Calibration of the SMM Coronagraph/Polarimeter Based On Observations of Jupiter

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1 Introduction

This technical note provides a description of Jupiter observations, measurements, and computational methods used to determine an absolute calibration for the High Altitude Observatory's (HAO) Coronagraph/Polarimeter (C/P) instrument, which was part of the scientific payload of the Solar Maximum Mission (SMM) satellite.

Coronal images from the C/P telescope were acquired using an SEC vidicon camera. The coronal images are photometrically calibrated by comparing raw pixel response levels (range: 0-255) with a *transfer* curve generated for each pixel using a series of flat-field images of varying exposure durations. Additional details describing the C/P telescope and the calibration method may be found in Appendix B.

The absolute brightness levels produced by the SMM C/P calibration have been questioned as a result of comparisons with other coronal data (MLSO Mark-III K-coronameter, 1980 HAO eclipse), and also due to derived K-corona brightnesses which are suspected to be too low. A study by Richard Munro (1985) involving a comparison of C/P observations with the 16 February 1980 eclipse images (taken by HAO eclipse camera) concluded that the C/P calibration was too low by about a factor of 2 to 3, depending upon the radial position.

The purpose of this study is to determine the absolute calibration level of the SMM C/P instrument.
Since no significant omissions or errors have been discovered in the C/P photometric calibration *procedure*, we have accepted it to be a valid means of producing images which are relatively calibrated in a consistent manner.

This document compares the *calibrated* C/P measurments of Jupiter with independent observations of Jupiter, thereby obtaining a multiplicative correction factor for calibrated C/P images. Once this factor is determined, it may be used to adjust calibrated C/P images so that the C/P brightness values agree with other observations of Jupiter. An absolute calibration of the C/P instrument will then be obtained.

2 Observations of Jupiter

At Jupiter's conjunction with the sun in June 1989, the planet passed through the SMM C/P field of view. This event provided an opportunity to use Jupiter to establish an absolute calibration of the C/P instrument.

Although a majority of the coronal images were taken using the coronagraph's green broad-band filter (5000-5350 $\AA$), it was NOT used to acquire images of Jupiter, since even at the shortest available exposure duration (1.024 seconds), an image of Jupiter is saturated (i.e., it exceeds the maximum measurable exposure level) on the C/P vidicon when using the green filter. By using the H_α filter (6563 $\pm$ 20 $\AA$), it was possible to obtain Jupiter images whose maximum pixel levels were approximately in the middle of the detectable range at an exposure duration of 6.144 seconds (which was a typical exposure duration used for coronal images).

During the conjunction period (7-11 June 1989), 71 high resolution images of Jupiter were acquired using the SMM coronagraph/polarimeter instrument. These observations are described in Appendix C. A sample image of Jupiter, acquired from the SMM C/P vidicon, is shown in Figure 1.

3 Predicted Brightness of Jupiter

When we observe Jupiter at H_α wavelengths (6563 ± 20 Å), we are seeing reflected sunlight. The flux of sunlight (i.e., mean intensity of the solar disk) in H_α is $F_S = 2.24 \times 10^6\ erg/sr/cm^2/Å/s$ (Allen 1955, p140). The solar flux received at Earth is :

$$f_{SE} = \pi F_S \left(\frac{R_S}{A}\right)^2 \ = \ 6.80 \times 10^{-5}\ F_S \ = \ 152.3\ erg/cm^2/Å/s$$

and the solar flux received at Jupiter is

$$f_{SJ} = \pi F_S \left(\frac{R_S}{A}\right)^2 \frac{1}{{a_J}^2} \ = \ 2.51 \times 10^{-6}\ F_S \ = \ 5.63\ erg/cm^2/Å/s$$

where R_S = solar radius = 6.96×10^5 km, A = 1 A.U. = 1.496×10^8 km, and a_J = heliocentric distance of Jupiter in A.U. = 5.2 A.U.

The reflectivity of Jupiter (≈ 0.75) has been measured as a function of wavelength and position on Jupiter and is generally quoted as the ratio I/F, where I is the specific intensity of Jupiter, and πF is the incident solar flux at Jupiter. Thus, the light reflected by Jupiter is :

$$\pi F_J = (I/F)\ \pi F_S \left(\frac{R_S}{A}\right)^2 \frac{1}{{a_J}^2}$$

The flux of reflected sunlight received at Earth is :

$$f_{SJE} = \pi F_J \left(\frac{R_J}{a_{EJ} \cdot A}\right)^2$$

$$= (I/F)\ \pi F_S \left(\frac{R_S}{A}\right)^2 \frac{1}{{a_J}^2} \left(\frac{R_J}{a_{EJ}}\right)^2 \frac{1}{A^2}$$

$$= (0.75)\left(2.51 \times 10^{-6}\right)\ \left(5.93x19^{-9}\right) \ = \ 2.50 \times 10^{-8}\ erg/cm^2/Å/s$$

where a_{EJ} is the distance between the Earth and Jupiter at conjunction in A.U. units (6.2) and R_J is the radius of Jupiter (7.14×10^4 km).

