Calibration of a ground-based solar coronal polarimeter

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ABSTRACT

The Mk4 K-coronameter records polarization brightness images of the solar corona from the Mauna Loa Solar Observatory, Hawaii, USA. Calibration is required to quantitatively measure coronal polarization brightness, which in turn is used to infer coronal electron density. Matrix techniques are used to map the instrument polarization response. Brightness scaling depends upon precise knowledge of properties of an opal glass attenuator and calibration polarizer, sky transmission, and telescope pointing. In addition, account must be made for polarization at the objective lens and from the terrestrial atmosphere. Calibration parameters are stable to a few percent over a day, but when coupled with uncertainties in calibration optics values, sky transmission, and pointing, the average measurement uncertainty is ±15% $\pm 6\times10^{-9}$ pB/B_{Sun}.

Keywords: Solar coronagraph, polarimeter

1. OVERVIEW OF THE MK4 K-CORONAMETER

The Mk4 K-coronameter operates at the Mauna Loa Solar Observatory on the island of Hawaii. White light mages of the polarization brightness of the corona from 1.12 R_{Sun} to 2.8R_{Sun} are recorded at a three-minute cadence over a five-hour observing day spanning approximately 1700UT to 2200UT and observations are possible about 300 days per year. The Mk4 is an augmentation to the MkIII K-coronameter[1] that operated from February 1980 through September 1999. The Mk4 began operation October 25, 1998 and observations overlapped the MkIII for nearly a year. During that time both instruments shared the same new computer control system, and software. An improved mechanism control system was installed and the calibration tilt plate registration was made mechanically stable.

1.1 OPTICAL LAYOUT

The Mk4 uses the same Lyot coronagraph as the MkIII[1] (Figure 1). The mounts for the objective lens through calibration tilt plates are fixed to the solar-pointed spar. From the occulting disk to the final focal plane, the entire telescope barrel rotates so that the corona can be scanned using a line array detector. Measurements are recorded in a radius-azimuth coordinate frame. Optical changes from the MkIII to Mk4 are all between I_2 and I_3 (Figure 2). The Polarization modulation rate is increased through the use of a ferroelectric liquid crystal (FLC) that superimposes a 240Hz chop on top of the 30Hz waveform created by the rotating retarder. An achromatic cube type polarizing beam splitter[2] is used in place of the MkIII's chromatic Glan Thomson beam splitter for better quality dual beam images. A Dalsa CL-C6-2048 line array camera is read at a 960Hz frame rate synchronized so that two frames are recorded per FLC state. This single line array with finer pixel spacing replaces two separate arrays and sets of read out electronics of the MkIII. A paper describing the Mk4 instrument in detail is in preparation.

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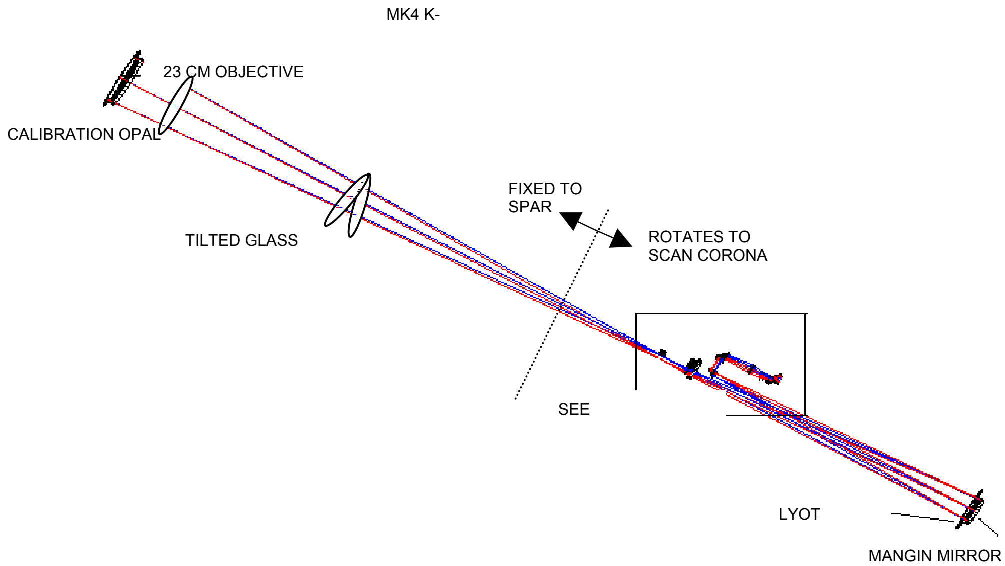

Figure 1. Mk4 K-coronameter. Optics from the objective through calibration tilt plates are fixed to the solar pointed spar. Optics from the occulting disk to the detectors are mounted in a rotating barrel used to scan the radial line array in azimuth around the Sun.

