

Mod-L Test: A Brief Report

1. Mod-L Sequence

Mod-L sequence can produce full Stokes parameters at a cadence of 90 seconds by combining filtergrams from both cameras, the front camera and the side camera. Within the 90-second, the front camera takes two sets of Left and Right Circular Polarizations (LCP and RCP) at 6 wavelengths; the side camera takes one set of Linear Polarizations ($I\pm Q$ and $I\pm U$) at 6 wavelengths. By combining two cameras, one can obtain full Stokes parameters of $[I, Q, U, V]$ at 6 wavelengths in 90 seconds. In normal Mod-C sequence that HMI currently uses, the front camera takes LCP and RCP at a cadence of 45 seconds, while the side camera takes observation of the full Stokes at a cadence of 135 seconds. Mod-L should be better than Mod-C for providing vector magnetic field data because (1) Mod-L increases cadence of full Stokes observation, which leads to higher temporal resolution of vector magnetic field measurement; (2) decreases noise in vector magnetic field data because it uses more filtergrams to produce $[I, Q, U, V]$. There are two potential issues in Mod-L that need to be addressed: (1) scaling intensity of the two cameras' filtergrams; and (2) if current polarization calibration works for the data from two cameras. The polarization calibration was tested for each camera.

2. Difference of Intensities From Two Cameras

Intensities from two cameras are slightly different. Figure 1 shows intensity ratio between camera 2 and camera 1 from calibration data (`hmi.lev1_cal`). The ratio is computed from medians of pixels within 0.99 rsun. The images are chosen with $FID = 10000$. FID is defined as, $FID = FID_0 + 10 \times wl + pl$, where $FID_0 = 10000$, wl goes from 0 to 19 in increasing wavelength order. 10 is the line center. 0 is continuum. pl refers to polarization, and 0 denotes the first of 4 polarizations for Mod-A. The intensity ratio between the two cameras varies in a range of 0.93 and 0.97. This variation is fairly smooth with time.

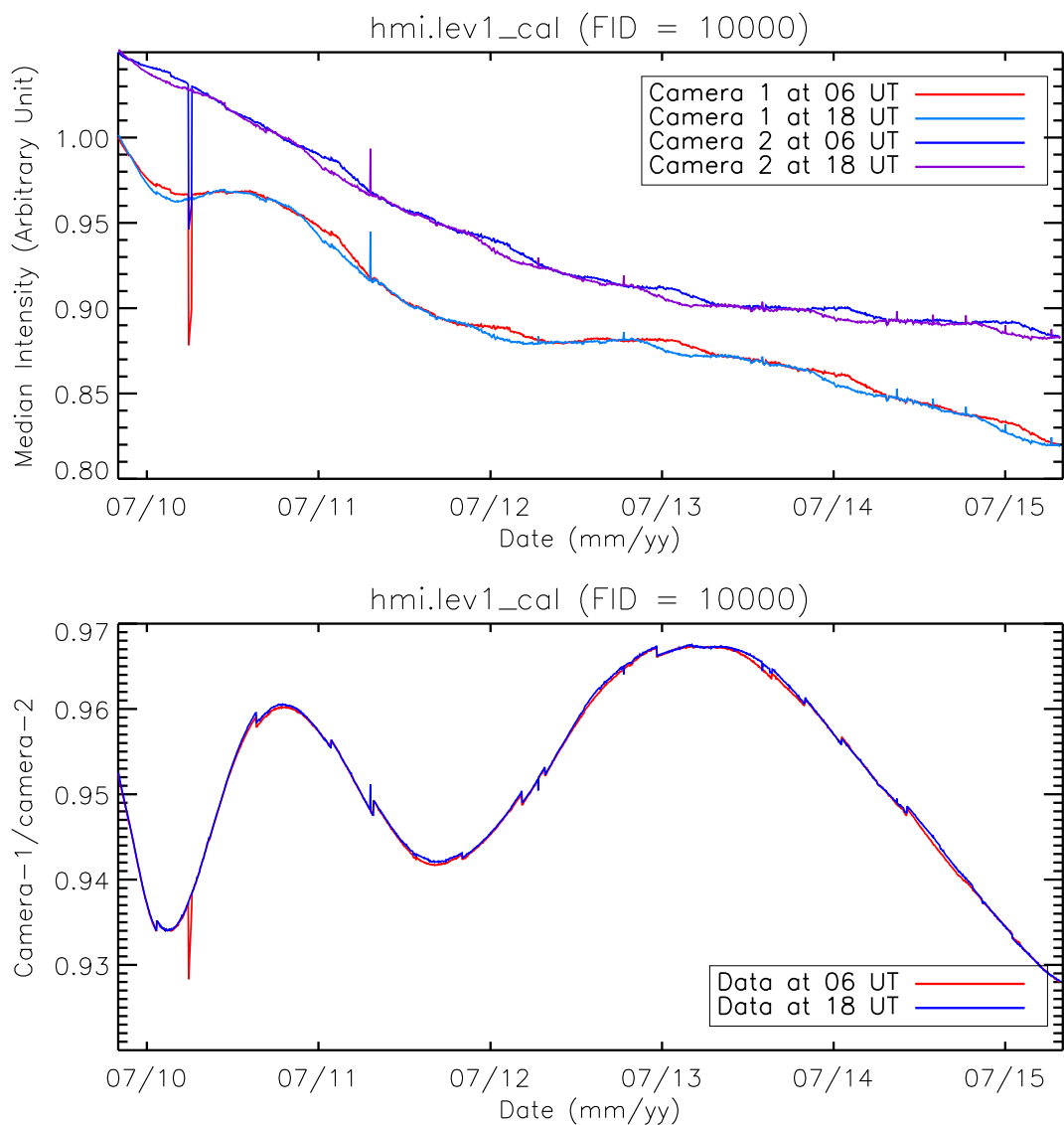


Fig. 1.— Top: Temporal profiles of the median of intensity taken at 06:00 UT (red) and 18:00 UT (light blue) from camera 1 and 06:00 UT (blue), 18:00 UT (purple) from camera 2 from May 2010 to August 2015. They are normalized by the first median value of camera 1. Bottom: ratio of medians between camera 2 and camera 1.