Now we can compare the intensity of Jupiter seen from Earth with the intensity of direct sunlight :

$$\left(\frac{f_{SJE}}{f_{SE}}\right) = (I/F)\ \left(\frac{R_J}{a_J \cdot a_{EJ} \cdot A}\right)^2$$

$$= 1.65 \times 10^{-10}$$

A discussion of the accuracy of this number is given in Appendix A. Meanwhile, note that this value is consistent with the comparison of the apparent magnitudes of the sun and Jupiter. [1]

What we actually *measure* with the SMM C/P instrument is the brightness (per pixel) of an object (assumed to be at a distance of 1 A.U.) relative to the brightness of the sun (i.e., B_{object}/B_{sun}). If we bring Jupiter to 1 A.U. and make it the same size as the sun (i.e., spread all the Jupiter photons over the angular size of the sun) [2] we have :

$$\frac{\text{Brightness of Jupiter}}{\text{Brightness of Sun}} = \frac{f_{SJE}}{f_{SE}}\frac{\Omega_S}{\Omega_J} = (I/F)\ \left(\frac{R_J}{a_J\ a_{EJ}\ A}\right)^2 \frac{\Omega_S}{\Omega_J}$$

[1] luminosity equation:

$$m_1 - m_2 = 2.5 \log\left(l_2/l_1\right)$$

So, the ratio of the luminosities of Jupiter and the Sun is

$$l_J/l_S = 10^{(m_S - M_J)/2.5} = 10^{(-26.86+1.9)/2.5} = 10^{-10}$$

[2] Angular sizes:

$$\Omega_{pixel} = \tan\theta^2 = 8.27 \times 10^{-10}\ sr$$

$$= (I/F)\left(\frac{R_S}{A}\right)^2 \frac{1}{a_J{}^2} = 6.03 \times 10^{-7}\ (\pm 0.19 \times 10^{-7})\ B_{sun}$$

Again, details about the numbers are given in Appendix A. This ignores issues of limb-darkening, variations in reflectivity of Jupiter across the disk (e.g., belts and zones), etc. Since Jupiter covers many pixels, the quantity above is really the intensity of the brightest pixels compared with the center of the solar disk ($B_{sun} = 199\ erg/cm^2/\AA/s$) and only depends on the reflectivity of Jupiter over the H_α waveband.

We can also estimate the *total intensity* of Jupiter, first with no limb-darkening. Jupiter covers Ω_J/Ω_{pixel} = 23.46 pixels, so

$$\frac{\text{Integrated Brightness}}{\text{Bsun}} = 6.03 \times 10^{-7}\ \times\ 23.64 = 1.42 \times 10^{-5}\ B_{sun}$$

This integrated brightness assumes Jupiter reflects as a flat disk, with uniform reflectivity of 0.75. We can use disk scans of Jupiter observations to obtain a disk-averaged reflectivity

$$\overline{(I/F)} = 2\int_0^1 I/F(r)\ r\ dr \approx 0.49$$

where we have taken N/S and E/W scans to get an average radial profile of I/F, which is then integrated numerically (see Appendix A). The integrated brightness, including limb-darkening, becomes:

$$\frac{\text{Integrated Brightness}}{\text{Bsun}} = 1.42 \times 10^{-5}\ \div 0.75\ \times 0.49 = 9.29 \times 10^{-6}\ B_{sun}$$

4 Comparison with Jupiter Observations

4.1 Brightest Pixel

Our prediction for the Brightest Pixel/Bsun = 6.03 ($\pm$0.19) $\times 10^{-7}$ may now be compared with the SMM coronagraph's observations of Jupiter. Appendix C shows the data in various forms. We found that the values for the post-conjunction observations (using the "East" and "West" sectors) were consistently brighter than pre-conjunction observations (using the "North" sector). We have taken the ratio of the predicted to observed brightness to produce the numerical factor by which the observed brightness needs to be increased to match the prediction.