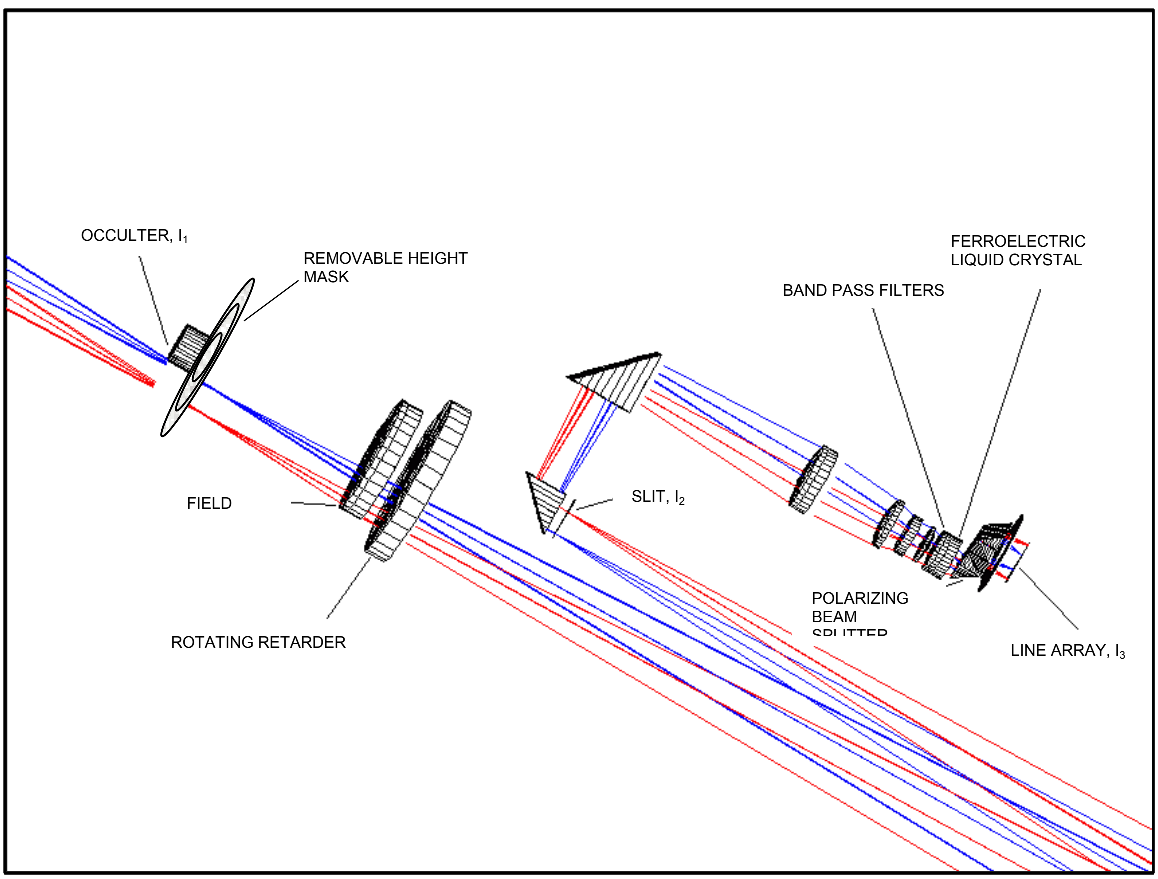

Figure 2. Rotating section of the K-coronameter. The prime focus solar image at I_1 is imaged onto the slit at I_2, then relayed to the line array detector, I_3. The rotating retarder creates a sinusoidal 30Hz modulation of linearly polarized light. The ferroelectric liquid crystal superimposes a 240Hz chop onto this waveform. A polarizing beam splitter sends two beams with polarization modulation of opposite phases to a single line array detector.

2. CALIBRATION ISSUES

The Mk4 measures 'Stokes' vectors at each of approximately 983 azimuths and about 350 unobstructed radii. The measured 'Stokes' vectors include intensity, I, and linear polarization elements, Q, and U. The polarization detection scheme is blind to V, circular polarization. Calibration includes all the steps required to flat field the camera, scale intensity measurements in solar brightness units, scale polarization relative to intensity, correct for cross talk among the Stokes parameters, correct the plate scale of the coronal images, center the images on the Sun, correct various electronic drifts, and correct for sky effects. All of these calibration issues except for sky correction must be performed for any coronameter, either in space or on the ground.

