

3.1 Center-to-limb variation (CLV)

The solar intensity varies depending on the distance from the solar disk center. This dependence of intensity on the radial direction is known as center-to-limb variation (CLV). In the case of the $H\alpha$ core, wing, and continuum, the intensity decreases from the center toward the limb. Since the CLV effect becomes more pronounced near the limb, incorporating it into the reference data is particularly essential when analyzing active regions close to the solar limb. As a first step in creating the reference data, we

construct data that reflect only the radial variation of intensity based on the CLV, removing any azimuthal dependence.

To this end, we perform a median-based averaging of the original solar data in the azimuthal direction. Let the intensity of the original data be denoted as $I(\lambda, x, y)$, where λ is the wavelength, and (x, y) are spatial coordinates. Here, $I(\lambda, x, y)$ is normalized by the full-disk integrated continuum near the $H\alpha$ line. We define the radial distance from the solar disk center as $r = \sqrt{x^2 + y^2}$. The solar image is divided into annular (donut-like) regions of width $\Delta r = 2 \times 1.23$ arcsec along the radial direction. Each annular region is represented by its radial distance r_i from the solar disk center, where the index i means ‘ i -th’ region from the disk center. For each wavelength λ , we compute the median of $I(\lambda, x, y)$ within the i -th annulus as follows:

$$\tilde{f}^{(1)}(\lambda, r_i) = \underset{r_i - \Delta r/2 \leq r < r_i + \Delta r/2}{\text{median}} I(\lambda, x, y), \quad (1)$$

where, $\tilde{f}^{(1)}(\lambda, r_i)$ represents the median intensity within the i -th annulus. The operator $\underset{r_i - \Delta r/2 \leq r < r_i + \Delta r/2}{\text{median}}$ denotes taking the median over the range of $r_i - \Delta r/2 \leq r < r_i + \Delta r/2$, which have the width of Δr . The black points in Figure 2 (a) to (d) show the $\tilde{f}^{(1)}(\lambda, r_i)$ as the function of r_i for $\lambda = H\alpha$ line center, $H\alpha + 0.5 \text{ \AA}$, $H\alpha + 1.0$, and $H\alpha + 3.0 \text{ \AA}$, respectively. Since data points near the disk center is insufficient and data near the limb becomes noisy, we restrict the computation range of r_i to $[100 \text{ arcsec}, R_{\text{sun}} - 10 \text{ arcsec}]$.

Next, we fit $\tilde{f}^{(1)}(\lambda, r_i)$ using an empirical CLV model;

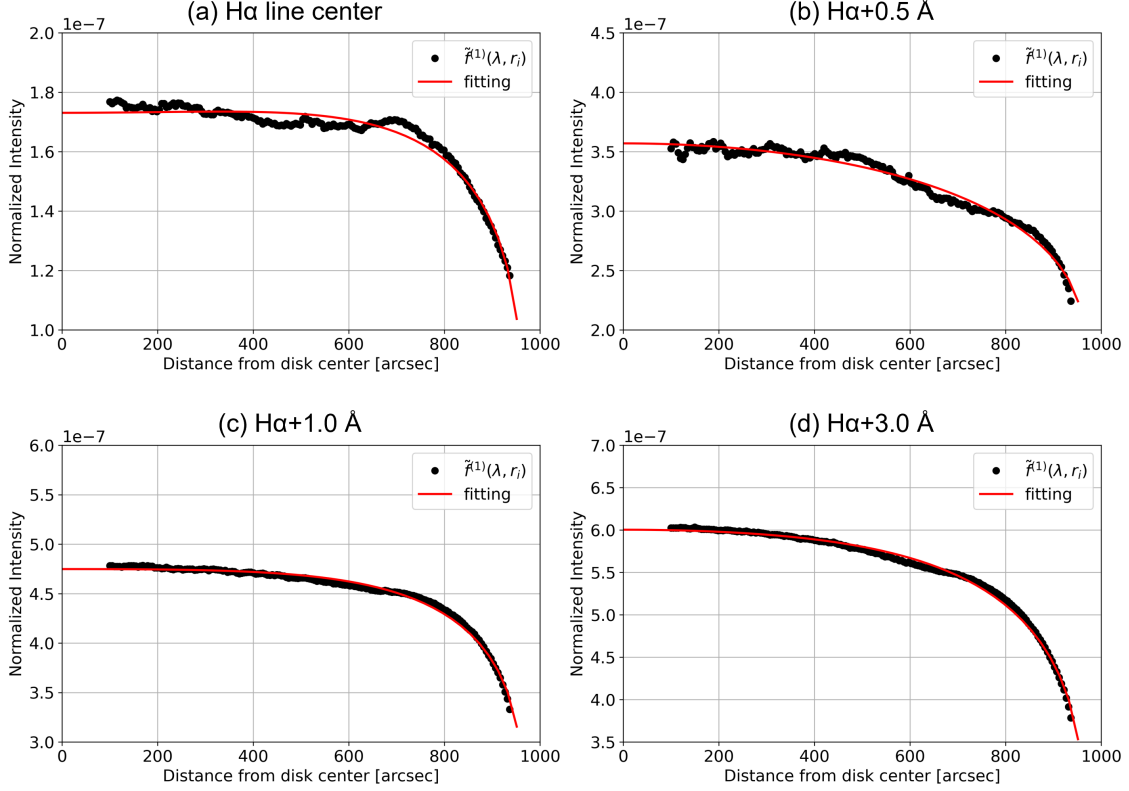


Figure 2. $\tilde{f}^{(1)}(\lambda, r_i)$ and $f^{(1)}(\lambda, r)$ as a function of the radial distance from the disk center indicating the CLV effect. The black dots and red solid line indicate $\tilde{f}^{(1)}(\lambda, r_i)$ and $f^{(1)}(\lambda, r)$, respectively. $\tilde{f}^{(1)}(\lambda, r_i)$ is computed over r_i in $[100 \text{ arcsec}, R_{\text{sun}} - 10 \text{ arcsec}]$. $f^{(1)}(\lambda, r)$ is obtained as the fitting result of $\tilde{f}^{(1)}(\lambda, r_i)$ and is extrapolated across the full disk from $r = 0$ to R_{sun} . In panels (a), (b), (c), and (d), results for $\lambda = \text{H}\alpha$ line center, $\text{H}\alpha + 0.5 \text{ \AA}$, $\text{H}\alpha + 1.0 \text{ \AA}$, and $\text{H}\alpha + 3.0 \text{ \AA}$ are shown, respectively.

$$f^{(1)}(\lambda, r) = a_\lambda + b_\lambda \cos(\theta(r)) + c_\lambda \cos^2(\theta(r)), \quad (2)$$

where $\cos(\theta(r)) = \sqrt{R_{\text{sun}}^2 - r^2}/R_{\text{sun}}$. The parameters a_λ , b_λ , and c_λ are wavelength-dependent coefficients. The red solid lines in Figure 2 (a) to (d) show the fitting results for $\lambda = \text{H}\alpha$ line center, $\text{H}\alpha + 0.5 \text{ \AA}$, $\text{H}\alpha + 1.0 \text{ \AA}$,

