COR-1B Vacuum Calibration, November 2004

William Thompson

November 18, 2004

We report here on the calibration and scattered light measurements of COR-1B, made in the NRL A13 vacuum tunnel, November 2004, prior to the formal delivery of the instrument to NRL. The primary purpose of this calibration activity was to test the scattered light properties, but it was also the first chance to test the instrument in vacuum, and with a cooled CCD. Using various configurations of the vacuum tank, the properties tested were scattered light, photometric calibration, resolution, and polarization.

The initial tests of the COR-1B objective showed a significant amount of scattered light, and it was determined that the objective had a small area of contamination on it. The objective was switched out, and this report is on the results with the replacement objective.

1 Noise

Liquid nitrogen was used to cool the CCD detector down to temperatures close to that which it will see in flight. An LN_2 dewer inside the vacuum chamber was thermally coupled to the radiator mass mockup attached to the FPA. Temperature could be controlled either through heaters at the dewer end of the copper strap, or on the CCD itself. We were able to cool the CCD down below -65 C, but never managed to get down all the way to the -75 C expected in flight.

The effect of cooling the CCD is demonstrated in Figure 1. On the left is a dark image made when the CCD was close to room temperature, at about +20 C, while the image on the right was taken when the CCD was close to operating temperature, at about -60 C. The images are not on the same scale—if they were, the cold case would appear completely black. The exposure time was 10 seconds for both images.

By taking a series of exposure times at various CCD temperatures, one can separate out the dark current effects from readout noise. Figure 2 shows the average dark current in the CCD as a function of temperature. The same data for COR-1A is overplotted in red. COR-1B shows about half the dark current of COR-1A at all temperatures.

There is a slight difference in thermal noise between images which use the shutter and those which don't. The reason has to do with overhead in the ITOS software associated with sending the commands for operating the shutter. The difference is approximately 0.05–0.20 seconds, which is much shorter than the 0.75 seconds seen for COR-1A. (However, that high value for COR-1A may have been anomalous—a re-examination of the data shows differences similar to those for COR-1B.) Running the detector cold reduces the effect of this difference—it's practically non-existent at -60 C.

As well as thermal noise, the instrument is also subject to readout and pickup noise. Because the cabling between the FPA and the CEB was considerably longer than flight, there's more pickup noise than would be expected in flight, with an RMS of $\sim$7 DN.

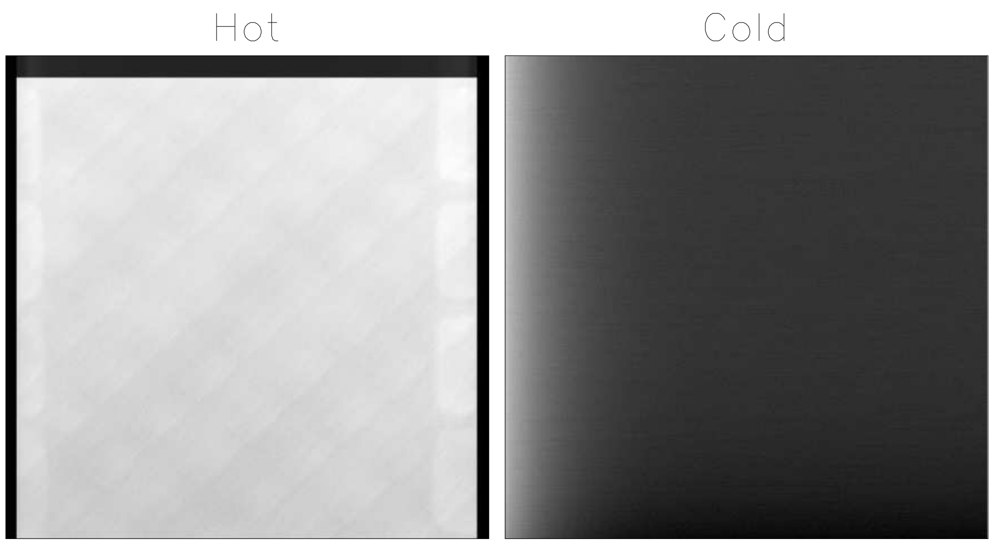

Figure 1: Dark images for “hot” (+20 C) and “cold” (-60 C) cases. Images are not on the same intensity scale.