2.1 FLAT FIELDING

Flat fielding consists of removing a dark signal due to electronic bias and to dark current, and applying a multiplicative factor to correct for gain differences from pixel to pixel due to the detector and transmission of the optics across the field of view.

Dark signal can be a function of temperature and may change the bias, dark current, or both. The Dalsa CL-C6 line array camera has very large pixels, 13µm by 500µm that generate significant dark current, even at a 960Hz line read rate. For correction, the camera is read with a dark shutter closed to establish a dark pattern across the array. For every azimuthal position in a solar image, masked pixels below the height of the occulting disk are used to measure the dark current. Coronal images are presented as data are collected. This requires a real-time dark signal and gain correction. To correct pixel dark current throughout the day, the ratio of the masked pixel dark current at the time of calibration to the masked pixel dark for each scan is multiplied by the pixel dark current for each scan.

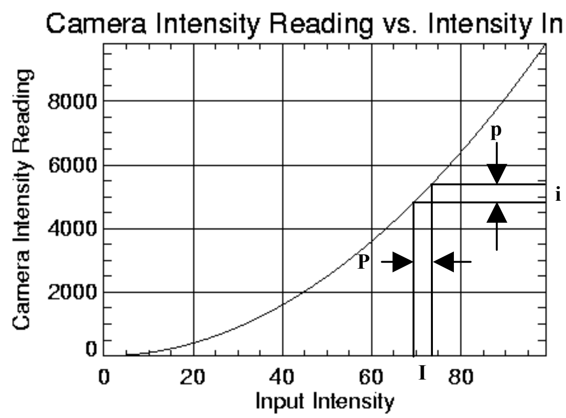

Figure 3. Scaling for a non-linear camera. The polarization signal, a small modulation on top of a large intensity, is scaled by the derivative of the intensity.

Pixel-to-pixel gain is measured with the calibration opal of known brightness in the beam. For a camera with linear response, the inverse of the signal measured is used as a multiplicative factor to correct the gain of each pixel. Data from the Mk4 camera used from September 1998 through May 2001 requires a non-linear camera correction. For non-linear correction, dark signal removed and the real-time gain is divided out. Measured intensity is $i=gI^{\gamma}$, where I is the intensity into the camera, g a gain constant, γ the non-linear constant, and i is the measured signal. The polarization signal is a small modulation riding on top of a large intensity. Modulation is proportional to the derivative of the intensity and is expressed by $p = gP\gamma I^{\gamma-1}$ where p is the measured polarization signal and P is the polarization signal input to the camera. Non-linearity was measured in the lab using the a constant exposure time, an illumination that varied by an order of magnitude across the field of view, and different light source brightness levels. A γ value of 3.3 makes the ratio of any exposure pair uniform across the field of view.

2.2 BRIGHTNESS SCALE

Mk4 intensity and polarization brightness values are calibrated relative to the HAO standard opal set[3]. The Mk4 calibration opal glass attenuator was recently calibrated relative to opal 5C of this set. Opal 5C is the closest in optical density to the calibration opal used in the Mk4. Other opals in the standard set were measured for verification. Recent calibrations used a Kodak Megaplus 1.6 camera, with a 500mm focal length lens, and opal mount on the front of the lens. The Mk4 calibration value is $1.38\times10^{-5} B/B_{Sun}$ at 775nm. A 'perfect' opal would produce a measured brightness of $1.011\times10^{-5} B/B_{Sun}$, and was applied to calibration of MkIII and Mk4 data processed before 2002. Data are being recalibrated with the new opal calibration value. The cited error for the 1970 opal brightness values is ±5%. The mean difference between the recent measurements and those in 1970 is ±5%.

2.3 POLARIMETER RESPONSE

The Mk4 measures three of the four elements of an input Stokes vector, I, Q, and U. Calibration follows a technique originally developed to describe the operation of the MkIII and later expanded to handle polarimeters in general[4].