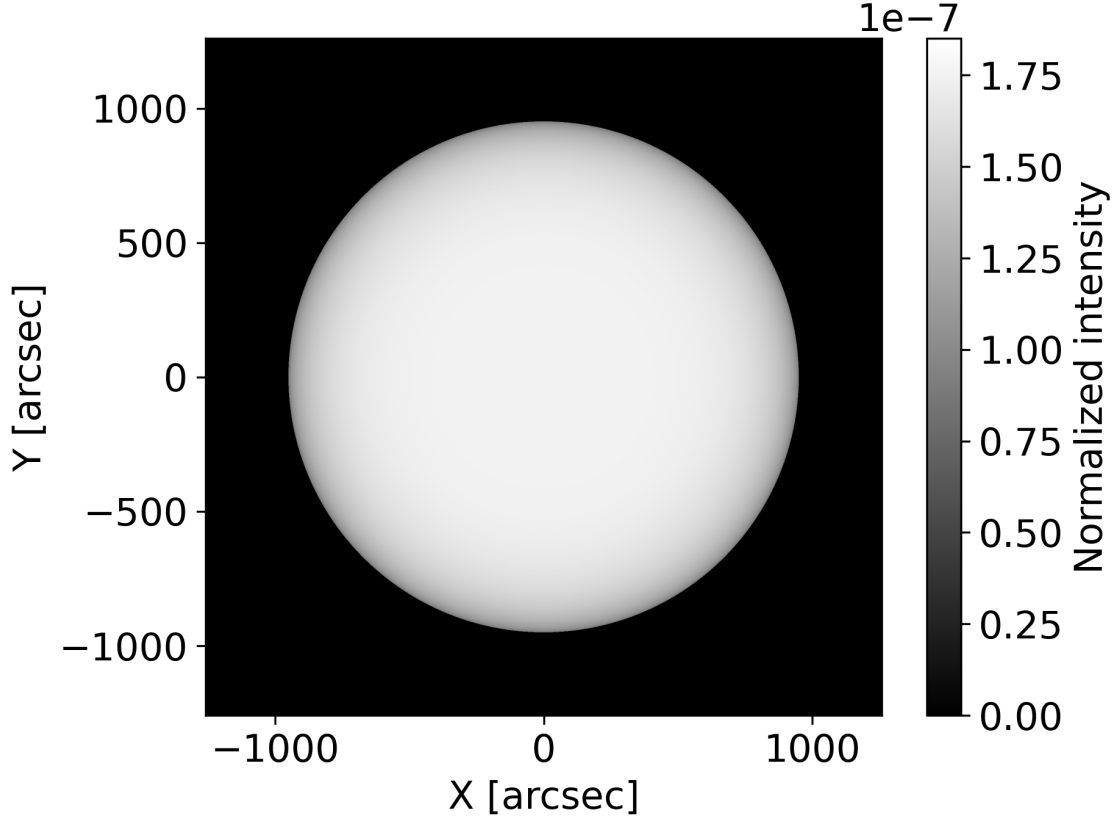


Figure 3. The two dimensional map of $f^{(1)}(\lambda, r = \sqrt{x^2 + y^2})$ for $\lambda = \text{H}\alpha$ line center. The intensity is normalized by the full-disk integrated continuum near the $\text{H}\alpha$ line. We note that the dynamic range is different from that in Figure 2.

and $\text{H}\alpha + 3.0 \text{ \AA}$, respectively. Although the fitting is performed over r_i in the range $[100 \text{ arcsec}, R_{\text{sun}} - 10 \text{ arcsec}]$, the fitted function is extrapolated across the entire disk, from $r = 0$ to R_{sun} . Consequently, for each wavelength, we obtain an azimuthally averaged intensity distribution $f^{(1)}(\lambda, r = \sqrt{x^2 + y^2})$ in the form of a two-dimensional map. Figure 3 shows the map of $f^{(1)}$ for $\lambda = \text{H}\alpha$ line center. Since $f^{(1)}$ includes only the radial dependence (i.e, the CLV effect), the resulting solar map appears smooth.

3.2 Effect of flat

The original data (level 1 data) presented in this technical report has undergone flat-field correction. However, some pattern having spatial non-uniformity still remain after this flat-field correction. If we use $f^{(1)}$ as the reference data for analyzing the original data (I) that includes an active region, the resulting difference $\Delta I^{(1)} = I - f^{(1)}$ will contain variations not only due to the active region but also due to residual spatial non-uniformity which presents in I but absents in $f^{(1)}$. To mitigate the influence of such non-uniformity, which generates differences between the original and reference data, we incorporate the spatial non-uniformity of the original data into the reference data. The following method does not alter the original data; therefore, it can be used even when the flat-field correction method is updated.

We assume that the dominant non-uniformity is common across all wavelengths, even though in reality the non-uniformity generally depends on wavelength. This is a rough assumption, but it is reasonable for mitigating the major effect. Based on this assumption, we multiply the ratio of the original and reference data at the continuum wavelength to $f^{(1)}$:

$$\tilde{f}^{(2)}(\lambda, x, y) = f^{(1)}(\lambda, r) \times I(\lambda_{\text{cont}}, x, y) / f^{(1)}(\lambda_{\text{cont}}, r), \quad (3)$$

where $\lambda_{\text{cont}} = \text{H}\alpha + 3.0\text{\AA}$. The non-uniformity is roughly corrected in $\tilde{f}^{(2)}(\lambda, x, y)$. However, $\tilde{f}^{(2)}(\lambda, x, y)$ is affected by sunspots, which exhibit significantly reduced intensity in the continuum. To eliminate the influence of sunspots, we use $f^{(1)}(\lambda_{\text{cont}}, r)$ in regions identified as sunspots. The sunspot regions