Observation	Brightest Pixel	Factor
North Sector	$1.7 \times 10^{-7}\ B_{sun}$	3.55
E/W Sectors:		
Maximum	$4.2 \times 10^{-7}\ B_{sun}$	1.43
Average	$3.0 \times 10^{-7}\ B_{sun}$	2.01
Minimum	$1.7 \times 10^{-7}\ B_{sun}$	3.55

where the size of a pixel is θ= 5.933 arcseconds.

$$\Omega_S = 4\pi\frac{\pi R_S^2}{4\pi A^2} = \pi\left(\frac{696,000}{1.496 \times 10^8}\right)^2 = 6.80 \times 10^{-5}\ sr$$

$$\Omega_J = \pi\left(\frac{R_J}{A}\right)^2 \frac{1}{a_{EJ}{}^2} = \pi\left(\frac{71,400}{1.496 \times 10^8}\right)^2 \frac{1}{6.2^2} = 1.88 \times 10^{-8}\ sr$$

$$\left(\frac{\Omega_S}{\Omega_J}\right) = \left(\frac{R_S}{R_J}\right)^2 a_{EJ}{}^2 = 3653$$

4.2 Integrated Brightness

Our computed value for the integrated brightness of Jupiter ($= 9.29 \times 10^{-6} B_{sun}$ with errors that are harder to estimate — probably no more than 10–15%) is compared below with the integrated brightness of Jupiter measured from C/P observations.

Observation	Integrated Brightest	Factor
North Sector	$3.7 \times 10^{-6}\ B_{sun}$	2.51
E/W Sectors	$4.6 \times 10^{-6}\ B_{sun}$	2.02

The plots (Appendix C: Figures 6-C and 8-C) show that the scatter is less for the integrated brightness observations than for the brightest pixel values, which may be due to pointing inaccuracies (spreading the light over more pixels). The differences between the N and the E/W sectors remains a puzzle.

Conclusion: The SMM C/P intensities should be increased by a factor of 2 while there remains $\approx$ 25-50% inaccuracy, which may be systematic over the field of view. The north sector images are not given as much credibility as the east and west sector data for the following reasons: (1) only a small number of observations are available in the north (only 4), and (2) in the north sector images, Jupiter appears near the top of the vidicon, an area which is more sensitive and less well calibrated than the rest of the detector.

5 Comparison with Mark III K-coronameter

This document has illustrated how the absolute calibration of coronameters is fraught with difficulties. We therefore show how the measurements of coronal brightness made by the SMM C/P telescope compare with ground-based observations acquired by the HAO/MLSO (Mauna Loa Solar Observatory) Mark-III K-coronameter in Hawaii. Figure 2 presents composite radial profiles of coronal polarized brightness from the Mark-III and SMM C/P telescopes at 10 degree intervals in polar angle on 26 May 1986 (i.e., at solar minimum, when the few hour difference between measurements should not be of importance). The Mark-III K-coronameter measures polarized brightness from 1.15 to 2.2 R_{sun} (units of solar radius), while the SMM C/P instrument supplies observations for the range of 1.8 to 4.0 R_{sun}. Thus, there is some overlap in radial coverage. The SMM C/P radial scan values in Figure 2 have been multiplied by a factor of 2.0 in accordance with the absolute calibration adjustment derived in this report.

When one allows for sources of error in the measurements (such as low signal-to-noise in the Mark-III instrument above 1.8 R_{sun}), the brightness profiles match remarkably well. The data from this day would suggest that the SMM C/P values might be increased even further in order to better match the Mark-III values. Further analysis of other days will allow us to assess whether this is a systematic trend.

Appendix A : Predicted Brightness of Jupiter Details

The predicted value for the intensity (either brightest pixel or integrated) is given by

$$\frac{\text{Intensity}}{\text{Bsun}} = (I/F)^{\alpha}_{J} \, \frac{1}{a_J^2} \left(\frac{R_S}{A} \right)^2$$

where $(I/F)^{\alpha}_{J}$ is the appropriate reflectivity of Jupiter in the H_α waveband. The Astronomical Almanac gives the following values for June 9–11, 1989:

$$\begin{array}{ll} a_J = 5.077837 - 5.081075 & = 5.079 \text{ A.U. } \pm 0.063\% \\ R_S & = 6.96 \times 10^5 \ km \ \pm 0.014\% \\ A & = 1.49 \times 10^8 \ km \ \pm 0.03\% \end{array}$$

This gives

$$\frac{\text{Intensity}}{\text{Bsun}} = (I/F)^{\alpha}_{J} \; 8.387 \times 10^7 (\pm 0.2\%)$$

Hence, the major uncertainty lies in the estimation of (I/F) for Jupiter over the 40Å waveband of the H_α filter.

For the brightest pixel intensity, we looked for a value of I/F around 6563 Å over the central region of Jupiter. However, we must consider the large range in reflectivity between the belts and zones. The Equatorial Zone (EZ) and the North and South Tropical Zones (NTrZ and STrZ) have much higher albedos than the North and South Equatorial Belts (NEB and SEB). We took 2 test pixels near the center of Jupiter, the expected location of the brightest pixel (illustrated in Figure 1-A). Values of I/F at H_α were extracted from spectra obtained at central meridian in these regions by Woodman et al. (1979). See Figures 2-A to 6-A.