$$\mathbf{s}_{\mathbf{measured}} = \mathbf{X}\mathbf{s}_{\mathbf{input}}$$

$$\mathbf{s}_{\mathbf{input}} = \mathbf{X}^{-1}\mathbf{s}_{\mathbf{measured}}$$

X is the 3×3 polarimeter response matrix. The input and output vectors are $\mathbf{s}_{\mathbf{input}}$ and $\mathbf{s}_{\mathbf{output}}$. The output vector is not a Stokes vector since it includes the modulation and demodulation techniques, response of the detector, and the analog to digital conversion constant. The difference of the intensity tangent to the solar limb minus the intensity radial to the solar limb is defined as Q. The intensity differences at 45° minus the intensity at 135°, measured CCW to the local tangent, is defined as U. Each element of the matrix, as well as the input and output vectors, are arrays either in height or in azimuth and height. The first column of **X** indicates the response to unpolarized input light. The output vector, when observing the calibration opal alone, is used to infer the first column elements. These vary both in azimuth and height and are therefore two-dimensional arrays. Element $\mathbf{X}_{11}$ is set to unity with its value used as a gain that multiplies all elements of **X**. Columns 2 and 3 of **X** indicate response to linearly polarized light, Q, and U. The polarization to intensity elements $\mathbf{X}_{12}$ and $\mathbf{X}_{13}$, are so small, they are set to 0. The internal elements $\mathbf{X}_{22}$, $\mathbf{X}_{23}$, $\mathbf{X}_{32}$, and $\mathbf{X}_{33}$ are 1-dimensional arrays in height. Values in columns 2 and 3 are determined using the calibration double-tilted glass plates. The BK7 glass plates have mechanical stops at an angle of 15° to the axis of the telescope. Calculation of the net polarization requires integration over the cone of rays falling on the plates and gives a fractional polarization of 0.0164.

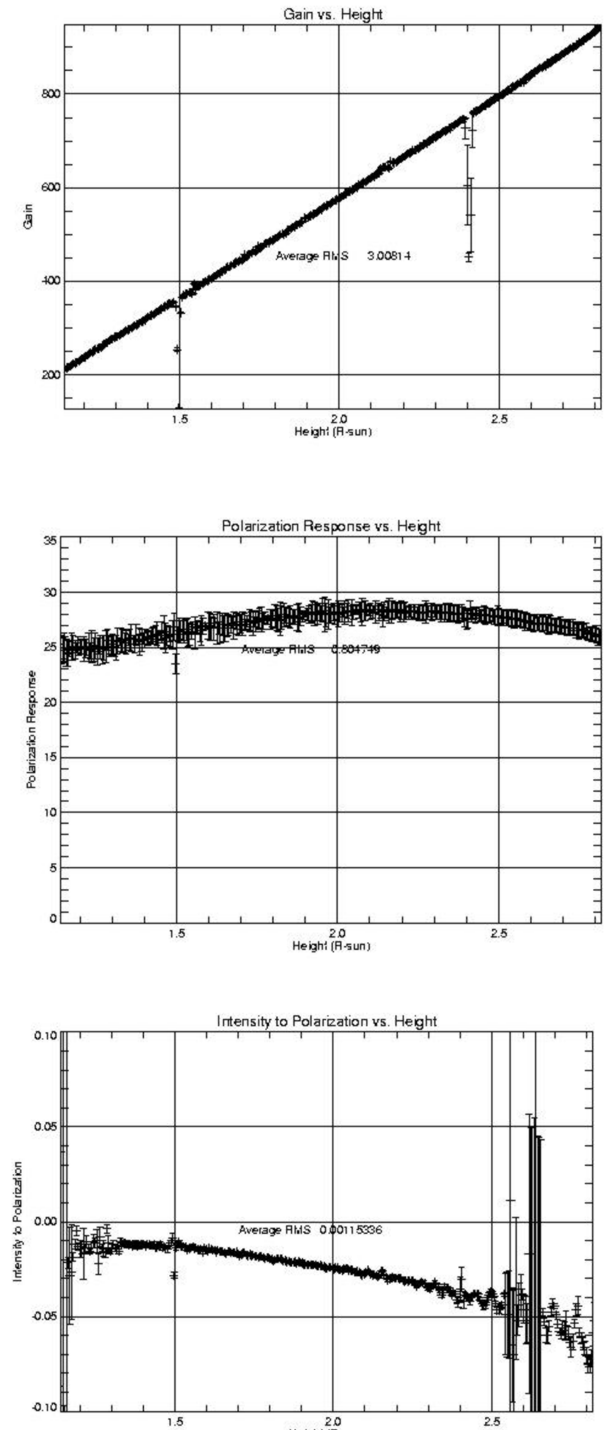

Figure 3a, 3b, & 3c. RMS variation of 6 calibrations spanning an observing day. 3a. Gain varies by ±.015 to ±.003 decreasing with height. 3b. Polarization response, (X_{22}) varies by ±.005. 3c. Intensity to polarization (X_{21}) scaled by X_{22} has an amplitude of 2×10^{-3} and varies by $\pm 4\times10^{-4}$.