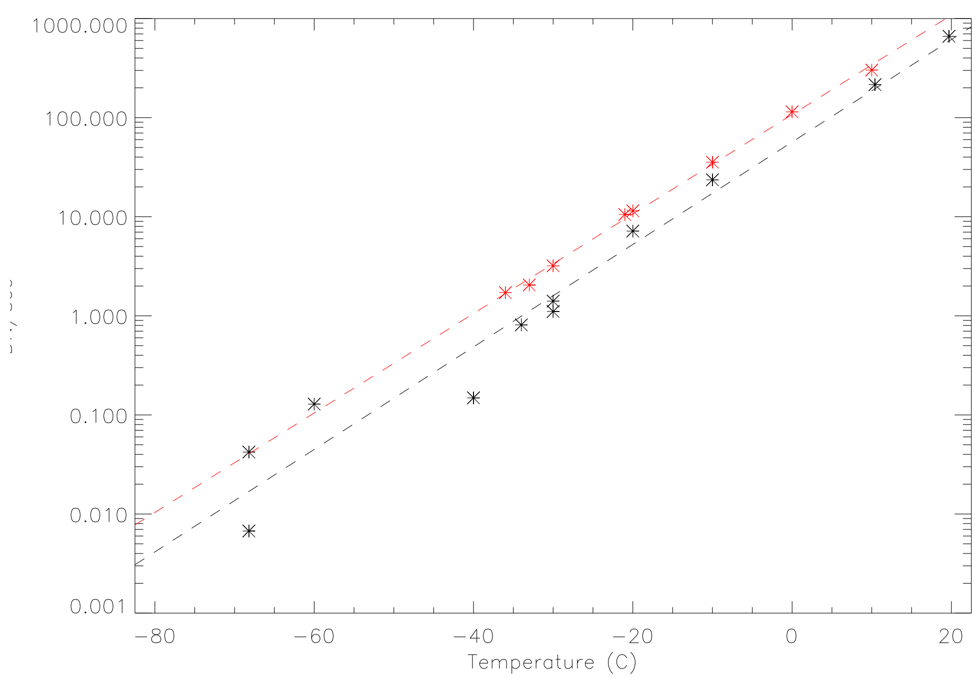

Figure 2: Average detector dark current as a function of CCD temperature. The red points are the same data for COR-1A.