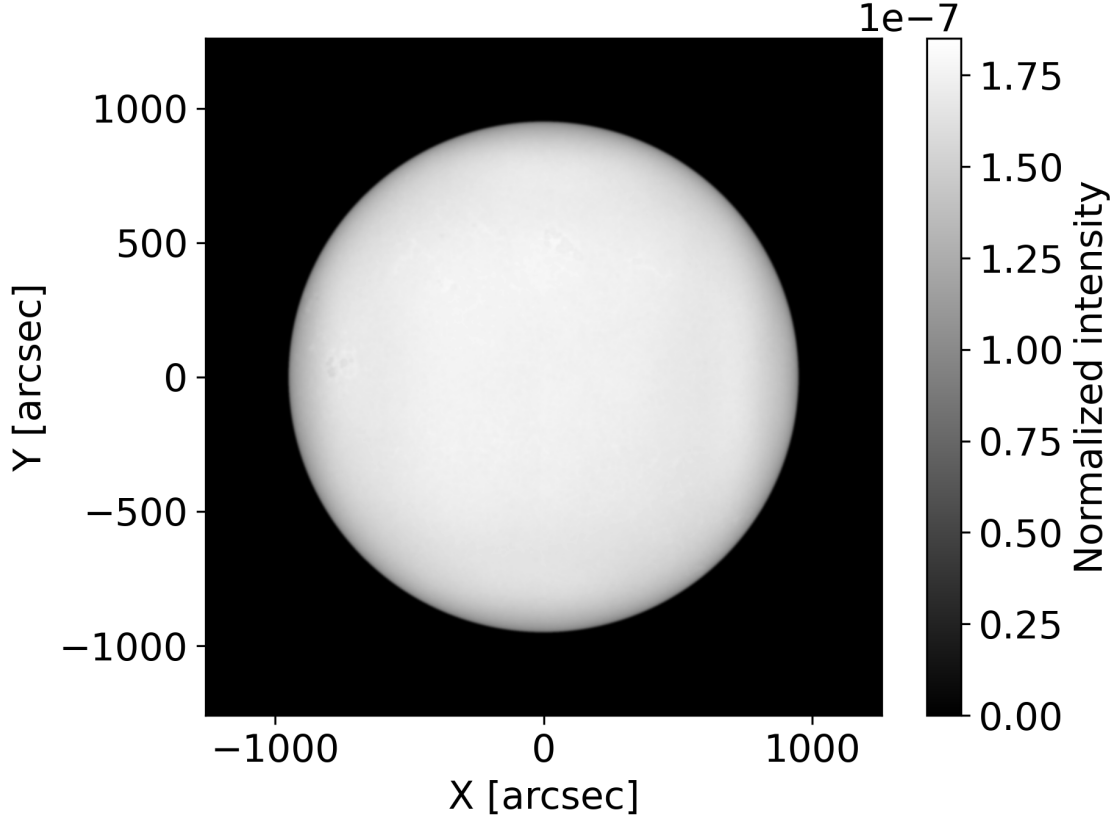


Figure 4. The two dimensional map of $f^{(2)}(\lambda, x, y)$ for $\lambda = \text{H}\alpha$ line center. The intensity is normalized by the full-disk integrated continuum near the $\text{H}\alpha$ line. We note that the dynamic range is the same with that in Figure 3.

are defined as areas where $I(\lambda_{\text{cont}}, x, y) \leq 0.95 \times f^{(1)}(\lambda_{\text{cont}}, r = \sqrt{x^2 + y^2})$. As a result, $f^{(2)}(\lambda, x, y)$ is given by,

$$f^{(2)}(\lambda, x, y) = \begin{cases} \tilde{f}^{(2)}(\lambda, x, y), & \text{if } (x, y) \text{ is outside sunspots} \\ f^{(1)}(\lambda, r), & \text{if } (x, y) \text{ is inside a sunspot.} \end{cases} \quad (4)$$

Finally, we applied a Gaussian filter with standard deviation of $\sigma = 3 \times 1.23$ arcsec to smooth the data. We redefined the filtered result as $f^{(2)}(\lambda, x, y)$. Figure 4 shows the two-dimensional map of $f^{(2)}(\lambda, x, y)$ for the $\text{H}\alpha$ line

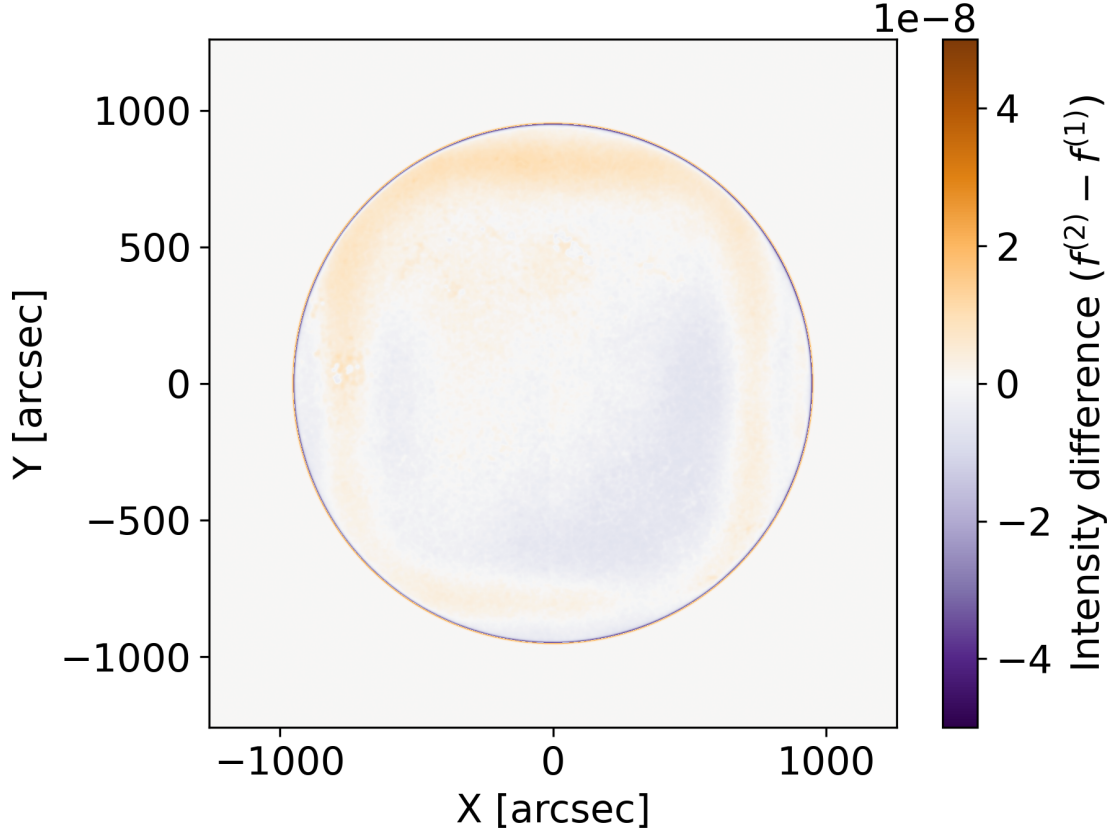


Figure 5. The two dimensional map of $f^{(2)}(\lambda, x, y) - f^{(1)}(\lambda, r)$ for $\lambda = H\alpha$ line center. The intensity is normalized by the full-disk integrated continuum near the $H\alpha$ line.

center, while Figure 5 shows the two-dimensional map of the intensity difference between $f^{(2)}(\lambda, x, y)$ and $f^{(1)}(\lambda, r)$ at the $H\alpha$ line center. In Figure 5, a square pattern can be seen, with the edges and interior mainly showing orange and purple, respectively. This pattern corresponds to the effect of the flat field.

3.3 Solar rotation

The solar rotation causes Doppler shifts in the $H\alpha$ spectra. If we use $f^{(2)}$ which does not account for solar rotation as reference data, then the differenced intensity $\Delta I^{(2)} = I - f^{(2)}$ will include variations due to line shift caused by solar rotation. Although the variation at each pixel is small compared with those from active regions, spatial integration in Sun-as-a-star analyses accumulates these small variations from solar rotations across the integral region. As a result, the total variation due to solar rotation in the spatially integrated data may become non-negligible compared to variations from active regions. Therefore, it is necessary to include the effect of solar rotation in the reference data.