A series of calibrations were performed spanning most of a day. The root mean square variation of the elements of the polarimeter response matrix gives an indication of the stability of the calibration (Figures 3a-c). Sample elements are the gain, g, response to polarized light, $\mathbf{X_{22}}$, and cross talk from intensity into polarization, $\mathbf{X_{21}}$. The fractional variation of the gain decreases from 1.5% near the limb to 0.3% at elevated heights. Fractional variation of the polarization response is about 0.5%. The most critical element of the polarimeter response matrix is $\mathbf{X_{21}}$. This element directly feeds instrumental polarization into the coronal signal. Light rays striking the two surfaces of the objective lens and the first surface of the rotating retarder are weakly linearly polarized. Light waves with the electric vector perpendicular to the plane of incidence at an optical surface are more easily reflected, such as at these optical surfaces preceding the modulator. Subtraction of the tangential component leaves a net radial polarization. This is seen as a negative $\mathbf{X_{21}}$ value that increases in magnitude with height to $-2\text{x}10^{-3} \pm 4\times10^{-4}$. For correct scaling, values in the $\mathbf{X_{21}}$ graph need to be multiplied by $\mathbf{X_{22}}$. Since the sky brightness is of order 10^{-5} B/B_{Sun} the correction to coronal polarization brightness is $2\times10^{-8} \pm 4\times10^{-9}$ B/B_{Sun}. This is comparable to the Mk4 noise level of about 4×10^{-9} B/B_{Sun}. At the most elevated heights in the field of view, polarization tangent to the limb of the Sun, thought to be due to vignetting in the telescope, is strong enough to make $\mathbf{X_{21}}$ become positive. This signal is not well measured using the calibration opal as the illumination especially near the edge of the field is not the same as when observing the corona. The mean of the noise envelope is used to set $\mathbf{X_{21}}$ for the highest pixels since coronal polarization at this height is below the noise level of the observation.

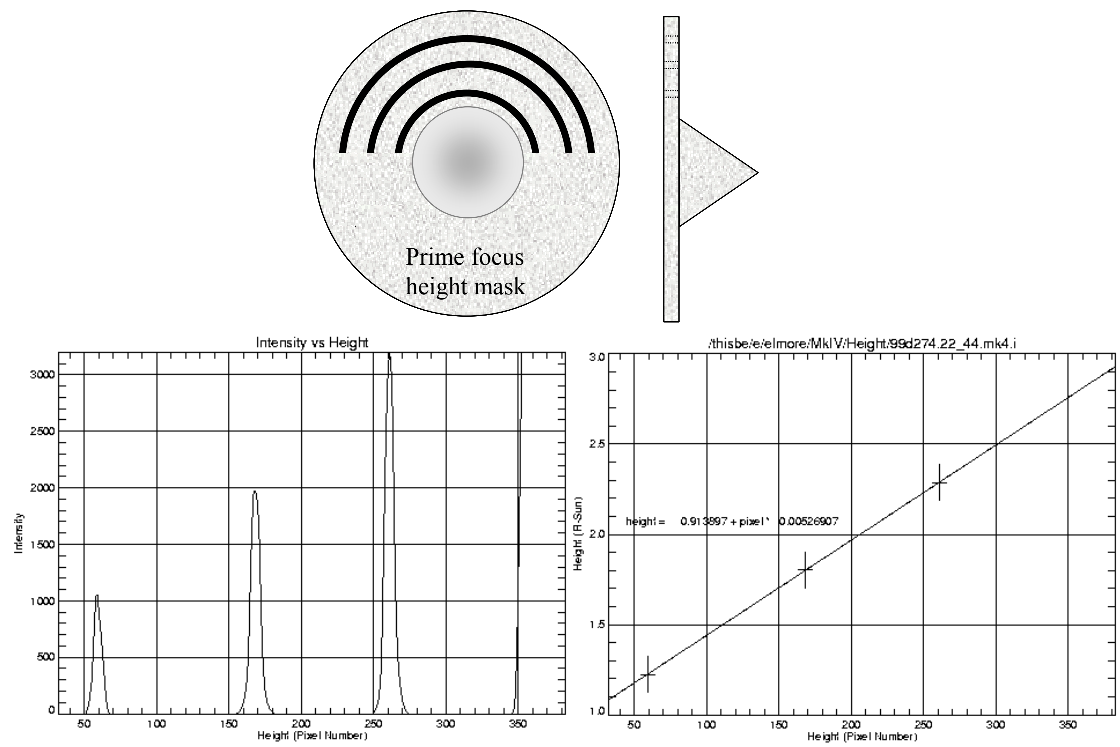

Figure 4a, 4b, & 4c. Prime focus height mask. Observed intensity vs. height shows images of the three slots. Gaussian fits give the pixel corresponding to the mechanically determined coronal height.

2.4 FLC THERMAL DRIFT

The amplitude of polarization modulation is a function of the FLC temperature. This temperature variation is present in all but the most recent Mk4 observations. For example, over the course of one winter day, the FLC temperature increased by about 20°C and the average coronal brightness increased by 15%.