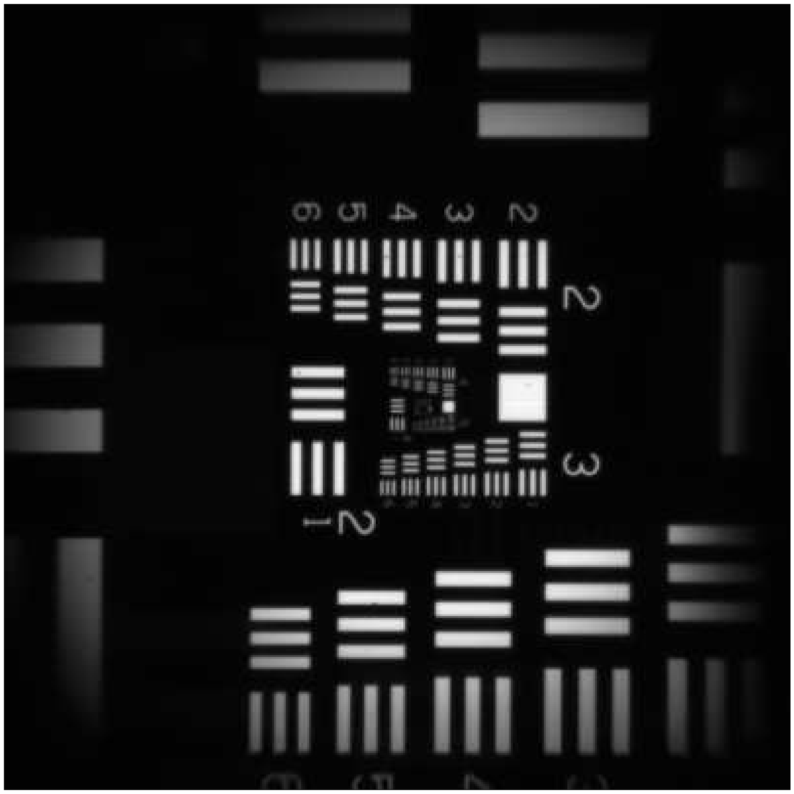

Figure 3: Sample Air Force target image in vacuum.

2 Resolution

When the instrument resolution was tested with the Meade telescope system, an offset was applied to account for the difference between vacuum and the nitrogen purge at one atmosphere of pressure. The vacuum testing at NRL afforded an opportunity to test the on-orbit resolution without any need for corrections. Also, it was the first opportunity to verify that the resolution was still maintained with the replaced objective. The collimator at the end of the tank was focused (during the COR-1A testing) to project an image of an Air Force 1951 resolution test target at infinity. The COR-1B instrument was then steered to place this image at various locations on the detector. A sample image is shown in Figure 3. A detailed examination of the images shows that the resolution extends down to the full-resolution Nyquist frequency (one line pair per 27 μm). These images were taken at a temperature of approximately -68 C.

When the resolution was tested during final assembly, the contrast was measured for group 4-1, whose bars were 1.5 full-resolution pixels wide. (When 2×2 binning is used, this would actually be above the Nyquist frequency.) Because the collimator used for the vacuum calibration has a slightly different magnification factor, the equivalent for this data set would be group 3-6. The measured contrast values are shown in Table 1.

These are the highest contrast values ever measured on either of the COR-1 instruments.

Table 1: Horizontal and vertical contrast values for bars 1.5 pixels wide, at various locations around the detector. The approximate pixel position for each group is also given.

Pixel Position	0°		120°		240°	
	H	V	H	V	H	V
(1000,1805)	0.540	0.504	0.556	0.608	0.539	0.544
(700,1415)	0.528	0.591	0.545	0.571	0.541	0.589
(485,715)	0.537	0.557	0.539	0.586	0.544	0.581
(460,985)	0.551	0.540	0.521	0.583	0.560	0.574

3 Photometric calibration

The COR-1B photometric calibration was not performed as intended. A color correction filter, used to change the color temperature of the lamp to match that of the Sun, was not placed in the beam. Also, the lamp brightness was mistakenly measured at the input to the double-opal diffuser, rather than the output. Fortunately, the lamp configuration was not changed, so the lamp brightness could be recalibrated, and a correction factor with and without the color filter could be established.

The first step in recovering the calibration was to establish the brightness difference of the lamp with and without the color correction filter, within the COR-1 bandpass. This was done in two ways. First, during the partial polarization test, the COR-1B instrument itself was exposed to both kinds of light. The images without the color filter in place were 10.09 ± 0.14 times brighter than those using the color filter. Next, after the double-opal diffuser was reinstalled in the chamber, its output was measured with a Gamma Scientific photometer, with bandpass filter #9 attached to the front, set to λ-mode at 656 nm. These measurements differed by a factor of 11.07, which is in good agreement with the previous value. Since there are slight variations between bandpass filters, we'll use the 10.09 value determined with the instrument itself.

The measurements of the lamp brightness going into the double opal source were 1.9×10^2 and 2.3×10^2 foot-lamberts, before and after the vacuum calibration respectively. By contrast, when we attempted to replicate this measurement after the double-opal diffuser was installed, we measured 1.72×10^1 foot-lamberts. It's believed that the exponents in the earlier measurements were recorded too high by one (see Section 4), which would make the measurements roughly compatible. Given the difficulty of making this measurement, since the light going into the double-opal source is not uniform, these three values are considered to be equivalent.