3. Pseudo Mod-L Derived From Mod-C Observation.

In principle, one can combine two cameras’ observations from Mod-C squence to produce pseudo Mod-L data sets. In norminal Mod-C sequence, the front camera takes LCP and RCP at a cadence of 45 secs. and the side camera takes full Stokes at a cadence of 135 secs. To mimic Mod-L sequence, one can take two sets of RCP and LCP from front camera, and one set of LP from side camera to produce full Stokes in 135 secs. It is similar to Mod-L but the cadence is longer.

The intensity difference between two cameras needs to be corrected when combining their observations. The way we do it is, for each pixel, to calculate the ratio of intensities between two cameras, and apply this ratio to the data to scale them up together. The total intensity from one camera is computed here by taking the average of summation of all filtergrams. This intensity is used to compute the ratio.

The data analyzed here was taken at 2015.05.04_20:24:00 (T_REC) with an orbital velocity of 1624 m/s. For each data cadence (135s), we use one set of linear polarization from the side camera, and two sets of RCP and LCP from the front camera. The filtergrams from front camera are scaled to be comparable to the side camera’s by dividing the derived pixel-dependent ratio, as mentioned above. All filtergrams were co-registered and resized for further interpolation and averaging. Similar to the norminal Mod-C 720-s data, 720-sec averaging over observation was also carried out. The resulting data then go through polarization calibration to derive Stokes [I,Q,U,V].

The inversion code *vfisv()* is used to retrieve vector magnetic field from this psuedo Mod-L Stokes data, and then compare the vector magnetogram derived from the norminal Mod-C data. In the left column of Fig 2 are field strength from pseudo-modL (top), norminal mod-C (second), and difference between them (third and bottom); In the right column are histograms of weak field (top and second), histogram of difference of field (third), and difference of field in percentage, i.e. $100 \times \delta B/B$. For the histograms in the third and fourth rows, only pixels with field greater than 100 G are used. The peaks of the histograms for two data, approximately the noise level of field strength, are about the same (110-120 Gauss). It is not surprising because both data uses almost the same [Q,U] (slightly different due to cross-talk correction that involves Stokes I) that contributes most of the field strength noise in quiet Sun regions.

Peak of difference of field strength (third row) shifts slightly toward negative, by about 1-2 Gauss. The pixels used here for the histogram have a field greater that 100 Gauss ($1-\sigma$). Would this shift imply that the noise in pseudo Mod-L is slightly smaller than norminal Mod-C because it uses more LCP and RCP data? Too small to tell.

The histogram in bottom is again from pixels with field greater than 100 Gauss. It may suggest a few percent difference between two data.

Fig. 3 shows comparison of inclination between two data. Difference of inclination (bottom panels) doesn't show any large-scale pattern.

Comparison of azimuth is in Fig. 4. As azimuth is determined by $[Q,U]$ that are from the same camera, it is not surprising to see fairly uniform running-difference-image between two data sets (bottom left). Again, there is no obvious large-scale pattern in the difference-image.

This comparison suggests that combining two cameras' observations does not introduce any obvious systematic bias.