Since May 2002, the FLC temperature has been controlled to ±1° thereby reducing this coronal brightness drift to below the limit of detection. The exact source of the drift is still under study, but analysis of each individual line array read indicates the response time of the FLC is limiting the magnitude of the polarization modulation. The response time of the FLC increases with decreasing temperature and therefore could be the source of the problem. For data collected prior to the FLC temperature stabilization the plan is to model diurnal drifts in modulation amplitude as a function of time of day and dome temperature and use the model to correct individual coronal scans.

2.5 PLATE SCALE

To determine plate scale for the Mk4, a mask with apertures defining three coronal heights is placed on top of the occulting disk at the prime focus of telescope, I_1 (Figures 4a-c). Since the focal length of the objective lens is known and the machined aperture diameters are known, the coronal height in arc seconds for each aperture is known. A scan using the opal is performed with the mask in place and the pixel height for each aperture as a function of scan azimuth is determined. The mean pixel value for each aperture is used to determine the pixel offset and scale factor. Depending upon the epoch of the instrument, the position of the relay lenses between I_2 and I_3 can be slightly different. Every time the optics are disturbed, a new height mask test is performed. A typical height scaling is $h_{960} = .914 + 0.00527 \times pixel\#$, where height is in solar radius, scaled to 960 arc seconds per solar radius. The variation in aperture height as a function of scan azimuth is 0.05 pixels RMS and is therefore neglected. The variation in aperture position over the course of a day is however; significant. A several pixel shift between sunrise and noon is possible. This height drift is due to a shift in the position of the camera relative to the slit at I_2. To correct for this drift, two hairlines are attached to the slit. Immediately after the height mask test, the pixel heights corresponding to these hairlines are measured to a fraction of a pixel. For every scan, images are translated and stretched in height so that the hairlines fall at the same pixel number as at the time of the height mask test.

2.6 SKY TRANSMISSION CORRECTION

Sky transmission varies with air mass along the line of sight to the Sun and therefore, an uncorrected coronal brightness measurement will vary as a function of air mass. The brightness of the disk of the Sun is measured using a sky transmission telescope. One could use the current solar brightness, and the zero air mass brightness reading to correct all coronal scans to zero air mass. Unfortunately, the sky transmission telescope electronics produce a waveform that, when read by the computer analog to digital converter, can sometimes give incorrect readings. Some days, all readings can look good; some days, all can look bad, and some days have a mixture. The calibration scheme is to look at the sky transmission telescope readings over the course of the whole day and an extinction curve is plotted (with obviously out-lying points eliminated). For 'good' days, the sky transmission curve vs. air mass is used to correct every coronal scan for sky transmission at the time of the scan. For 'bad' days, nearest previously good curve is used. The observed maximum difference between an average daily model sky transmission and the extinction curve on a 'good' day is ±2% at low air mass and ±7% at 5 air masses.

As part of the objective guider modernization program, the sky transmission telescope electronics will be updated. This will allow correction of each scan, or perhaps every scan position as a function of the current sky transmission.

2.7 SKY POLARIZATION CORRECTION

A small polarization in the sky can introduce significant signals in the coronal measurements since the sky is several orders of magnitude brighter than the corona. Polarization tangent to the limb is expected, due to scattering of sunlight by the atmosphere along the line of sight to the corona. This polarization is maximum at 90° to the direction to the sun and can easily been seen using Polaroid sunglasses. Polarization peaks strongly at 90° and is small enough over the Mk4 field of view to be removed through use of the coronal signal at elevated heights when computing the intensity to tangential polarization cross talk, the X_{21} computed as part of the normal polarimeter response matrix determination.

A more significant source of spurious polarization for Mk4 is due to sunlight reflected off the Earth and then again by the atmosphere into the line of sight. Both of these reflections polarize parallel to the horizon. Over the course of a coronal scan in a local solar radius and solar azimuth coordinate frame, the polarization, fixed in the plane of the sky, is proportional to $\sin(2\theta+\varphi)$ where θ is the scan azimuth and φ is an offset between heliocentric and geocentric coordinates. In the coronal polarization brightness data, this signal is difficult to separate from that of the corona. In fact, through much of the morning, this polarization pattern peaks predominantly in the east and west and overlaps the coronal streamer belt. Since the calibrated 'U' signal shows no coronal signal it can be used as a diagnostic for this sky polarization by fitting $\sin(2\theta+\varphi)$ of the U/I signal at each height. The amplitude of the sinusoidal modulation is then fit as a function of height. The average φ is used for all heights. Fit the the U/I signal, shifted in azimuth by 45°, is multiplied by the local intensity and subtracted from pB (calibrated Q).