Region	Area Fraction	Zone	(I/F)	AVERAGE
1	50%	STrZ	0.78	
	25%	SEB	0.69	0.73
	25%	EZ	0.675	
2	75%	STrZ	0.78	
	25%	SEB	0.69	0.76

Note - Woodman et al.(1979) only measured the NTrZ. Orton(1975) shows the STrZ to be 1.05 times brighter than the NTrZ, so we are using an average of Orton's value for the STrZ (0.77) and 1.05× Woodman et al.'s value (0.79) for the STrZ. This makes our best guess for I/F for the brightest pixel to be 0.75 (±0.02).

For the integrated brightness, we have to average the reflectivity over the disk

$$\overline{(I/F)} = 2 \int_0^1 I/F(r) \; r \; dr$$

The radial profile, I/F(r), was derived by averaging limb-scans of Pilcher and Kunkle (1976). We superposed N/S (Figure 7-A) and E/W (Figure 8-A) scans to make an average I/F(r) smoothing about ±0.1 variations (Figure 9-A). A simple numerical integration of this profile (given in Table 1-A) provides an average value of $\overline{I/F} \approx 0.49$.

Appendix B : Coronagraph/Polarimeter Instrument

Overview

A brief overview will be presented in this section in order to familiarize the reader with the SMM Coronagraph/Polarimeter project.

The High Altitude Observatory (HAO) operated an externally-occulted Lyot coronagraph (a telescope designed to acquire images of the solar corona) which flew aboard the NASA Solar Maximum Mission satellite, along with several other solar instruments. For a more detailed description of the telescope design, consult the 1974 and 1980 references for MacQueen listed at the end of this report.

The SMM satellite was launched into Earth orbit at an altitude of about 500 km on 14 February 1980. Due to failures in both the spacecraft attitude control system and the C/P electronics, observations were terminated in September, 1980, until a repair mission was accomplished by the Challenger Space Shuttle crew in April, 1984. Coronal observations resumed in June, 1984, and continued (with a few interruptions) until mid-November, 1989, when the SMM satellite began its fiery re-entry into the Earth's atmosphere. Approximately 240,000 images were taken by the C/P instrument using a Westinghouse SEC vidicon detector ($\sim$ 6 arcsec resolution).

An image was produced by reading (i.e., scanning) the vidicon with an electron beam and digitizing each sampled signal level to a value in the range of 0 to 255. The vidicon was scanned left to right, and top to bottom. The acquired images (maximum size: 896$\times$896 pixels) were temporarily stored on a digital tape recorder located on-board the SMM spacecraft.

Several times each day, these images were then transmitted to either ground tracking stations or the Tracking Data Relay Satellite (TDRS), which relayed the data to a receiving station at White Sands, N.M. Image data was subsequently transmitted to Goddard Space Flight Center, where it was formatted by computers and stored on 1/2" digital magnetic tape.

C/P instrument description

A description of the SMM C/P instrument will be presented here in order that the reader may more easily understand the terms and details mentioned elsewhere in this report.

The C/P instrument is an externally-occulted coronagraph telescope. An occulting disk assembly (consisting of 3 disks supported by a pylon) shields the primary optics and sensor (SEC vidicon) from the direct light of the solar photosphere (and also the lower corona) out to a distance of about 1.5 solar radii. The optical design provides a 360-degree view of the corona from $\approx$ 1.8 to 6.0 solar radii (R_{sun}), with the exception of the shadow cast by the pylon which supports the occulting disks. A graphical representation of the C/P instrument is presented in Figure 1-B, and the optical configuration is shown schematically in Figure 2-B.

In order to obtain the highest spatial resolution possible ($\approx$ 6 arcsec/pixel), an 8-position nutating "sector" mirror is used to reflect approximately a 90-degree view (i.e., quadrant) of the corona onto the vidicon detector. Each position of the sector mirror is designated by that portion of the corona (N, NE, E, SE, S, SW, W, NW) which is seen when the SMM spacecraft is oriented at its nominal (0 degree) roll position. Figure 3-B shows the approximate location of the occulting disk shadow in each of the 8 sector views of the corona.

The C/P instrument also includes a green-line filter (5300-5306 Å), a spectral filter wheel, and a polaroid filter wheel. The green-line filter was not used in observations acquired for this study. The spectral filter wheel consists of the following filters: wide-band: 4435-5075 Å, clear: (no filter) 4000-7000 Å, Hα: 6543-6583 Å, red: 5990-6464 Å, green: 5000-5350 Å, and blue: 4440-4775 Å. All images taken for this study employed the Hα filter, for reasons which are discussed in Appendix C. The polaroid wheel contains 4 filter positions: one clear quartz glass filter, and three identical HN38 polaroid filters, oriented at 60 degrees with respect to each other. The clear polaroid position was used for all of the observations of Jupiter in this study. A secondary optical path is provided for calibration purposes, with a tiltable mirror to select either the coronal or calibration light to be imaged on the vidicon.