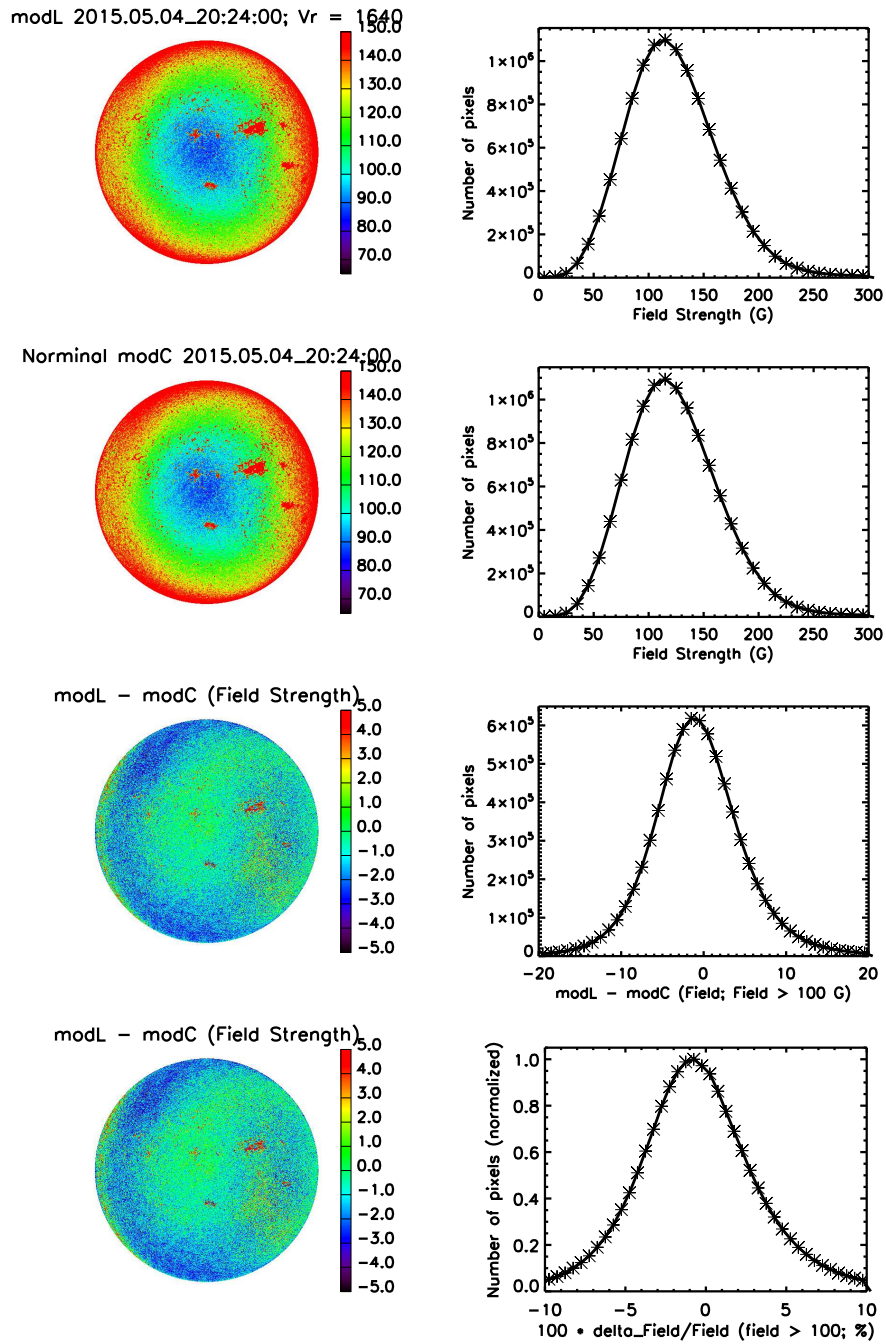


Fig. 2.— Comparison of field strength between pseudo Mod-L and Mod-C data.

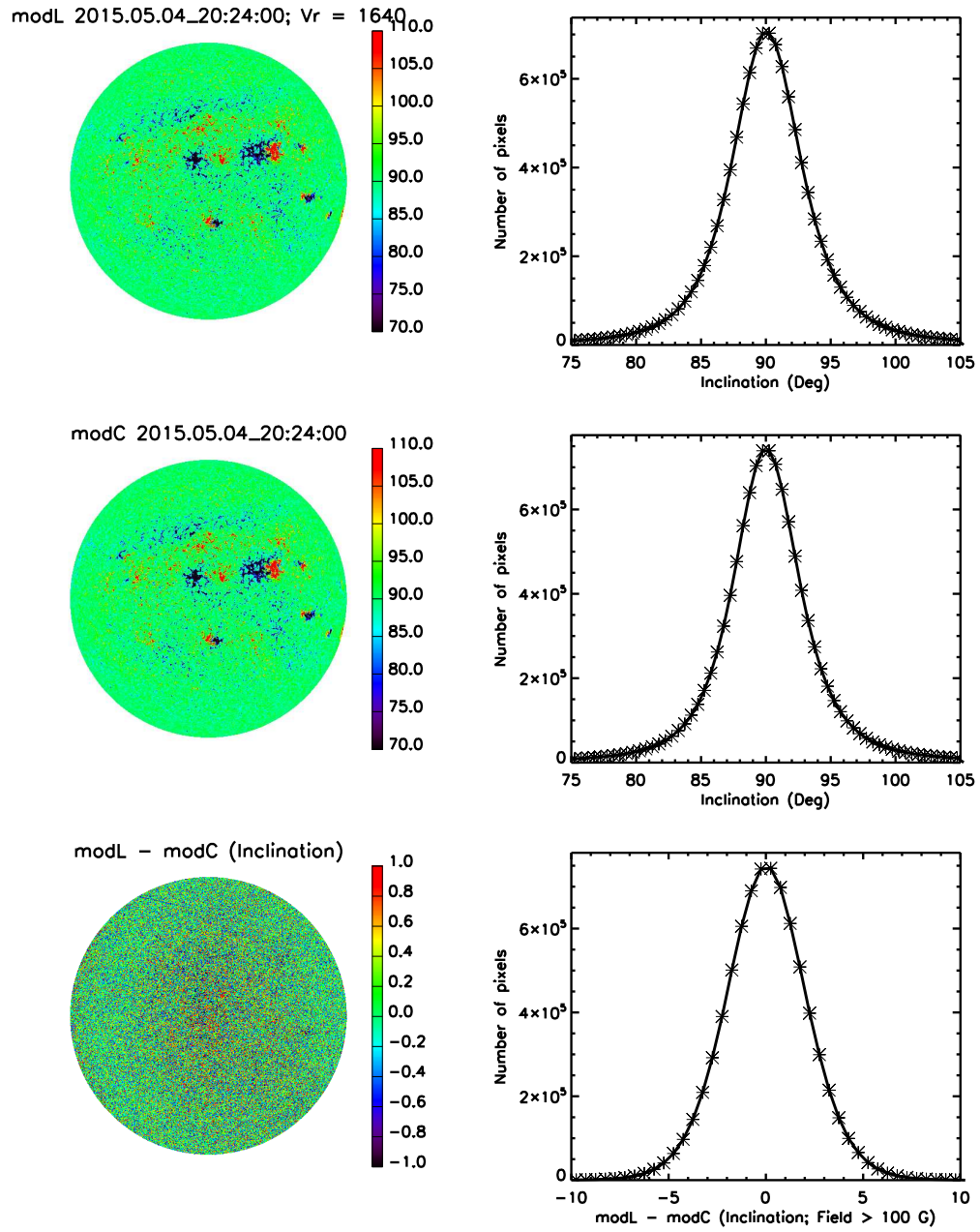


Fig. 3.— Comparison of inclinations between pseudo Mod-L and Mod-C data.