2.8 TRACKING

There are two stages of Mk4 guiding: the spar, and the K-coronameter objective lens. The spar uses a quad cell guider with feedback to the speed of the RA drive roller and Declination drive. The measured spar tracking accuracy (derived from another solar pointed instrument mounted to the spar) is ±2 arc seconds RMS over 30 seconds. The K-coronameter objective lens is mounted on an X-Y stage with a range of ±40 arc seconds. The analog servo positions the X-Y stage in response to signals from four photocells that view reflections from the periphery of the K-coronameter occulting disk. The objective lens guider has had electronic and mechanical problems over the years, and at times has not been in action, depending upon its status at the time. Tests from June 2001 to July 2002 showed that the objective lens has excursions of up to 40 arc seconds, even when the spar was smoothly tracking. These O_1 excursions add noise to coronal maps. The coronal image can drift as much as the full range of the guider in an observing day, or ±40 arc seconds, even with the guider active. This is the single largest source of error in Mk4 calibration. Since this is a monotonic drift, not a random motion, the average tracking error is about ±20 arc second. At 1.2 R_{Sun} a ±20 arc second tracking error becomes a ±11% error in pB using a $pB(R)\propto R^{-6}$ coronal model. This value decreases to 4.5% at 2.8 R_{Sun}. Since tracking errors are due to a drift over a day, and since the spar guide telescope and O_1 guider are aligned during the middle of the observing day, one could expect errors due to tracking to be the largest early and late with the image of corona moving from west to east over the day.

As of July 2002, the objective guider is set to the center of its range and the spar guide telescope is aligned so that the mean error signals from the guider electronics are around zero. The objective lens guider servo is currently deactivated. In this mode, the O_1 guider excursions over the course of a scan have been eliminated, but the diurnal drift in coronal position still remains. Plans call for changing the objective guider sensor system from one using reflections off the periphery of the occulting disk to sensors using blue solar photospheric light spilling around the occulting disk. Electronics will be replaced with more modern and maintainable circuits.

Calibration techniques to correct the pointing of previous observations are under development. One technique showing promise is use of the residual corona signal in the calibrated U to infer the amount of off-pointing for that coronal map. Presently this $\sin(\theta+\alpha)$ signal is considered an error and is removed in a fashion similar to polarization fixed in the plane of the sky.

2.9 SCAN AZIMUTH

The K-coronameter barrel angle is read from a synchro-to-digital converter. This angle encoder has no zero point reference, and from time to time over the life of the K-coronameter, due to disassembly and reassembly of the front of the rotating section of the telescope, it has changed its reading relative to the barrel. The calibration tilt plates are fixed to the east face of the spar and therefore can be used as a geocentric reference. As part of the calibration, the phase of the polarization signal recorded during the scan of the opal plus calibration tilt plates is used to correct the azimuth reading of the barrel angle encoder for that day.

2.10 MEASUREMENT NOISE

Noise was measured by plotting the calibrated pB values and their root mean square deviation from the mean for a single coronal azimuth over the course of an observing day (Figure 5). From about $1.1R_{Sun}$ to 1.35 R_{Sun} the RMS is about 7.5% of the measurement. A peak deviation is about 3 times the RMS and the average deviation half the peak, or about ±11%. This is compatible with the tracking error estimates. At elevated heights, instrumental noise dominates at a level of $\pm 4\times10^{-9}$ pB/B_{Sun}. The instrumental noise can and is reduced by image summing. The average image of the day is typically a factor of 3 to 4 lower in instrumental noise (Figure 6).

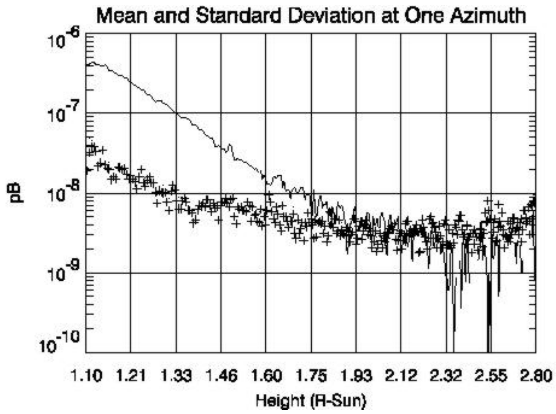

Figure 5. Mean and standard deviation of pB for one azimuth over a day.

2.11 ERROR SUMMARY

The vector sum of all the errors listed is used to infer a total error estimate for the Mk4 (Table 1). Entries are given at three coronal heights. Tracking error is the main error source low in the corona. The total of other calibration uncertainties dominate at more elevated heights. The instrumental noise (section 2.10) and uncertainty in X_{21} (section 2.3) set a limit on measurement accuracy at elevated heights. The root sum square of these two contributions is $\pm 6\times10^{-9}$ pB/B_{Sun}.