C/P Calibration Method

This section will describe the *method* used to calibrate images obtained by the SMM C/P instrument. A more detailed discussion of the C/P calibration method may be found in the De La Pena reference (1985).

The C/P telescope was designed with two optical paths, one for coronal images, and the other for calibration purposes. The calibration path allows light from the solar photosphere to be directed through a diffusion filter to a calibration reticle, which consists of an MTF (Modulation Transfer Function) pattern and a 3-step neutral density filter (where the transmission is given by 10^{-n} for n=0, 1.15, and 2.3). A nutating (i.e., rotating) sector mirror is used to select either a 90-degree quadrant of the corona, or a region of the calibration reticle, to be imaged onto the SEC vidicon, depending upon the position of the calibration mirror.

With the calibration mirror commanded to the *in* position, the *south* sector mirror position is used to select a view which is wholely contained within the 1.15 neutral density (ND) filter, thereby providing a uniform source of illumination to the vidicon detector. Approximately once each month, a series of images of varying exposure durations was acquired. Using such a sequence of observations, a set of *transfer* curves (one for each pixel location) is derived by fitting a mathematical function to the data (vidicon response versus exposure duration). Once a set of transfer curves is obtained (as represented by the coefficients of the the function), the *characteristic* response of the vidicon for varying amounts of exposure is determined.

The word *characteristic* is emphasized here since it is recognized that, in actuality, the transfer curves represent the behavior of the vidicon only for the circumstances which existed when the calibration images were taken. The vidicon response for coronal images may vary somewhat from that indicated by the transfer curves, due to fitting errors, anomalous environmental conditions, and other unpredictable effects.

A tangent function was initially used as the fitting function, but after noticing that there were some difficulties in matching a tangent curve to the data points, especially for short exposure durations, a 3rd-order polynomial equation was used instead.

For a coronal image, the exposure duration and the vidicon response (DN level) are both known, but the intensity of illumination at each pixel is not. By using the fitting function with the appropriate coefficients (obtained from the transfer curve fit), an *equivalent exposure time* may be computed. This value indicates the exposure duration that would be required to achieve the same vidicon response using the uniform light provided by the calibration optical path (using the ND 1.5 filter). Since the illumination through the calibration path is known and unvarying (i.e., the visible light from the photosphere is essentially constant), the coronal brightness may be computed in units of B_{sun}, which is a ratio of the coronal brightness to the average brightness of the photosphere at disk center.

A sample transfer curve plot is shown in Figure 4-B. The transfer curve equation described above is simply:

$$T_i = A_0 + A_1 \cdot V_i + A_2 \cdot V_i^2 + A_3 \cdot V_i^3$$

where T_i is the equivalent exposure duration through the calibration optical path at pixel i; A_0, A_1, A_2, and A_3 are the coefficients of the 3rd-order polynomial fitting function; and V_i is the vidicon intensity value (range: 0-255) at pixel i.

The photometric calibration is then applied according to the equation:

$$B_i = (T_i/t) \cdot B_{cm}$$

where B_i is the brightness of pixel i (in B_{sun} units), t is the exposure duration of the coronal image, and B_{cm} is the known brightness (B_{sun} units) of the light reaching the vidicon through the calibration reticle ND 1.5 filter.

Following the photometric calibration, a geometric transformation is applied to coronal images to rectify the distortion introduced by the SEC vidicon. Figure 5-B shows the vidicon distortion in an image of a rectangular grid pattern taken prior to the SMM satellite launch. In Figure 6-B, the same image has been corrected for geometric distortion.

A similar comparison may be made with raw and calibrated coronal images. Figure 7-B depicts a raw coronal image containing a coronal mass ejection. Figure 8-B is the same image after it has been photometrically calibrated and geometric distortion of the vidicon has been corrected.

C/P Image Artifacts

Two major classes of phenomena are known which affect the quality of C/P images: (1) vidicon instabilities and (2) optical artifacts. Within each class, several different phenomena will be described below.

<u>Vidicon Problems</u>

The response of the C/P SEC vidicon to light is affected by the amount of residual signal (i.e., electrical charge) remaining from any previous images which have been captured. During 1980, three flood/erase sequences were typically performed prior to the acquisition of each coronal (or calibration) image. The "flood" operation was executed by illuminating the vidicon with a bright internal light source so that all regions of the vidicon would be elevated to a saturated level. The "erase" operation was performed by reading out the entire vidicon, which supposedly drained the cathode of all of its electrical charge. By repeating this flood/erase cycle several times, the vidicon target would eventually be restored to a nominal (unbiased) state.