We adopted an empirical model of solar differential rotation and projected the rotational velocity onto the line-of-sight direction (e.g., [Howard & Harvey 1970](#); [Beck 2000](#)):

$$V_{\text{rot}} = (A + B \sin^2 \phi + C \sin^4 \phi) \times R_{\text{sun}} \cos \phi \sin L, \quad (5)$$

where V_{rot} is a rotation velocity along the line-of-sight direction, while ϕ and L are latitude and longitude, respectively. The factor $\cos \phi \sin L$ in Equation 5 represents the projection to the line-of-sight direction. The coefficient A is the equatorial rotation rate, and B and C describe differential rotation. For the coefficients A , B , and C , we adopted the values from [Rao et al. \(2024\)](#), who derived them for various altitudes from the solar surface using $H\alpha$ spectra in different wavelength ranges. We selected the $H\alpha \pm 0.5 \text{ \AA}$ range, where the coefficients are $A = 3.022$, $B = -0.141$, and $C = -0.581 \mu \text{ rad}$

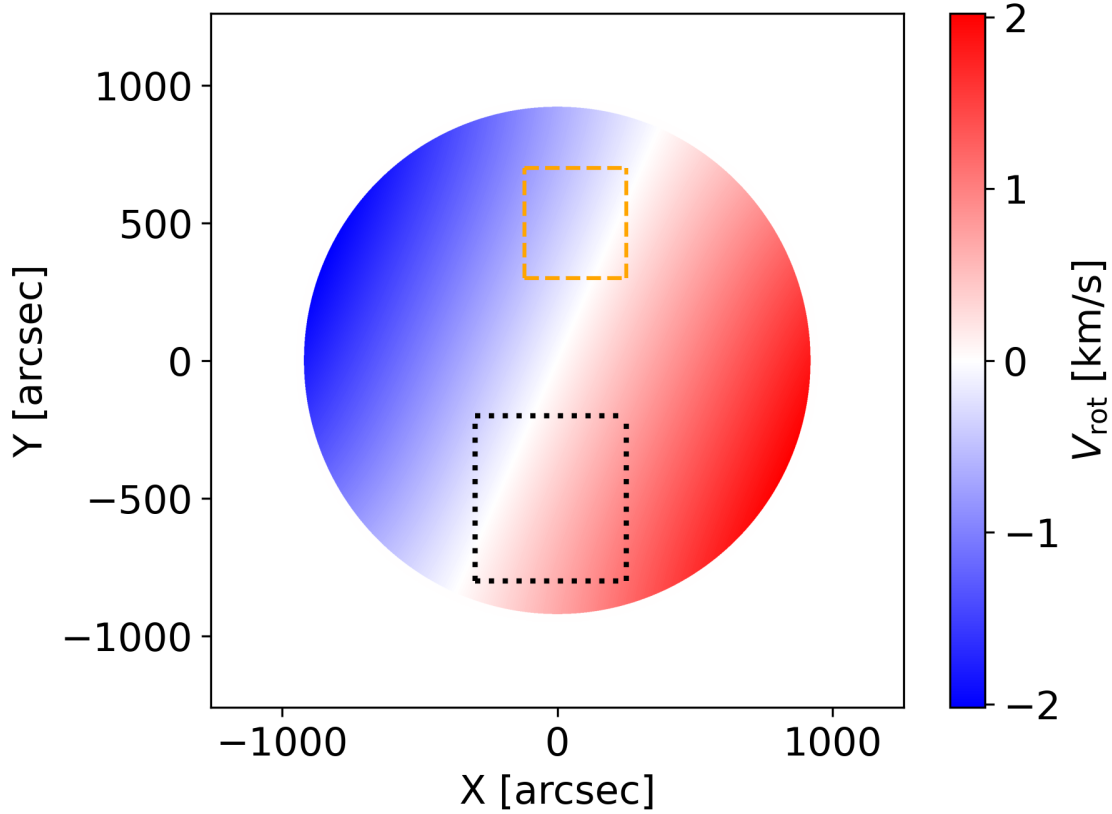


Figure 6. Map of the line-of-sight component of the solar rotation velocity at 01:05 UT on 2024 May 3. Red and blue colors correspond to the motions moving away from and toward the observer, respectively. Top is the celestial north and right is the celestial west. The orange dashed and black dotted regions indicate areas including NOAA 13663 and a quiescent filament in the southern hemisphere, respectively (see Figure 1).

s^{-1} . We note that our method does not account for the effects of the Earth’s rotation and the solar B angle for simplicity. The effect of Earth’s rotation is minor compared with that of solar rotation. Similarly, the effect of the solar B angle on the line-of-sight projection is expected to be negligible compared with the contributions from latitude ϕ and longitude L . These effects will be incorporated in future updates to further refine our method. Figure 6 shows the distribution map of V_{rot} . The top of Figure 6 is celestial north, and the

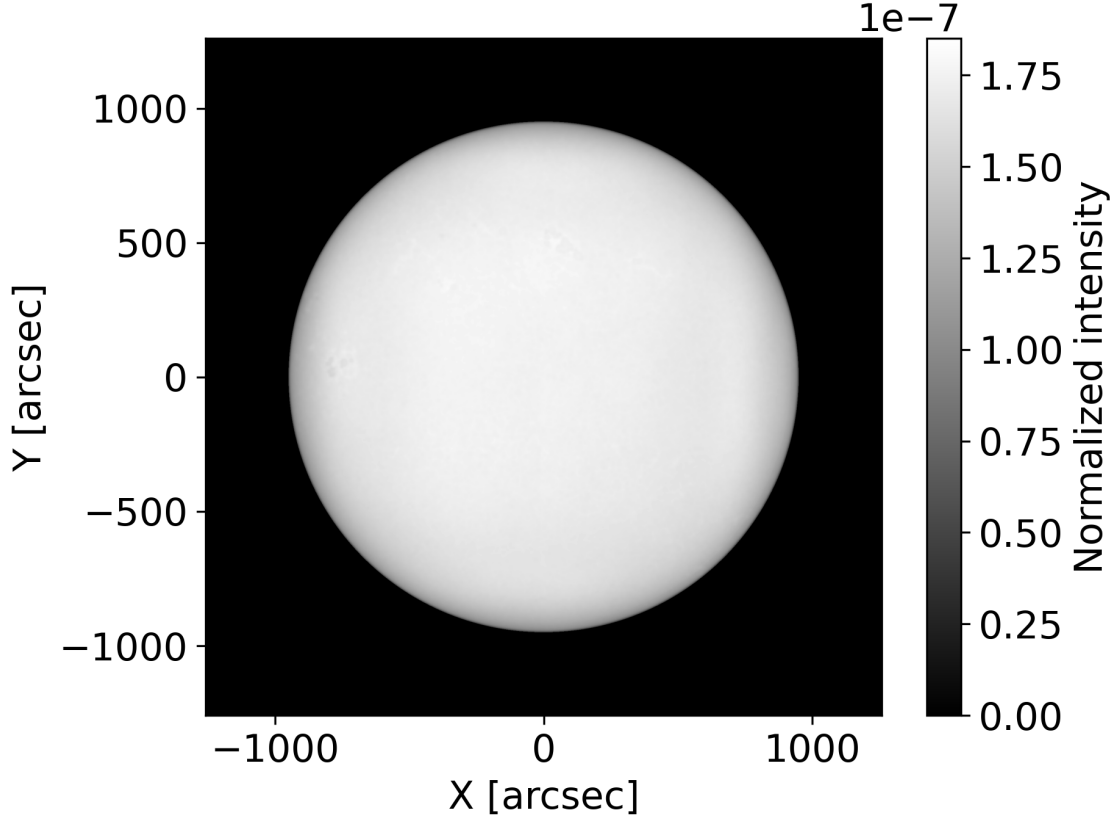


Figure 7. The two dimensional map of $f^{(3)}(\lambda, x, y)$ for $\lambda = \text{H}\alpha$ line center. The intensity is normalized by the full-disk integrated continuum near the $\text{H}\alpha$ line. We note that the dynamic range is the same with that in Figure 3.