The correctly performed calibration of the output from the double-opal diffuser gives a brightness of 5.3×10^{-2} foot-lamberts. Using the scaling factor of 0.563 foot-lamberts being equal to $10^{-9} B/B_\odot$, we can calculate that the calibration source is equal to 9.41×10^{-11} $B/B_\odot$. An 18% correction for in-band light (determined during the COR-1A calibration) raises this number to 1.11×10^{-10} $B/B_\odot$. Applying the 10.09 correction value established above for not using the color filter raises this again to 1.12×10^{-9} $B/B_\odot$.

The average signal was measured to be 515 DN at an exposure time of 50 seconds. Thus, a data rate of 1 DN/sec is equivalent to 1.09×10^{-10} $B/B_\odot$. Note that these numbers are based on the average signal at the detector. Because the internal polarizer only allows one state of polarization through, and thus cuts unpolarized light in half, the calibration parameter to be applied to B or pB values derived by rotating the polarizer is 5.44×10^{-11}.

These results are consistent with those for COR-1A within 10%. Note that the measurements made during the scattered light testing below would imply that the 18% in-band correction used above would be somewhat smaller. However, if true, it would also be true for COR-1A, and the resulting calibrations would still be consistent within 10%.

4 Scattered light

To test scattered light, a very bright xenon arc lamp is sent down the tunnel. An aperture at the window where the light enters the tunnel defines the source size. The distance between this aperture and the COR-1B objective was 11 meters. The aperture size depends on the amount of defocus of this finite source at the occulter, combined with the chromatic aberration of the objective lens. Taking these considerations into account, the final aperture was sized at 68.0 mm. With this aperture, the solar brightness was measured to be 2.1 W/m^2 after the chamber was re-opened. This measurement was made with bandpass filter #9 and the Gamma Scientific photometer in λ-mode at 656 nm. Given the measured characteristics of this filter, a solar brightness would be measured at 32.9592 W/m^2. Thus, we were exposing the instrument to $1/15.7^{th}$ of a solar brightness.

When the NRL white-light photometer was used to measure the same xenon source, combined with a 45° Macbeth Plaque, the result was 7.45×10^3 foot-lamberts. In this configuration, 160 foot-lamberts is equivalent to 0.013 $B/B_\odot$. Thus, the brightness should be $1/1.65^{th}$ of a solar brightness. This is highly unlikely, and is suspiciously close to being exactly a factor of 10 different from the Gamma Scientific measurement. It's believed that the exponent for the white-light photometer was recorded too high by one, so that this should instead be 7.45×10^2 foot-lamberts, and thus $1/16.5^{th}$ of a solar brightness (see also Section 3). We'll use the Gamma Scientific measurement, as it specifically addresses the COR-1 bandpass.

Figure 4 shows the measured scattered light, multiplied by 15.7 to take the brightness of the lamp into account, and calibrated using the results from Section 3. The brightest spot in this image is 1.4×10^{-6} $B/B_\odot$. (The requirement for small features such as this is that they be below 3×10^{-6} $B/B_\odot$.) Based on their brightness and size, it is believed that the small arc-shaped features at various locations around the image are scattering sources on the front surface of the field lens. Figure 5 shows the average scatter as a function of radial distance from the center of the mask as determined in Section 5.

The data in Figure 4 were taken with an exposure time of 10 seconds. With a full solar flux, an exposure time of 0.6 seconds would give the same level of exposure. At the design goal of 1 second, the brightest point in the image would be at saturation, or just over. The general scattered light wouldn't start to saturate until at least 6 seconds.

The general level of scattered light does not appear to be polarized, although some of the bright points show a polarization signal. There's also a polarization signal related to the flat-field scattered light profile shown in Figure 6.

Note that the above measurements with the two photometers imply a different correction for in-band light of 5%. For consistency, we've used the same 18% correction used for COR-1A. The implications for using a different correction are discussed in the conclusions.