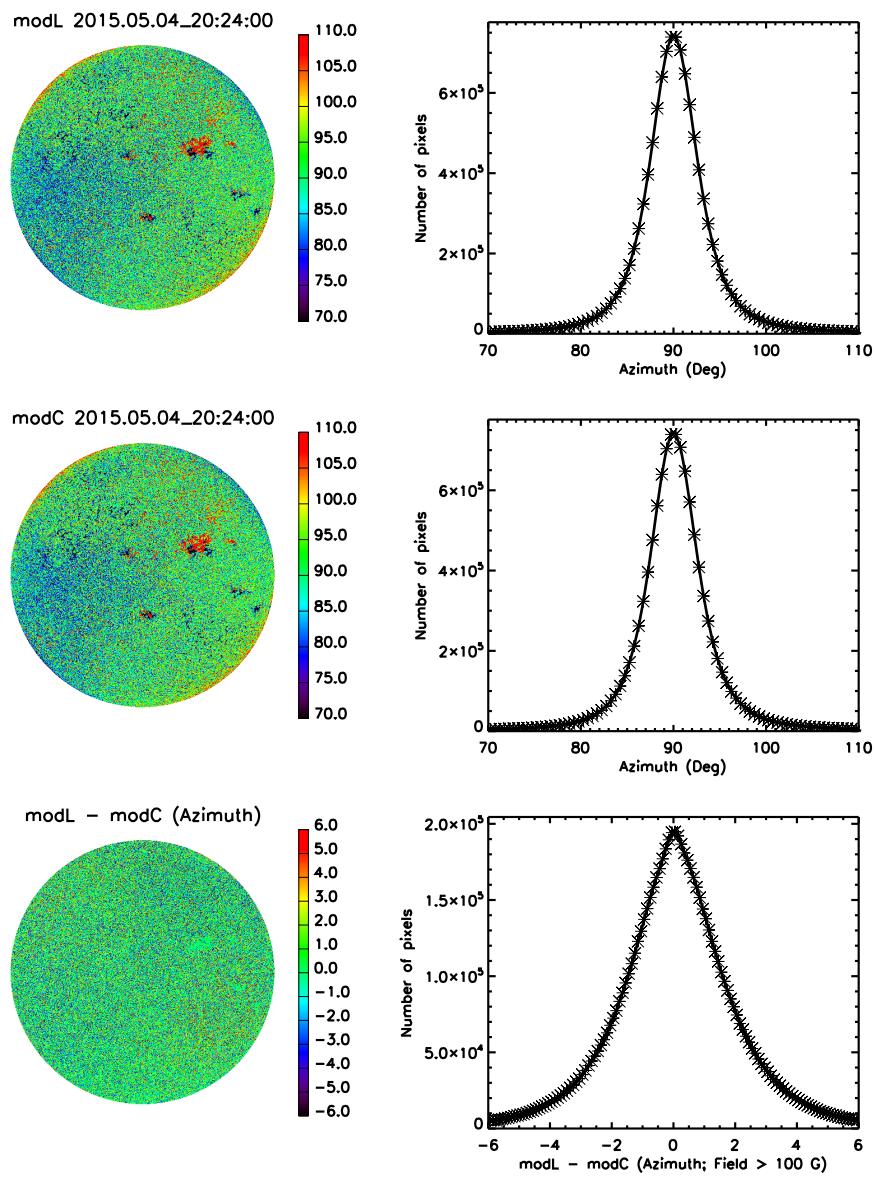


Fig. 4.— Comparison of azimuths between pseudo Mod-L and Mod-C data.

4. Test with Scaling Ratio

There are several ways to scale filtergrams from one camera to the other. The test carried out here is to examine if different scaling methods would lead to significant difference in resulting vector magnetic field data. It is also desirable to see if Mod-L produces better vector magnetic field data than Mod-C, as expected.

In this test, we produced three sets of vector magnetic field from Mod-L sequence using three rescaling schemes. (1) Rescaling each filtergram taken by the front camera using a scaling image (pixel-dependent scaling hereafter). That is, the scaling factor is pixel dependent. This scaling image is calculated from average of filtergrams by the front camera divided by average of filtergrams by the side camera. The resulting Stokes IQUV are inverted to derive vector field. (2) Rescaling each front camera filtergram by a constant scaling factor. This scaling factor is computed by taking the average of data mean (in keyword) at wavelength 5 (near continue) from front camera divided by the average from side camera. This scaling factor does not depend on location (pixels). The resulting IQUV are inverted to derive vector field (constant scaling hereafter). (3) No scaling factor is applied to any filtergram. The resulting IQUV are inverted to derive vector field (no scaling hereafter).