Error source	1.2 R_{Sun}	2.0 R_{Sun}	2.8 R_{Sun}
Reference opal calibration	± 5%	± 5%	± 5%
Mk4 opal relative to reference	± 5%	± 5%	± 5%
X matrix determination	± 1.5%	± 1.0%	± 0.6%
Sky transmission	± 7%	± 5%	± 3%
Total calibration error	± 10%	± 9%	± 8%
Average tracking error	± 11%	± 7%	± 5%
Average Mk4 error	± 15%	± 11%	± 9%

Table 1. Summary of Mk4 calibration errors. Uncertainty in the calibration dominates except at low coronal heights where tracking errors become important.

The average Mk4 error shown in Table 1 is in terms of percentage of calibrated polarization brightness. With instrumental noise added, the Mk4 error is $\pm15\% \pm 6\times10^{-9}$ pB/B_{Sun}.

3. CALIBRATION STEPS

Mk4 calibration software accesses a table of instrument parameters for each epoch of Mk4 operation. This table contains many parameters describing the instrument at any given time. Entries include the camera non-linear γ correction, height scaling parameters, heights of the reference hairlines, and the range of good pixels. Following is a list of the calibration steps. Details from the actual software are available upon request.

3.1 ALL SCANS

- From data files extract 384 height × ~985 azimuth uncalibrated I, Q, and U images, Sky transmission at each azimuth, telescope barrel angle at each azimuth, and time at each azimuth.

- Correct digital artifacts, such as a jump in camera read phasing
- Spline fit each height from ~985 azimuths to 720 azimuths
- Correct height scaling using reference hairlines
- Correct intensity data for zero offset using ‘dark’ pixels.
- Depending upon epoch, correct intensity and polarization signal for camera non-linearity
- Correct for sky transmission

3.2 FINDING THE POLARIMETER RESPONSE MATRIX

- Use the scan of the opal alone to determine the solar brightness scale factor
- Use scan of opal alone to determine I to Q, and I to U cross talk
- Use scan of corona to adjust I to Q and I to U cross talk at elevated coronal heights
- Use scan of opal plus double tilted glass plates to determine Q and U response to polarization , and cross talk between Q and U
- Use the phase of the linear polarization to correct the barrel angle readings

3.3 CORONAL SCANS

- Apply the inverse polarimeter response matrix to each coronal scan to produce calibrated brightness, B, calibrated polarization brightness, pB, and calibrated U
- For each coronal height, use calibrated U to infer polarization fixed in the plane of the sky
- Transform polar coordinate image to Cartesian
- Remove polarization fixed in the plane of the sky from both U and pB.
- Create average image of the day, Figure 6.
- Create jpeg movies for each day
- Extend synoptic maps
- Store calibrated data in FITS format to archive accessible from http://mlso.hao.ucar.edu

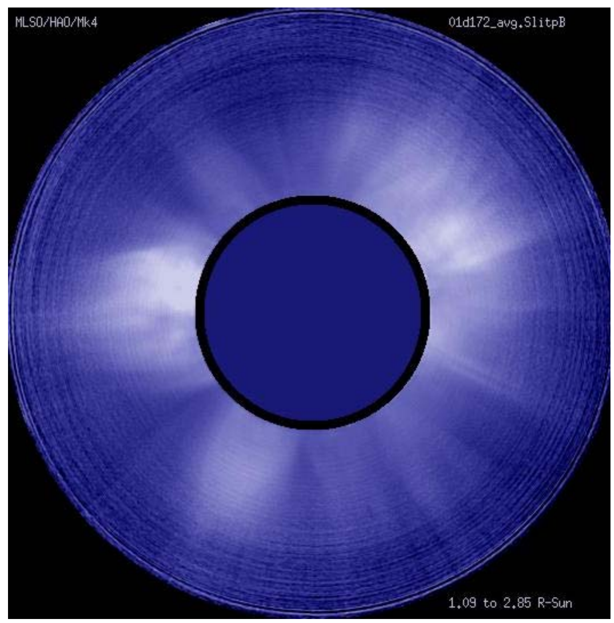

Figure 6. Average image of the day for eclipse day, 21 June, 2001.

3.4 MLSO QUICK LOOK IMAGES

- Multiply pB by inverse coronal model to reduce the dynamic range of data to be displayed
- Do a coordinate transformation to heliocentric X and Y for qualitative display
- Convert to animated gif images
- Show to observers
- Send to http://mlso.hao.ucar.edu

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