solar north is tilted by 23.2 degrees toward the west. As shown in Figure 6, the variation in V_{rot} is primarily caused by the line-of-sight projection, whereas the contribution from differential rotation is minor. Using V_{rot} , we calculated the wavelength shift of $\text{H}\alpha$ due to solar rotation as

$$\Delta\lambda_{\text{rot}} = V_{\text{rot}} \times \lambda_0/c, \quad (6)$$

where λ_0 is the reference wavelength of $\text{H}\alpha$ and c is the speed of light. To apply this shift to $f^{(2)}$, we performed a Fourier transform:

$$\hat{f}^{(3)}(k, x, y) = \int f^{(2)}(\lambda, x, y) e^{-i\lambda k} d\lambda. \quad (7)$$

and then applied the inverse Fourier transform with a phase shift of $\Delta\lambda_{\text{rot}}$:

$$f^{(3)}(\lambda, x, y) = \int \hat{f}^{(3)}(k, x, y) e^{i(\lambda - \Delta\lambda_{\text{rot}})k} dk. \quad (8)$$

In practical implementation, we used Fast Fourier Transform with *numpy.fft.fft* in Python. Figure 7 shows the two-dimensional map of $f^{(3)}(\lambda, x, y)$ for the H α line center, which is visually similar to the map of $f^{(2)}$ in Figure 4. The resulting $f^{(3)}(\lambda, x, y)$ is the reference data intended to be obtained in this technical report and can be used for Sun-as-a-star analyses of active regions.

4 Examples

In this chapter, we show examples of results of Sun-as-a-star analyses with $f^{(3)}$. In particular, we compared results of $f^{(3)}$ with those of $f^{(1)}$ and $f^{(2)}$.

4.1 Sun-as-a-star analysis of an active region

As the examples, we demonstrate results of Sun-as-a-star analyses of an active region and a filament on 2024 May 3. We define the intensity of the original data as $I(\lambda, x, y)$ as in the previous sections, while we define $f(\lambda, x, y)$ as the reference data. Although we use $f = f^{(3)}$ in the practical analysis, we also use $f^{(1)}$ and $f^{(2)}$ for the comparisons. On the real image of the Sun, there can be many active regions. Although the true Sun-as-a-star analysis should be included all of them, we focus on only the target

active region and neglect the variation at the other region to extract the contribution from one active region to spatially-integrated data. We define the area including the target active region as A .

Our motivation is extracting the contributions from the target active region. Thus, we assume that the variation of intensity outside of the A is zero. Furthermore, to obtain the contribution from the active region or filament, we make the mask M having the large absolute value of $\Delta I = I - f$. At each pixel in the region A , when the $|\Delta I|$ is larger than 15% of f at least one wavelength point, we set $M = 1$. Within the other region, we set $M = 0$. In the equation,

$$M(x, y) = \begin{cases} = 1, & \text{if } |\Delta I(\lambda, x, y)/f(\lambda, x, y)| > 0.15 \text{ for at least one } \lambda \\ = 0, & \text{others.} \end{cases} \quad (9)$$

The threshold value (15%) is chosen so that most of the structures in the active region or filament are visually covered by the mask. The exact value of the threshold is not critical for evaluating the differences among $f^{(1)}$, $f^{(2)}$, and $f^{(3)}$. However, the threshold must be chosen carefully for practical Sun-as-a-star studies, because an excessively high threshold enhances noise, whereas an excessively low threshold may miss contributions from target regions. Finally, we calculated spatially-integrated (Sun-as-a-star) differenced spectra as follows:

$$\Delta S(\lambda) = \int \Delta I(\lambda, x, y) \times M(x, y) \, dx dy. \quad (10)$$

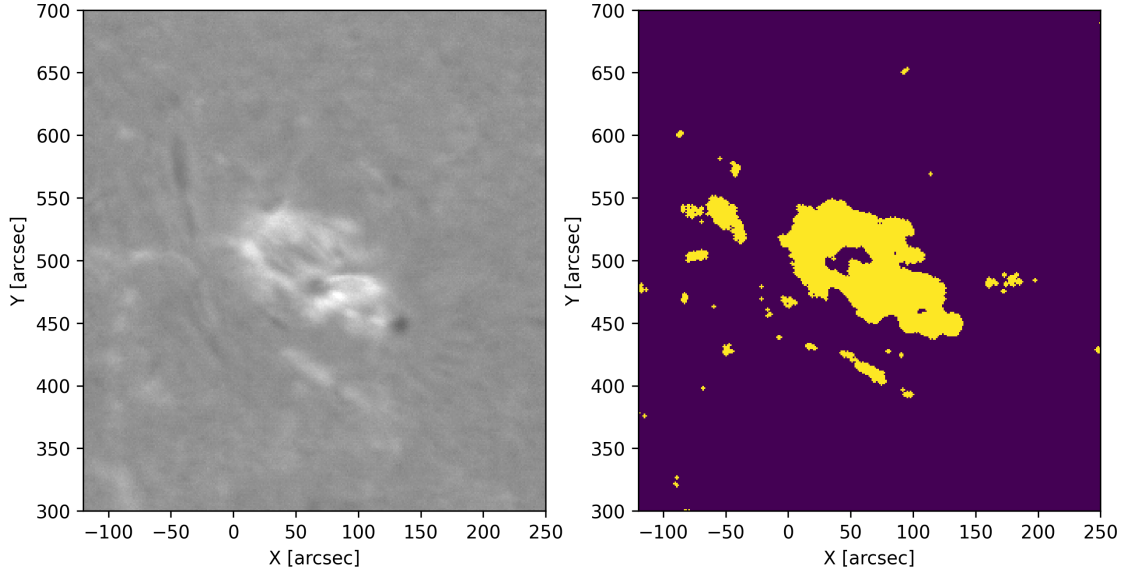


Figure 8. Zoomed-in image and mask region of AR 13663 at 01:05 UT on 2024 May 3. Left: Zoomed-in image of AR 13663. Right: The mask region.

We note that $\Delta I(\lambda, x, y)$ is normalized by full-disk integrated continuum near the $H\alpha$ line (see section 3.1). In our previous studies, Sun-as-a-star differenced spectra were also normalized by full-disk integrated continuum (Otsu et al. 2022; Otsu & Asai 2024; Otsu et al. 2024). Therefore, we can quantitatively compare $\Delta S(\lambda)$ with the results in our previous Sun-as-a-star studies of solar active phenomena such as flares.