For inversion of vector magnetic field from Stokes [I,Q,U,V], because the inversion (module *vfisv()*) also uses parameters of photon noise for Stokes [I,Q,U,V], they need to be adjusted for Mod-L. For 720-sec average data, the photon noises for Mod-C are $\sigma(I) = 0.118\sqrt{I}$, and $\sigma(Q, U, V) = 0.204\sqrt{I}$, where I is the observed intensity for the same pixel and wavelength, assuming that the exposure time is 120 ms (Schou 2015). Since the polarimetric efficiency per unit time is the same for Mod-C, one gets the same numbers there.

When the two cameras are combined (Mod-L), Stokes Q and U are averaged with more frames, and thus the photon noise should be decreased. For the front camera the same number of images are taken, so for comparison a 720 second average there would give $\sigma(I) = 0.118\sqrt{I}$, and the same for V that is $\sigma(V) = 0.118\sqrt{I}$, as the all the images are also used to make V . For Q and U we now take 3/2 as many as before, so the errors reduce by a factor of $\sqrt{3/2}$ for Q and U , and thus, $\sigma(Q) = \sigma(U) = 0.167\sqrt{I}$ (Schou 2015).

Shown in Fig. 5 are field strengths from one Mod-L sequence with different scaling schemes. From first to third rows are pixel-dependent scaling, constant scaling, and no scaling schemes, respectively. As a reference, the bottom panels show field strength from a nominal Mod-C data, 24 hours apart. Its orbital velocity is very close to the one for the Mod-L data. One can see the noise in pixel-dependent scaling (top) and constant scaling (second) is smoother and slightly smaller than the no scaling (third) and Mod-C (bottom). It implies that the Mod-L data with reasonable scaling scheme leads to slightly lower noise

in the inverted vector field data.

Obviously, intensity ratio between two cameras depends on location. This spacial variation may also lead to slightly difference in inverted vector field if it is not taken into account. Fig. 6 shows comparison of inverted vector field from pixel-dependent scaling and constant scaling Mod-L data. Left column shows differences of field strength (top and second rows), inclination (third), and azimuth (bottom); in right column are histogram of difference of field strength in value (top), percentage (second), inclination (third), and azimuth (bottom) from pixels with field greater then 100 G only. Large-scale patterns are visible in the difference-image of field strength though the difference is only about a few percent. Thus using pixel-dependent scaling scheme is necessary.

