Abstract. We analyze the co-alignment between Hinode’s BFI-Gband images and simultaneous SP maps with the aim of characterizing the general offsets between them and the second order non-linear effects in SP’s slit scanning mechanism. We provide calibration functions and parameters to correct for the nominal pixel scales and positioning.

1. Introduction

Hinode [Kosugi et al. 2007; Tsuneta et al. 2008; Suematsu et al. 2008; Shimizu et al. 2008; Ichimoto et al. 2008] hosts the first spaced-based visible Spectro-Polarimeter (SP) for high resolution observations of vector magnetic fields on the solar Photosphere. This instrument measures the full Stokes profiles of two magnetically sensitive Fe I lines on a one-dimensional slice of the solar surface at a time. The slit spans \( \sim 160'' \) in the N-S direction, and the scanning mechanism can displace the image of the Sun at the spectrograph slit by up to \( \pm 152'' \), in increments of about \( \sim 0.15'' \). The Focal Plane Package (FPP) of the Solar Optical Telescope (SOT) includes broad-band and narrow-band imaging capabilities that can work simultaneously with SP. However, in order to be used simultaneously for scientific purposes, we need an accurate spatial co-alignment between both instruments.

This work aims at determining the general offsets between SP and Gband images, as well as providing accurate values of the pixel scales. The drift and the non-linearity of the slit scan mechanism are also characterized.

2. Observations and method

Two full field of view (FOV) SP maps taken at disk center (on March 10, 2007 and October 15, 2007) with simultaneous relatively-high cadence Gband data were chosen to make a first estimate of the co-alignment between the two instruments. We used a local correlation procedure to measure, pixel by pixel, the displacement between each pair of SP and Gband images. Since the SP maps are constructed from 2047 scanning steps that take 4s each, the difference in time between the beginning (East) and the end (West) of the map is of several hours. For this reason, we cannot compare the SP map with a single Gband
image, but we need to consider the closest Gband neighbor for every scanning step of SP.

Before feeding the images to the local correlation procedure we have to do some pre-processing:

- We first run the data through the standard reduction packages.
- SP data consist of the full, spectrally-sampled Stokes vector. In order to compare them to a Gband map we need to construct a continuum image from the Intensity spectral profiles.
- Due to the time-span of a full FOV SP map and the short granulation time-scales, in order to run a correlation with the Gband data, we need to construct a compound Gband image made up from slices of the Gband time series. Each slice is taken from the closest Gband neighbor in time to the corresponding SP scanning step.
- We have to rescale both maps to the same pixel sizes. For this we take as a reference the nominal scanning step, i.e. 0.1476 ″. We rescale the SP map in the direction along the slit to make the pixels square. Then we rescale the Gband map to this same pixel size and we center the images.

2.1. Definitions

For every position \([X_{SP}, Y_{SP}]\) in the SP image we find the one in the Gband image \([X_{GB}, Y_{GB}]\) that yields the largest value in the local correlation process. The displacements in the scanning direction and along the slit (\(\Delta X = X_{GB} - X_{SP}\) and \(\Delta Y = Y_{GB} - Y_{SP}\), respectively) are both a function of the scanning step and the position along the slit.

3. Analysis

The average displacements, \(\Delta X\) and \(\Delta Y\), between the two images as a function of the scanning step \(X_{SP}\) and position along the slit \(Y_{SP}\) are shown in Fig. [1].

3.1. Slit orientation

The spectrograph slit is not oriented vertically with respect to a column of pixels in the Gband image. The deviation is around 4 pixels along the length of the slit. The inclination with respect to the vertical (\(\alpha\)) was obtained by fitting to a straight line (\(\Delta X = a + bY_{SP}\)) the average displacement in the scanning direction, \(\Delta X\), as a function of the position along the slit, \(Y_{SP}\) (see top right panel of Fig. [1]). The inclination of the slit is given by:

\[
\frac{\partial \Delta X}{\partial Y_{SP}} = b = \tan(\alpha)
\]

where \(b\) is the slope obtained from the linear fitting to the data. SP images have to be rotated by \(\alpha = 0.26^\circ\) counter-clockwise with respect to the Gband images in order to correct for the inclination of the slit.
Figure 1. Average displacements, $\Delta X$ and $\Delta Y$, between the two images as a function of the position along the slit, $Y_{SP}$, and the scanning step, $X_{SP}$.