After carefully examining the images gathered during the 1980 era, it was noticed that *ghost* (or latent) *images* of bright objects were often visible in one or more later frames. In general, regions which were unusually dark in a reference frame were brighter in the next few frames, and areas which were unusually bright in the reference image were somewhat dimmer in the next few frames. In an effort to eliminate ghost images, the number of flood/erase sequences between images was increased from 3 to 6 beginning with the resumption of observations in 1984, and no obvious residual images were noticed after this procedural change was implemented.

A less well-understood phenomenon is the apparent variability in the response of the vidicon. It is estimated that as much as a 10% variation may occur in the overall response level of the vidicon from one image to the next. No operational pattern or environmental source has been identified which correlates with this variability. However, there is some indication that the overall image brightness may decrease as the beam blemishes (described below) become more pronounced (i.e., larger in size).

Digital images from the C/P vidicon were often partially corrupted by a problem which has been labeled *beam blemishes*. The visible effects are that in specific areas of the image, the pixel intensities are dramatically reduced (or darkened). The electron readout beam was placed in various positions in the active area of the vidicon tube during different phases of the vidicon operations cycle (idle, flood, erase, expose, read). Apparently, the electron readout beam was not always fully disabled during "rest" periods, and it therefore slowly diminished the charge on the tube wherever it happened to be positioned for relatively long periods of time (i.e., a few milliseconds or more).

A dark vertical line (with two bright lines on either side) often appears in the middle of the image, effectively dividing it in half. This is the position where the electron beam was kept while it waited for the readout buffer to be written to the on-board spacecraft tape recorder. In addition, two dark, disk-shaped areas appear in most C/P images: one is at the center of the image, and the other is located approximately in the middle of the lower-left quadrant of the vidicon. These were also "rest" positions during other phases of the vidicon activity cycle. Finally, there are also two dark lines (more or less diagonal): one connects the two dark disk regions, and the other connects the central dark disk with the upper left corner of the vidicon.

Some or all of these beam blemishes are visible in a majority of the C/P images, although the frequency of occurrence is much less during 1980, and the width of the vertical line is much worse during the period 1987 through 1989 (when the C/P was forced to use tape recorder A, which operated at a much slower rate than tape recorder C). A sketch showing all of the vidicon beam blemishes is presented in Figure 9-B.

A set of *reseau dots* (or registration marks) were painted onto the faceplate of the vidicon. These appear as very small, dark dots in a regularly-spaced, grid-like pattern (5 rows, with each containing 5 dots, except the top row, which only has 4 dots). When viewed in detail, these dots typically darken 1-4 clustered pixels. The approximate locations of these reseau dots are shown in Figure 10-B.

Two additional dark artifacts appear in C/P images. In 1980, near the center of the image, a thin, curved line appears. It has the appearance of a small hair. This artifact is gone after 1980, but another twisted, fiber-like obstruction becomes visible in the upper right quadrant of the vidicon in on 30 July 1986. These two artifacts are also shown in Figure 10-B.

There are also several *bright points* which appear in nearly constant positions in the C/P images. These are small pinholes in the vidicon target. There are 6 such bright spots which appear in all C/P images, with two or three more bright dots visible on images during the years 1984 through 1989. Another small blemish located near the left edge (about 2/3 of the distance up from the bottom) becomes visible sometime during the 1980 observations. It is dark, about 15×15 pixels in size, and it has a white halo on the right side. This may be a piece of debris which became lodged in the vidicon target. The pinhole locations are depicted in Figure 11-B.

Another disruptive phenomenon which affects the quality of the C/P vidicon images is known as *streaking*, which appears as adjacent horizontal line pairs of varying length, one of which is somewhat brighter than normal, and the other is somewhat dimmer than normal.

A C/P image consists of a series of rows (or scans), each of which is created by destructively sampling (i.e., the read operation discharges the vidicon signal at the sample location) the vidicon at regularly-spaced intervals of time as an electron beam is moved horizontally from left to right. The first row is scanned at the top of the vidicon, the second is acquired just below the first, and so on, until the last row is scanned at the bottom. It seems likely that this streaked pattern may be caused by the readout beam erratically shifting (vertically) back and forth from its proper position as the target image is being scanned and digitized. This streaking effect sometimes affected the entire area of the vidicon, and at other times, it only corrupted selected portions of an image. The severity (the amount of abnormal brightening/darkening) of the streaking was also variable. An example of streaking may be seen in Figure 12-B.