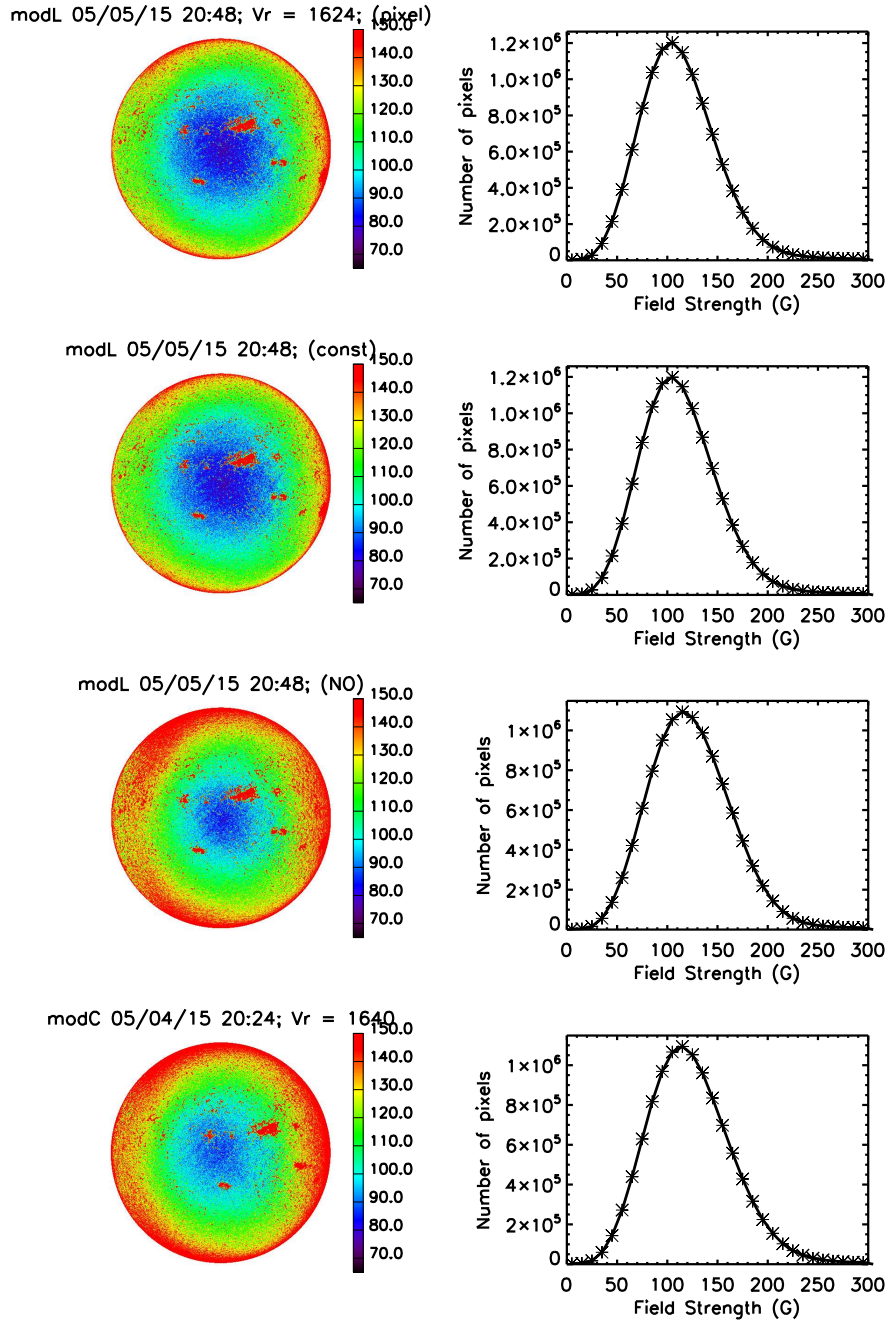


Fig. 5.— Images of field strengths (left) and histogram of weak field (right) from pixel-dependent scaling (top), constant scaling (second), no scaling (third) Mod-L data. As a reference, the bottom panels show field strength from a normal Mod-C data, 24 hours apart. Its orbital velocity is very close to the one for the Mod-L data.

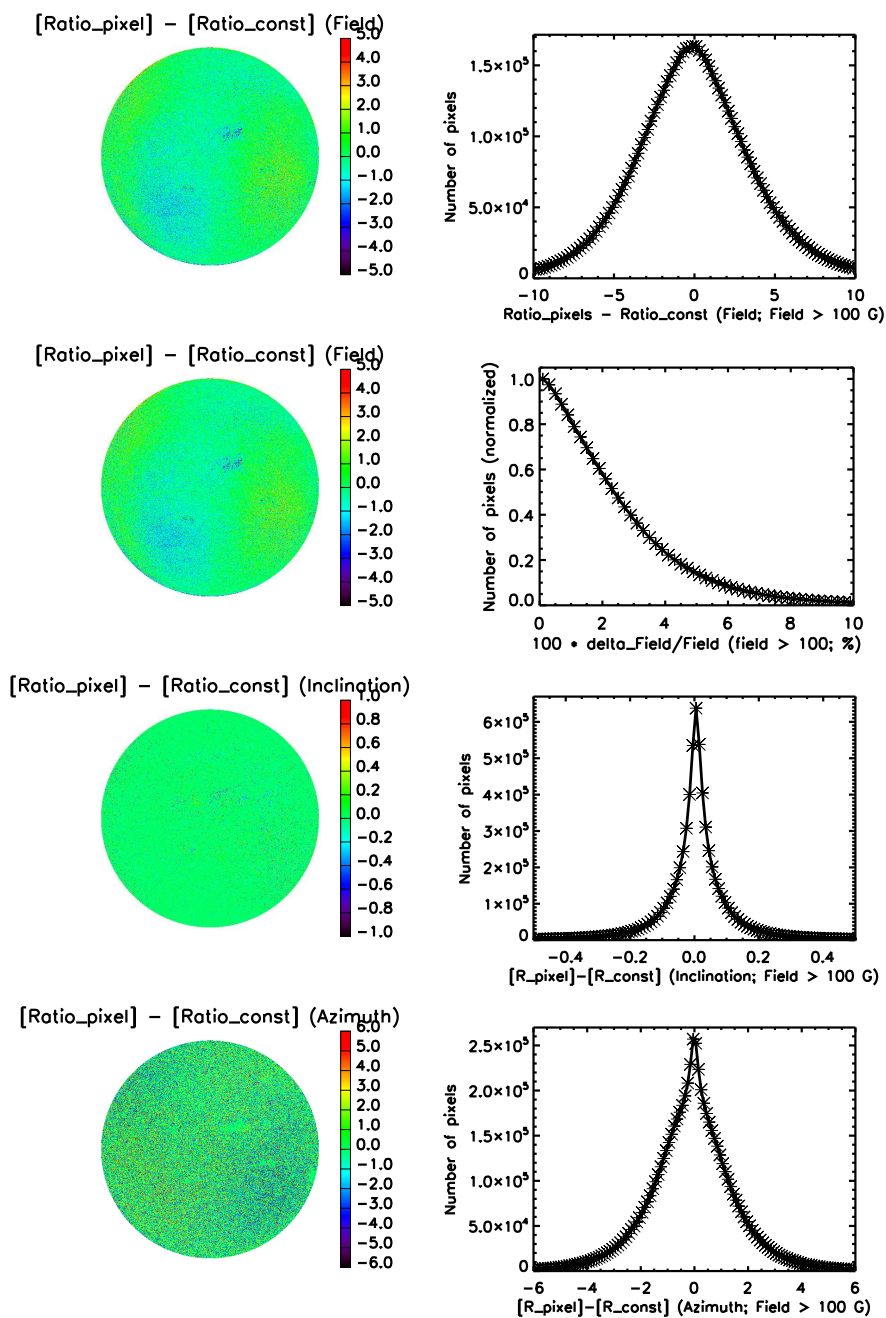


Fig. 6.— Left: Difference images of field strength (top and second), inclination, and azimuth of vector field between pixel-dependent and constant scaling schemes. Right: Histograms of the differences for the pixels with field greater than 100 G ($1\text{-}\sigma$).

5. Cross-talk in Mod-L Stokes

HMI took continuous 25 hours Mod-L observation from 2015.05.14_20:00:00 to 2015.05.15_21:00:00. This is a reasonable data set to examine if combining two cameras data are well calibrated with current polarization calibration model.

We repeated the test shown in Fig. 4 in the calibration paper (Couvidat et al. 2016) to check if Stokes [I,Q,U,V] from Mod-L processing have any additional cross talk.