4.2 Results

We use the $H\alpha$ data taken by SDDI at 01:05 UT on 2024 May 3 (Figure 1) for the example data. This data is also used in Section 3. We focus on two regions: A_1 including the active region NOAA 13663; A_2 including a quiescent filament. The regions A_1 and A_2 are defined as the orange dashed

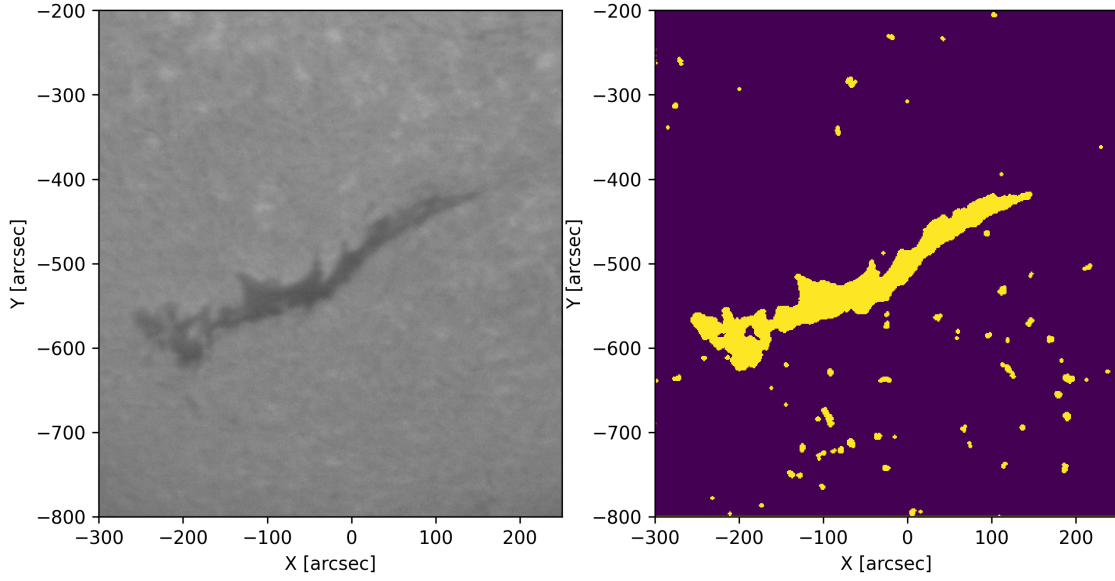


Figure 9. The same as Figure 8 but for a filament.

square and the skyblue dotted square regions in Figure 1, respectively. Figure 8 shows the zoomed-in image of the region A_1 at the $H\alpha$ line center (left panel) and the corresponding Mask data $M(x, y)$ made with $f^{(3)}$ (right panel). In the yellow regions, M is equal to 1, whereas M is equal to 0 in the purple regions. Figure 9 is the same with Figure 8 but for the region A_2 including the filament.

By using these data and mask, we calculated $\Delta S(\lambda)$ in the cases of $f = f^{(1)}, f^{(2)}, f^{(3)}$ for each region. We note that the same masks made with $f^{(3)}$ are used in all three cases. We refer to ΔS for a region A calculated using $f^{(1)}, f^{(2)},$ and $f^{(3)}$ as $\Delta S_A^{(1)}, \Delta S_A^{(2)},$ and $\Delta S_A^{(3)}$, respectively. For each region, we compare $\Delta S_A^{(1)}$ with $\Delta S_A^{(2)}$, and $\Delta S_A^{(2)}$ with $\Delta S_A^{(3)}$ to assess the improvement of the reference data achieved by the method proposed in this technical report.

Figure 10 shows the comparison between $\Delta S_{A_1}^{(1)}$ and $\Delta S_{A_1}^{(2)}$. Near the line

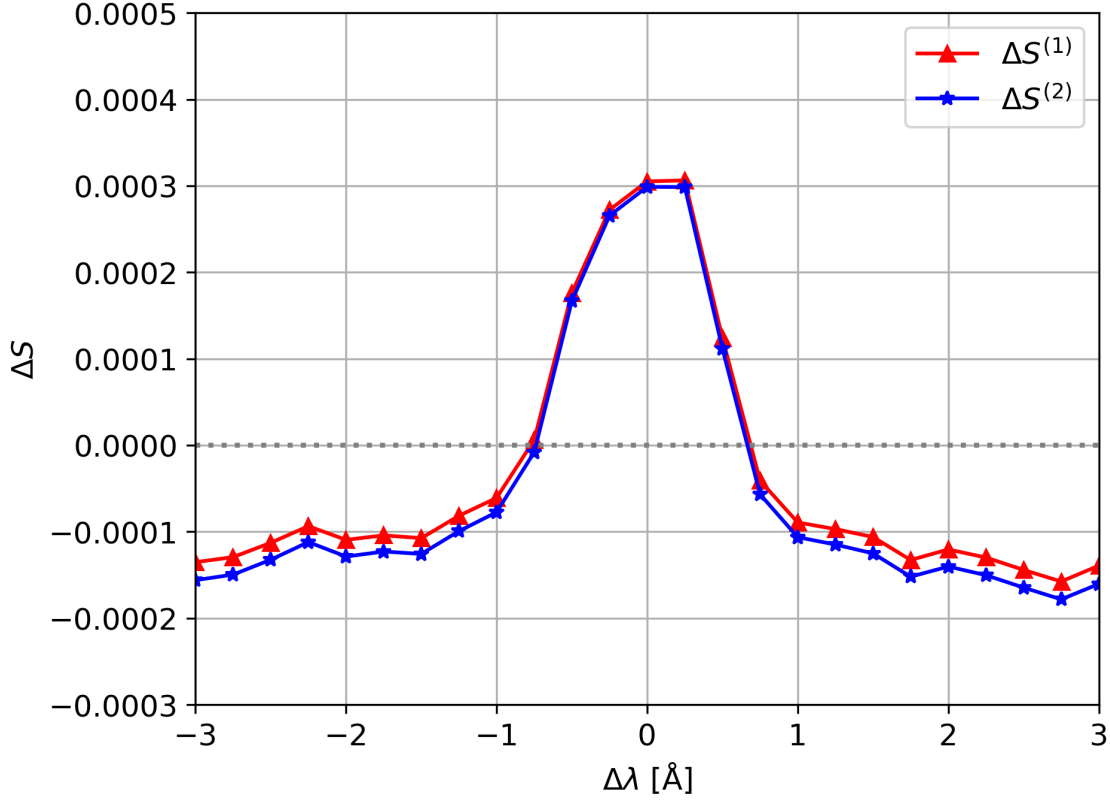


Figure 10. $\Delta S_{A_1}^{(1)}$ and $\Delta S_{A_1}^{(2)}$ as a function of difference of wavelength from the $H\alpha$ line center ($\Delta\lambda$). The red triangles and blue stars correspond to $\Delta S_{A_1}^{(1)}$ and $\Delta S_{A_1}^{(2)}$, respectively.

center, both of them are enhanced due to the plage. On the other hand, the continuum intensities of them are reduced due to the sunspots. The remarkable difference between them is that continuum level of $\Delta S_{A_1}^{(1)}$ is higher than that of $\Delta S_{A_1}^{(2)}$. For $f^{(1)}$, the flat-field correction is not applied, which is likely the cause of the difference between $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(1)}$, particularly in the continuum. Figure 11 is the same with Figure 10 but for the region A_2 including the filament. In this case, the difference between $S_{A_2}^{(1)}$ and $S_{A_2}^{(2)}$ are clear especially at continuum. The region A_2 includes only the quiescent filament. Thus, continuum of the differenced spectra should have no change