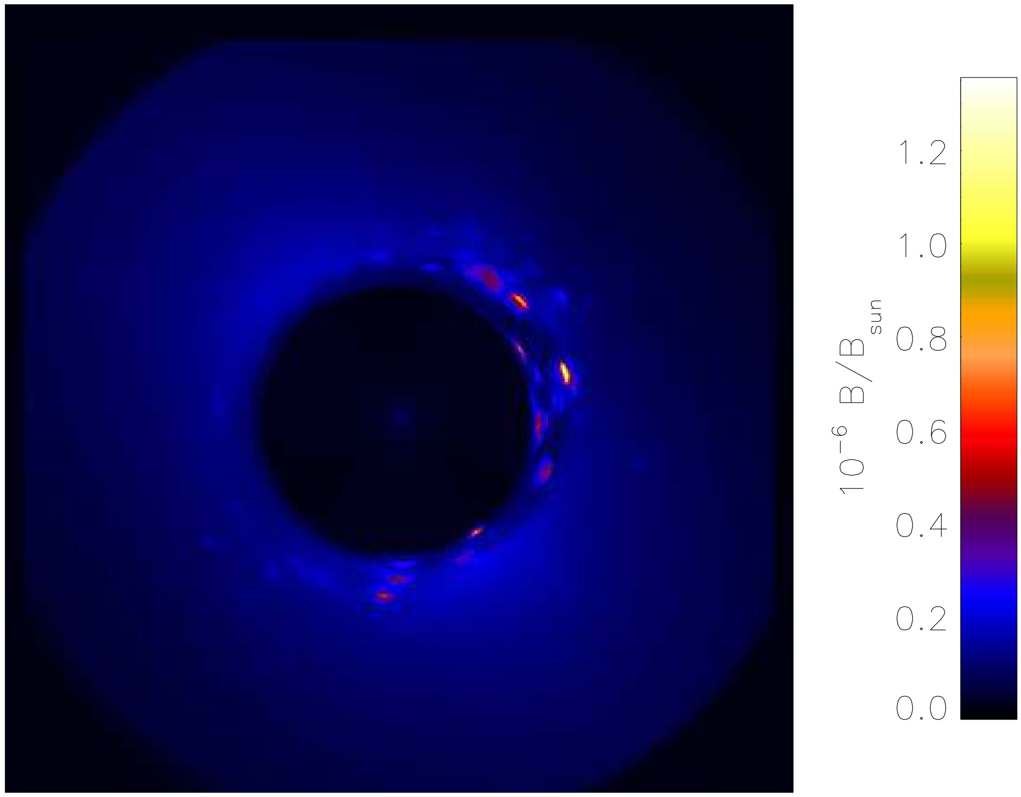

Figure 4: Scattered light image.