The Mod-L data were processed to produce Stokes [I,Q,U,V] using pixel-dependent scaling scheme. These 25-hour Stokes data were (1) rebinned to 256×256 ; (2) [Q,U,V] were divided by the corresponding Stokes I; (3) averaging each of Stokes parameters at wavelength 0 ([I0,Q0,U0,V0]) and wavelength 5 ([I5,Q5,U5,V5]) to obtain Stokes [I,Q,U,V]; and finally (4) for each pixel, compute the median of [I,Q,U,V] from these 25-hour data. These images of medians are shown in the left panels of Fig. 7. As a reference, we also repeated the above processing with 25-hour Mod-C data 72 hours apart, from 2015.05.10_20:00:00 to 2015.05.11_21:00:00. The results are shown in the right panels. Both data show very small values of residual of [Q,U,V], and they are very similar. This indicates that current polarization calibration model works well with Stokes Mod-L sequence.

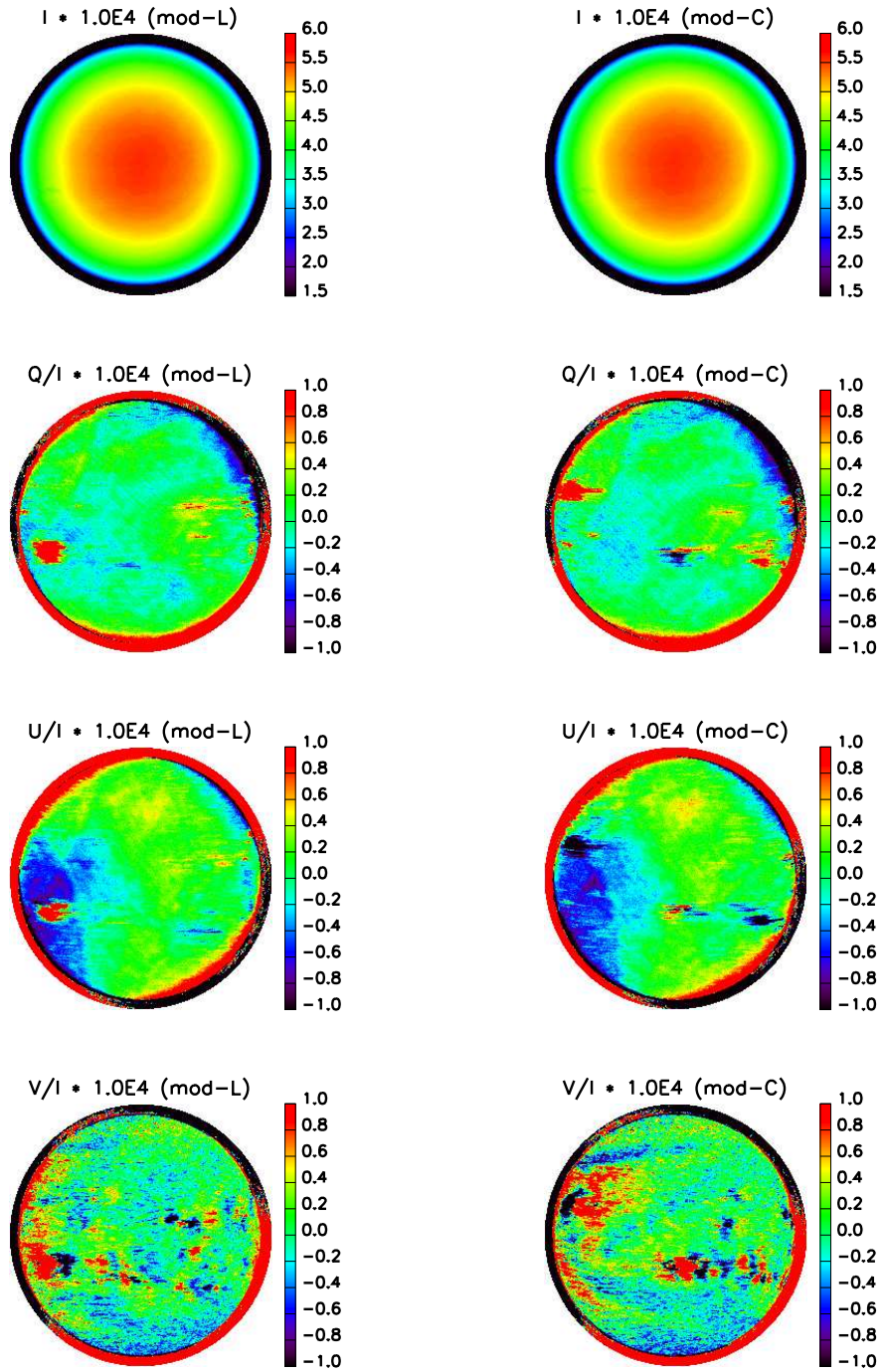


Fig. 7.— Medians of Stokes [I,Q,U,V] from 25-hour Mod-L (left) and Mod-C (right) sequence data, respectively.