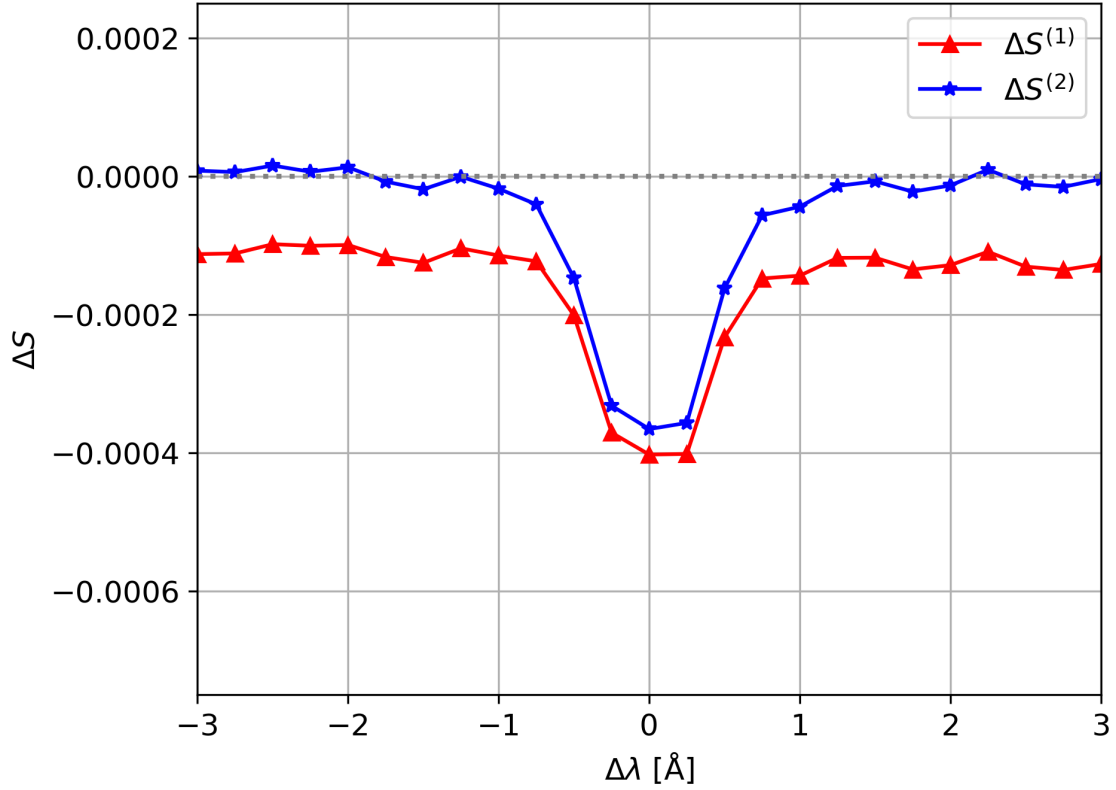


Figure 11. The same as Figure 10 but for $\Delta S_{A_2}^{(1)}$ and $\Delta S_{A_2}^{(2)}$.

compared to reference spectra. However, $\Delta S_{A_2}^{(1)}$ at continuum wavelength is lower than zero. This is caused because that $f^{(1)}$ used for $\Delta S_{A_2}^{(1)}$ is non-corrected for the flat modulation. On the other hand, $\Delta S_{A_2}^{(2)}$ at continuum wavelength is approximately zero and $\Delta S_{A_2}^{(2)}$ has absorption only near the $H\alpha$ line center. This result demonstrates that the correction methods related to the flat in Section 3.2 are effective.

Figure 12 shows the comparison between $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(3)}$. In contrast to the difference between $\Delta S_{A_1}^{(1)}$ and $\Delta S_{A_1}^{(2)}$, the continuum levels of $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(3)}$ are almost the same. This is because both $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(3)}$ are corrected for the flat-field effect. Although the difference between $\Delta S_{A_1}^{(2)}$

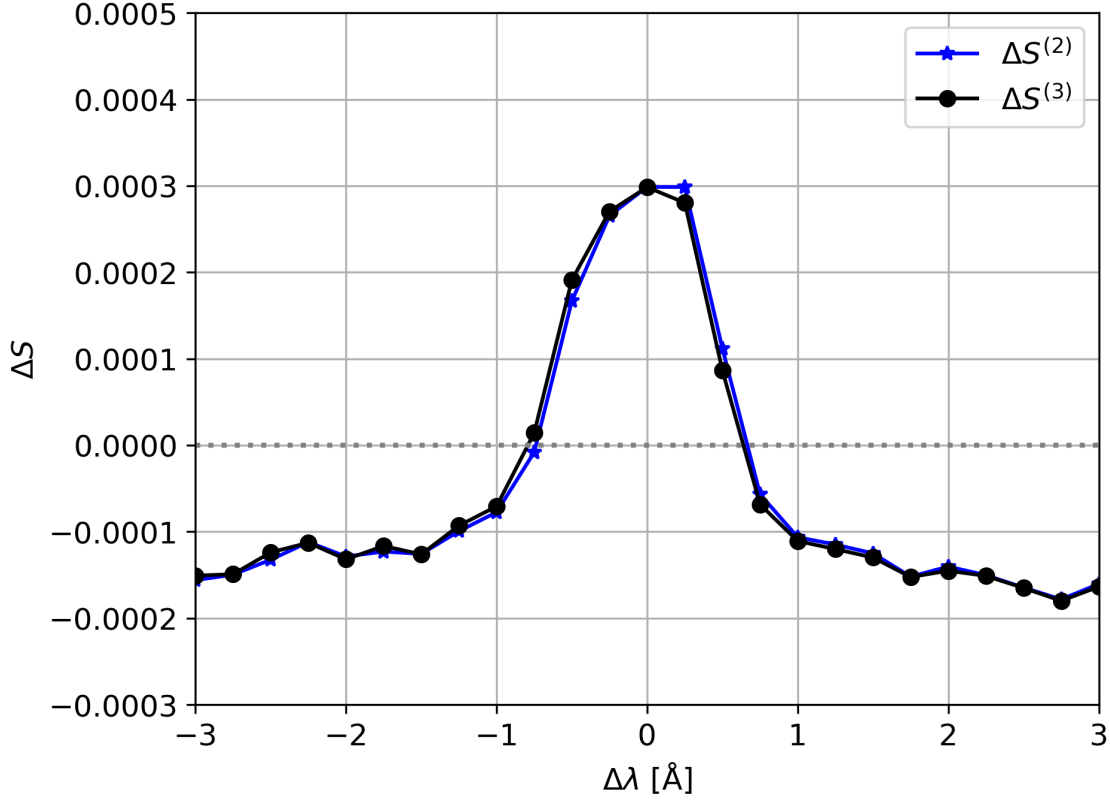


Figure 12. The same as Figure 10 but for $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(3)}$. The blue stars and black circles correspond to $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(3)}$, respectively.