A final source of vidicon disturbance is high frequency electronic noise, and it was manifested as a series of vertical "lines". A close examination of C/P images reveals this to be a modulation pattern of alternating enhanced and diminished responses to light, which gives the impression of fine vertical bars appearing throughout the image. The general pattern and magnitude of this effect remains approximately constant throughout the SMM mission. A magnified view of a C/P image which reveals this high frequency pattern is shown in Figure 13-B.

Optical Effects

Two optical effects also degrade coronal images taken by the SMM C/P instrument : stray light, and vignetting.

Stray light appears in coronal images due to diffuse light scattered inside the C/P telescope. When the C/P instrument is properly pointed directly at the center of the sun, the stray light level is quite high near the occulting disk, but it drops dramatically with increasing radius, and it is approximately $3 \times 10^{-10} B_{sun}$ beyond $2.5 R_{sun}$.

Since the SMM spacecraft was often pointed somewhat off-center from the solar disk, the C/P instrument used an independent pointing control system (consisting of 4 light sensors and a dual-axis motor drive) in order to keep the C/P telescope pointed at sun center. Unfortunately, the C/P pointing control motors were damaged in 1980 when they were inadvertently driven against their mechanical stops due to a spacecraft clock malfunction. Thereafter, the pointing motors did not always function smoothly, and therefore, the coronagraph's pointing precision was degraded (i.e., less reliable).

The stray light of the C/P instrument has been determined only as a function of radius. This was done by measuring reflected light from the moon as it passed through the C/P field of view during an annular solar eclipse (10 August 1980). It is assumed that the stray light pattern is essentially uniform azimuthally, unless the C/P telescope is not properly pointed at sun center. Fortunately, the C/P telescope was off-pointed slightly away from the sun for the observations of Jupiter which were used for this study. Therefore, any stray light variability should be negligible.

The stray light pattern is predominately amorphous and has the appearance of a dramatic radial brightening as one approaches the occulting disk below about 2.5 R_{sun}. However, a somewhat subtle component of stray light is visible as an annulus (i.e., ring-shaped) region called the Lyot ring, which appears from about 3.5 to 4.5 solar radii. In this region, the light level is elevated by approximately $1 \times 10^{-10} B_{sun}$. Figure 14-B shows the inner and outer edge positions of the Lyot ring for a north sector coronal image. Its intensity profile is visible in the stray light plot (Figure 15-B). Somewhat by coincidence, all of the Jupiter observations used in this study were taken from images in which Jupiter appeared in the Lyot annulus. Although there is clearly some variation in light level (as a function of radius) within the Lyot ring, this effect should be relatively small, and it has therefore been ignored.

Since the source of stray light is ordinarily the sun, it was clearly inappropriate to apply the measured C/P stray light to the Jupiter observations used in this report, since the telescope was not pointed at the sun.

Vignetting is an optical effect caused by light passing near an obstruction, such as the edge of each of the three C/P occulting disks. The visual manifestation is a series of alternating bright and dark concentric rings whose modulation and radial thickness diminish rapidly with increasing radius. In addition, there is a radially-dependent attenuation of light which increases toward the occulting disk edge. A plot of this attenuation is shown in Figure 16-B. Unless noted otherwise, all brightness measurements in this study which use C/P images have been corrected to eliminate the effect of vignetting.

Pre-Launch Calibration Tests

The amount of light reaching the vidicon through the calibration path was measured during sun tests using the C/P instrument at Ball Aerospace (BASD) in a clean room during the period 13 April through 10 May, 1978. Results of these measurements are reported in HAO/SMM memos written by William Wagner (5 June 78, 21 July 78, 5 December 80, 20 Sep 82). Sunlight was directed through the calibration path of the C/P telescope, and images were captured on film in a camera located at the vidicon position. The density of the film was measured using a densitometer, and the measurements were compared with film exposed to sunlight using calibrated HAO opals. By comparing the two measurements, a transmission factor (units of B_{sun}) was obtained for each optical configuration (green-line/spectral filter, polaroid filter) of the C/P instrument. Since only the H_α filter was used for observations of Jupiter, the relevant transmission factor is the one for H_α ($4.63 \times 10^{-9} B_{sun}$).

Appendix C : C/P Jupiter Observations and Measurements

Jupiter Observations and Their Analysis

During the period 7-11 June 1989, the SMM C/P instrument was configured to acquire short duration (6.144 second) exposures of Jupiter using the Hα narrow band filter (6563 $\pm$ 20 $\AA$). Three different sector mirror positions (N, E, W) were used, with various roll orientations of the SMM spacecraft, in order to place the image of Jupiter in regions of the C/P vidicon which were unaffected by various electronic "artifacts" (or blemishes) which typically corrupt specific areas on the vidicon.