3.2. Vertical drift of the slit

The bottom right panel of Fig. 1 shows the averaged measured displacement of the slit in the vertical direction as a function of the scanning step. The linear fit of Eq. 2 yields a slope of $s = -0.0023$, indicating that SP’s slit shifts southwards with respect to the Gband image an amount of $0.0023$ pixels for each scanning step, producing a skew effect on the image. The off-set, $Y_{OFF}$, gives us the bulk vertical displacement between both images.

$$\Delta Y = sX_{SP} + Y_{OFF}$$

3.3. Pixel scales

Pixel scale along slit The average Y-displacement varies linearly as a function of the position along the slit (see bottom left panel of the figure), implying that the nominal SP pixel size in this direction should be corrected by a constant factor. The slope of the linear fit gives us the correction of the pixel size (which should be increaseded by 0.94% times its original size).

Pixel scale in the scanning direction The average X-displacement as a function of the scanning step (top left panel of Fig. 1) can be characterized as the sum of a cosine function and a straight line:

$$\Delta X = A\cos(2\pi/\Omega X_{SP} + \delta) + F_x X_{SP} + X_{OFF}$$
The linear trend, $F_x$, gives us information about the correction to the size of the scanning step with respect to its nominal value, while $X_{OFF}$ corresponds to the bulk off-set in the horizontal direction between both images. Due to a mechanical problem, the size of the scanning step in SP is not a constant, but it varies periodically over a period of $\sim 650$ steps, creating the illusion of a breathing effect on the image. We characterized this issue using a cosine function with three free parameters $A$, $\Omega$ and $\delta$ (see Eq. 3), that correspond to the amplitude of the oscillation, its period and its phase at the origin of the reference system.

4. Conclusions

We characterized the general off-sets, relative pixel scales and second order non-linear effects between the images produced by the SP and the Gband instruments on board the Hinode spacecraft. After carrying out a preliminary calibration with the two datasets described in Section 2, we run a warping procedure over a series of 10 different datasets (with dates spanning over more than a year), to fine-tune the calibration parameters and draw significant average values. The final calibration parameters are compiled in the following table:

| Parameter                        | Value     |
|----------------------------------|-----------|
| Mean scanning step ($X_{scale}$) | 0.1486″   |
| Pixel scale along slit ($Y_{scale}$) | 0.1599″ |
| X offset ($X_{OFF}$)              | −4.98″    |
| Y offset ($Y_{OFF}$)              | 7.26″     |
| Breathing amplitude ($A$)         | −0.649″   |
| Breathing period ($\Omega$)       | 649.8 steps |
| Breathing phase ($\delta$)        | 0.55 rad  |
| Skew ($s$)                        | −0.00032″/step |
| Slit angle                        | 0.26°     |

SP’s data reduction routine in the Solar Soft package (sp_prep) uses this calibration to compute the corrected values for the FITS file’s header keywords XSCALE, YSCALE, XCEN and YCEN.

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References

Kosugi, T., Matsuzaki, K., Sakao, T., et al. 2007, Solar Phys., 243, 3
Tsuneta, S., Ichimoto, K., Katsukawa, Y., et al. 2008, Solar Phys., 249, 167
Suematsu, Y., Tsuneta, S., Ichimoto, K., et al. 2008, Solar Phys., 249, 197
Ichimoto, K., Lites, B., Elmore, D., et al. 2008, Solar Phys., 249, 233.
Shimizu, T., Nagata, S., Tsuneta, S., et al. 2008, Solar Phys., 249, 221