and $\Delta S_{A_1}^{(3)}$ is not so large, the trend of the difference is that $\Delta S_{A_1}^{(2)}$ is slightly larger than $\Delta S_{A_1}^{(3)}$ in the red wing (from the $H\alpha$ line center to $H\alpha + 1.0$ Å) and slightly smaller in the blue wing (from the $H\alpha$ line center to $H\alpha - 1.0$ Å). Since ΔS is given as the integral of $I - f$ (Equation 10), the inequality between $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(3)}$ is determined by the overall trend of the inequality between $-f^{(2)}$ and $-f^{(3)}$. Over most of area A_1 , $f^{(3)}$ is blueshifted relative to $f^{(2)}$ due to the effect of solar rotation velocity projected onto the line-of-sight direction (see the orange dashed region in Figure 6). As a result, $f^{(2)}$ is smaller than $f^{(3)}$ (i.e., $-f^{(2)} > -f^{(3)}$) at redshifted wavelengths near the

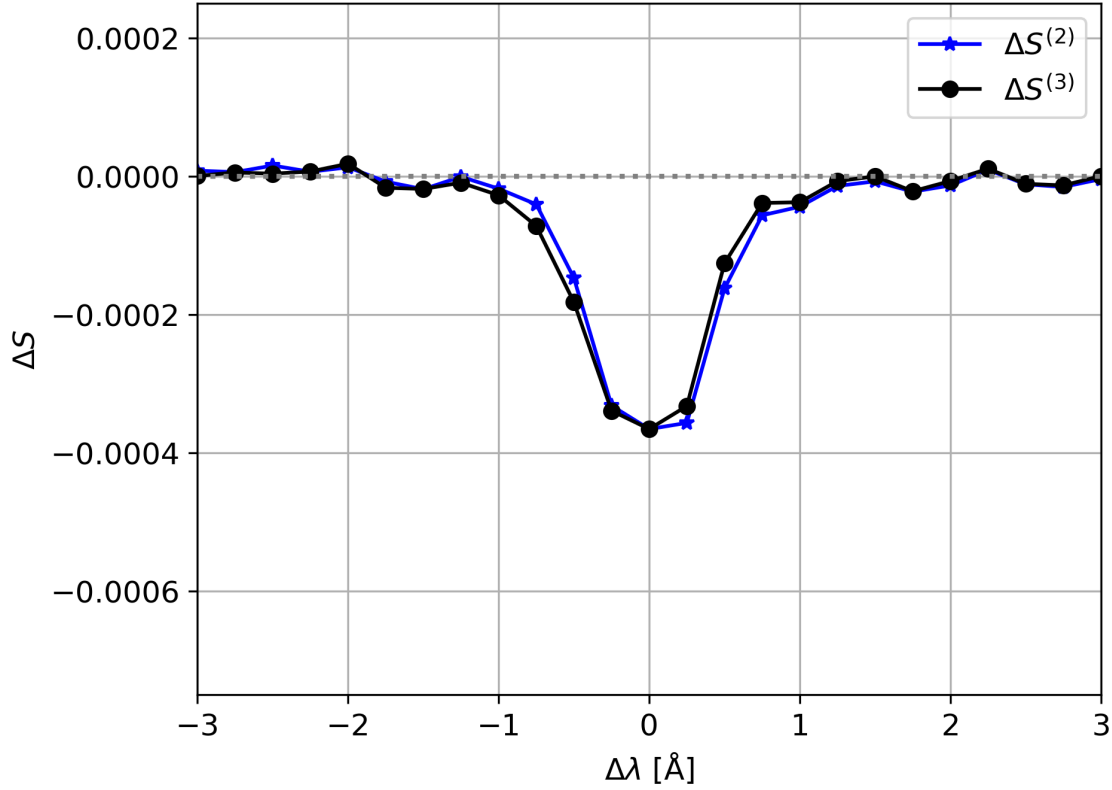


Figure 13. The same as Figure 10 but for $\Delta S_{A_2}^{(2)}$ and $\Delta S_{A_2}^{(3)}$.

line center whereas $f^{(2)}$ is larger than $f^{(3)}$ (i.e., $-f^{(2)} < -f^{(3)}$) at blueshifted wavelengths near the line center, over most of area A_1 . Accordingly, the relations $\Delta S_{A_1}^{(2)} > \Delta S_{A_1}^{(3)}$ in the red wing and $\Delta S_{A_1}^{(2)} < \Delta S_{A_1}^{(3)}$ in the blue wing hold. Thus, the difference between $\Delta S_{A_1}^{(2)}$ and $\Delta S_{A_1}^{(3)}$ is caused by the lack of rotational correction in $\Delta S_{A_1}^{(2)}$. In other words, $\Delta S_{A_1}^{(3)}$, in which $f^{(3)}$ includes the effect of the apparent variation in solar rotation velocity due to line-of-sight projection, is successfully modified from $\Delta S_{A_1}^{(2)}$. Figure 13 is the same with Figure 12, but for the region A_2 including the filament. The continuum levels of $\Delta S_{A_2}^{(2)}$ and $\Delta S_{A_2}^{(3)}$ are also almost the same, as in the case of Figure 12. In the case of Figure 13, $\Delta S_{A_2}^{(2)}$ is slightly smaller than $\Delta S_{A_2}^{(3)}$ in the red

wing and slightly larger in the blue wing. Over most of area A_2 , $f^{(3)}$ is redshifted compared with $f^{(2)}$ due to solar rotation velocity projected onto the line-of-sight direction (see the black dotted region in Figure 6). As a result, $f^{(2)}$ is larger than $f^{(3)}$ (i.e., $-f^{(2)} < -f^{(3)}$) at redshifted wavelengths near the line center whereas $f^{(2)}$ is smaller than $f^{(3)}$ (i.e., $-f^{(2)} > -f^{(3)}$) at blueshifted wavelengths near the line center, over most of area A_2 . Therefore, in contrast to the case of A_1 , the relations $\Delta S_{A_2}^{(2)} < \Delta S_{A_2}^{(3)}$ in the red wing and $\Delta S_{A_2}^{(2)} > \Delta S_{A_2}^{(3)}$ in the blue wing hold. Thus, the difference between $\Delta S_{A_2}^{(2)}$ and $\Delta S_{A_2}^{(3)}$ is also caused by the lack of rotational correction in $\Delta S_{A_2}^{(2)}$. In other words, $\Delta S_{A_2}^{(3)}$, in which $f^{(3)}$ includes the effect of the apparent variation in solar rotation velocity due to line-of-sight projection, is successfully modified from $\Delta S_{A_2}^{(2)}$.

As shown in these comparisons, $f^{(3)}$ is improved from the cases with $f^{(1)}$ and $f^{(2)}$. These comparative examples demonstrate that we can use $f^{(3)}$ as the reference data for Sun-as-a-star analyses of active regions and filaments. Also, we think that $f^{(3)}$ can be used for the background data in cloud model fitting of erupting filaments. In these examples, we only showed qualitative features of the results with $f^{(3)}$. For the further confirmation of the validity of $f^{(3)}$, statistical analyses of active regions and filaments with our method are needed.

5 Summary and Future work

In this technical report, we proposed the method for creating reference data of SMART/SDDI to investigate active regions and filaments in Sun-as-a-star studies. The examples presented in Section 4 demonstrate that our reference data ($f^{(3)}$) is improved compared to the other reference data ($f^{(1)}$, $f^{(2)}$). To quantitatively verify the validity of $f^{(3)}$, we plan to conduct statistical Sun-as-a-star analyses of active regions and filaments in the near future.

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