The shortest exposure duration allowed for the C/P instrument is 1.024 seconds. Since Jupiter is significantly brighter than typical coronal features (observed between 1.5 and 6.0 R_{sun}), it was necessary to use a filter with a narrower bandwidth than the green broad-band filter (5350 - 5000 = 350 $\AA$), which was ordinarily used for coronal observations.

In order to achieve an exposure for Jupiter which was approximately in the middle of the C/P vidicon dynamic range (0 - 255), a combination of the Hα filter and an exposure duration of 6.144 (= 6 $\times$ 1.024) seconds was chosen. Due to the effects of vignetting and the non-uniform response of the vidicon, the actual maximum intensity level did, of course, vary considerably from this predicted level, especially for the north sector images, in which Jupiter appears near the top of the vidicon. The C/P vidicon is unusually sensitive in the region constituting the top 15-20% of the detector, and the brightest pixel's intensity for Jupiter ranges from 121 to 252 in the north sector images. In the east and west sector images, the brightest pixel's intensity ranges from about 140 to 210.

A total of 71 high-resolution (5.933 arcseconds/pixel) images were acquired by the SMM C/P instrument during the 1989 period surrounding the conjunction of Jupiter and the Sun. In order to avoid images in which the signal-to-noise was too low, we restricted our samples to cases in which Jupiter's position was within the range of 3.0 to 4.5 R_{sun}. This left us with 33 images to examine.

SMM C/P images are currently available in what is called *raw* image format. Such data consists of a computer file containing the following information: (1) housekeeping data: instrument configuration, voltages, and temperatures, (2) bit map: data specifying whether a segment of image data (112 pixels) is real data or zero-filled (due to loss during transmission), and (3) 2-dimensional array (896$\times$896 for a full-size, high resolution image) representing the image digitized from the vidicon. Pixel values range from 0 to 255.

Following the loss of the coronagraph's dedicated on-board tape recorder (C) (7 December 1986), C/P images had to be recorded onto the remaining operational tape recorder (A) in the telemetry space originally assigned to the HXIS (Hard X-ray Imaging Spectrometer) instrument, which was no longer functioning. Since tape recorder A operated at a much slower rate than C/P's dedicated tape recorder, only full-size low resolution images could be written to to tape recorder A in a reasonable time (6.5 minutes). In order to acquire high resolution images of Jupiter during the 7-11 June 1989 period, it was therefore necessary to save only one quarter of the vidicon's pixels. This approach was entirely satisfactory, since an image of Jupiter occupies only an area about 5x5 pixels in size on the C/P vidicon, and one quarter of the vidicon is represented by 448x448 high resolution pixels.

From a raw C/P image, a calibration program (calcp) may be executed to transform it into a *calibrated* image. This process basically performs two functions: (1) photometric transformation from vidicon intensities (called DN, for vidicon Digital Number) to a scientific unit B_{sun}, which is a ratio of the brightness of the object (usually the corona) to the brightness of the solar disk (i.e., photosphere), and (2) geometric distortion correction.

The purpose of this study is to compare the *calibrated* C/P measurements of Jupiter with independent observations of Jupiter, and thereby obtain a multiplicative correction factor to adjust the calibrated C/P intensities so that they agree with a known reference: the brightness of Jupiter.

For each image, in both raw and calibrated forms, we accumulated the following information: (1) brightest pixel location (radius, x/y position), (2) brightest pixel intensity, (3) integrated brightness of a square region centered about Jupiter, and (4) integrated brightness of a "background" region surrounding Jupiter.

The term *brightest pixel* is self-explanatory: it is the brightest pixel observed from the image region representing Jupiter.

The term *integrated brightness of Jupiter* refers to a summation of pixels whose intensity exceeded a specified threshold within a 22×22-pixel box centered about the brightest pixel. The threshold we used is equal to 5 times the average "background" level found in a perimeter region surrounding the 22×22-pixel box containing Jupiter.

The integrated brightness of the background region represents a summation of the pixel brightness values in a "perimeter" region (8 pixels wide) surrounding the 22×22-pixel box centered about Jupiter's brightest pixel, which we shall call the "inner" box. The *average background brightness* was computed by separately integrating both the inner box and an outer box (a 30×30-pixel box region also centered about Jupiter's brightest pixel), then subtracting the sum of the inner box from that of the outer box, and dividing by the number of pixels in the perimeter region ($= 30 \times 30 - 22 \times 22 = 416$).

The *threshold* level (5× average background brightness) was chosen to provide a criterion by which we could separate the pixels representing Jupiter from those which do not. This seemed to be a reasonable choice, since the brightest pixel of Jupiter is typically about 10 times as bright as the average background level.

The results of these measurements are listed in Tables 1-C through 3-C and depicted in Figures 1-C through 14-C.

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