6. Vector Field Inversion *vfisv()* With Different Phasemaps

Stokes [I,Q,U,V] from Mod-L are derived by combining two cameras' observations. The phasemap used in the vector field inversion module (*vfisv()*) should also be adjusted by combining two cameras' phasemaps together. This test is to evaluate if only using one phasemap in *Mod - L* is acceptable. The test uses nominal mod-C data (hmi.S_720s), but we run the module *vfisv()* twice with different phasemaps: the front camera phasemap, and the side camera phasemap. Comparison of the two solutions is shown in Fig. 8. On the right column are differences of field strength (top and second), inclination (third), and azimuth (bottom); on the right are histograms of the differences. The pixels with field strength greater than 300 G ($3\text{-}\sigma$) were selected for the histograms. One can see the difference is negligible: difference of field strength is peaked at 0.1 G, inclination at 0.1 degree, and azimuth at 0.0 degree. Thus it is acceptable to only use one phasemap to do vector magnetic field inversion.

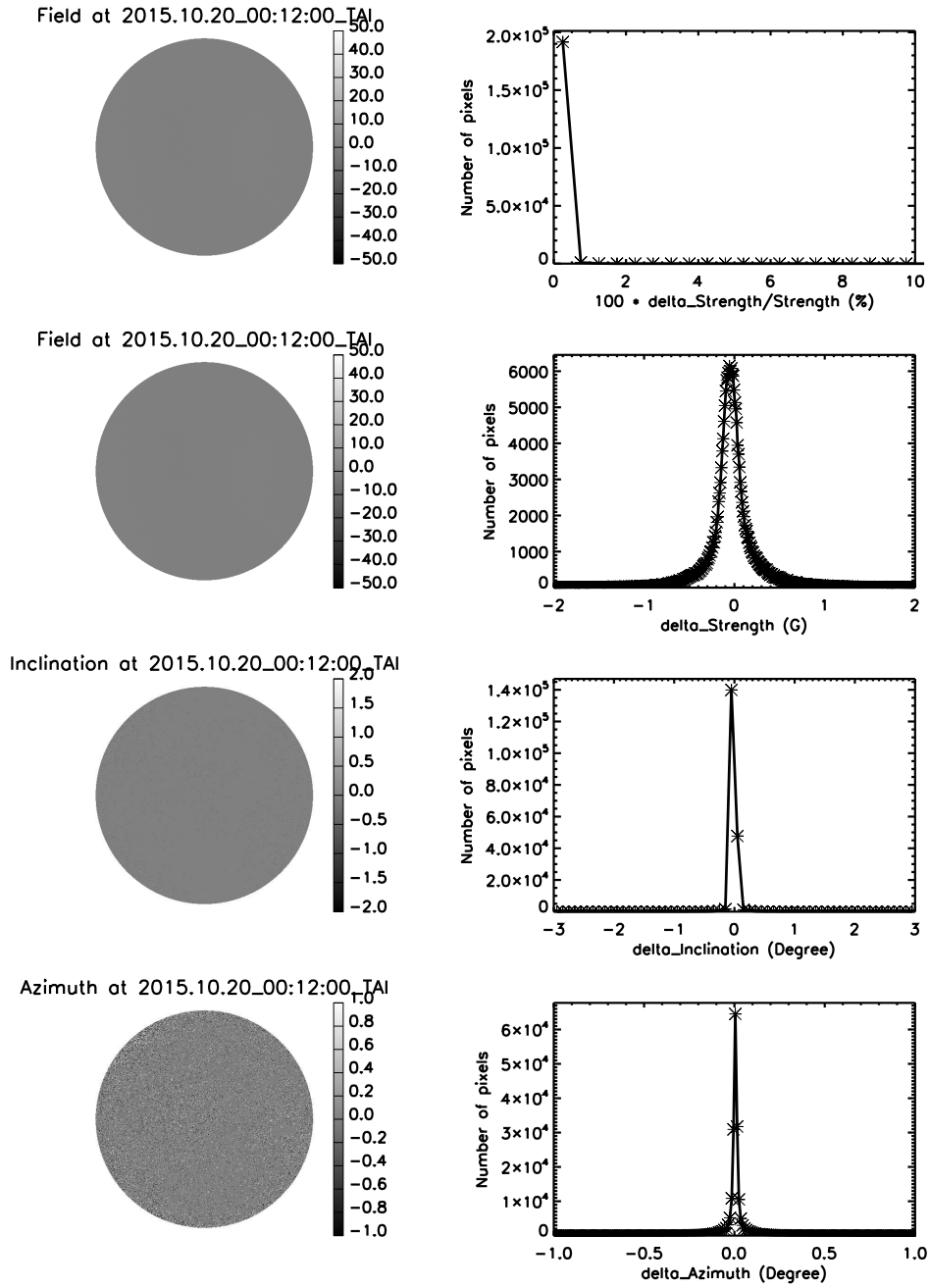


Fig. 8.— Difference of inverted vector magnetic field using two different phase maps: phase map for camera 1 and phase map for camera 2. Left: images of the differences of field strength (first and second), inclination (third), and azimuth (bottom). Right: histograms of the differences. Only pixels with field strength greater than 300 G are counted.

7. Conclusions

We have evaluated potential possibility of combining two cameras' observations to measure and derive vector magnetic field, i.e. the Mod-L sequence. We conclude that (1) combining two cameras' observations does not introduce appreciable systematic errors into the resulting inverted vector magnetic field data; (2) Mod-L sequence, after the intensities are properly scaled, leads to lower noise in inverted vector magnetic field data, as expected because this mode includes more frames than nominal mod-C; (3) pixel-dependent scaling scheme might demonstrate slightly better solution of vector magnetic field inversion than constant scaling scheme; (4) Current polarization calibration model works well with Mod-L sequence; and (5) Using different phasemaps in inversion module *vfisv()* does not lead to any appreciable difference in inverted vector magnetic field data.