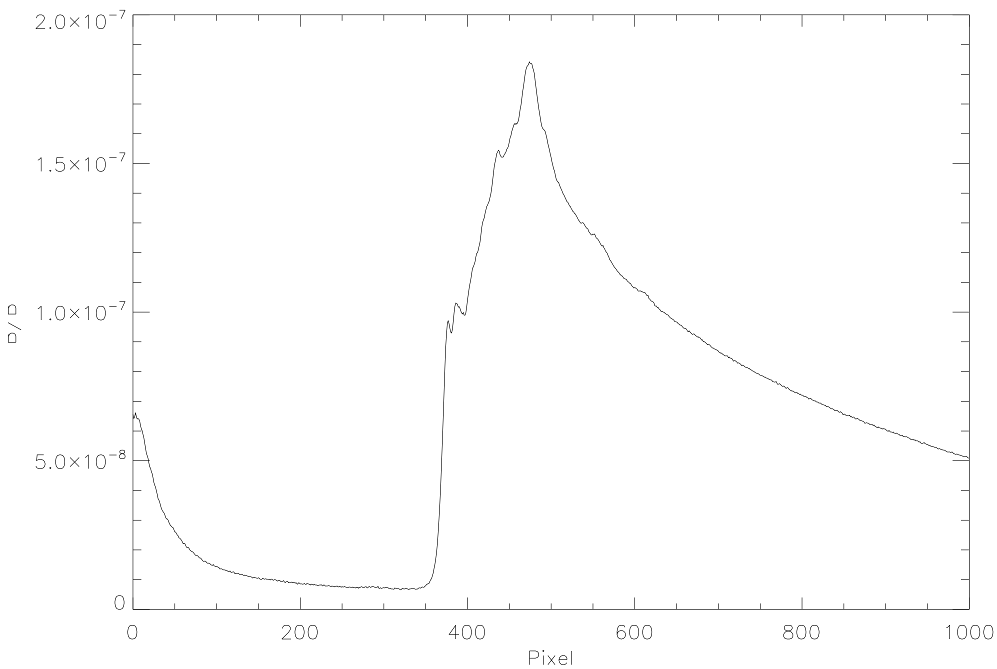

Figure 5: Average scattered light as a function of radial distance from the center of the focal plane mask.

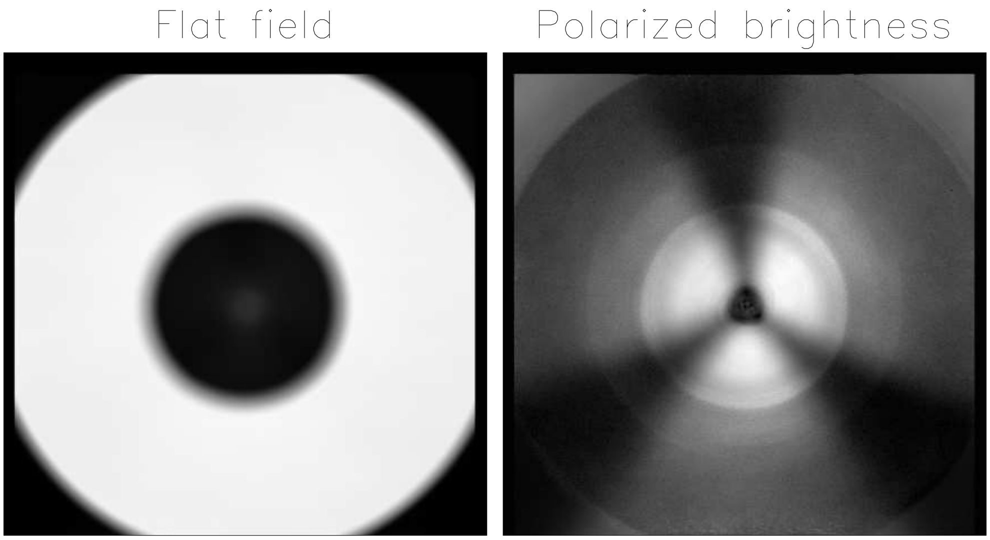

Figure 6: Flat field image, using the Xenon arc lamp shining on the calibration window in the COR-1B door. Also shown is a polarized brightness image of the scattered light associated with the flat field.

5 Flat field

When the Xenon source used for the scattered light test is used with the door closed, it simulates the Sun shining on the door during flight. The resulting flat-field image is shown in Figure 6. The response is highly flat. There's a slight ∼0.6% contamination from scattered light extending outward from a central point in the middle of the mask shadow. This scattered light component shows up in a polarized brightness map, and has three dark spokes separated by 120°, which is probably related to one of the lens mounts.

The image in Figure 6 was taken with an exposure time of 10 seconds. Given that the source was $1/15.7^{th}$ of a solar brightness, an exposure of 0.6 seconds on orbit would give a similar exposure level on the detector, which is well within the capabilities of the instrument.

The inner and outer edges of the mask shadow are at radial distances of 374.8 and 482.5 pixels respectively. The center of the mask pattern is at pixel $i = 1068.19$, $j = 1018.49$.

6 Polarization response

To test the polarization response, a filter wheel was used to place a selection of polarizers in front of the double-opal used for the photometric calibration. One polarizer was oriented at 0°, and the other was oriented at -45°. In both cases, the results are consistent with 100% polarization within the noise. The polarizer offsets were measured to be $-0\overset{\circ}{.}662 \pm 0\overset{\circ}{.}088$ and $1\overset{\circ}{.}831 \pm 0\overset{\circ}{.}086$

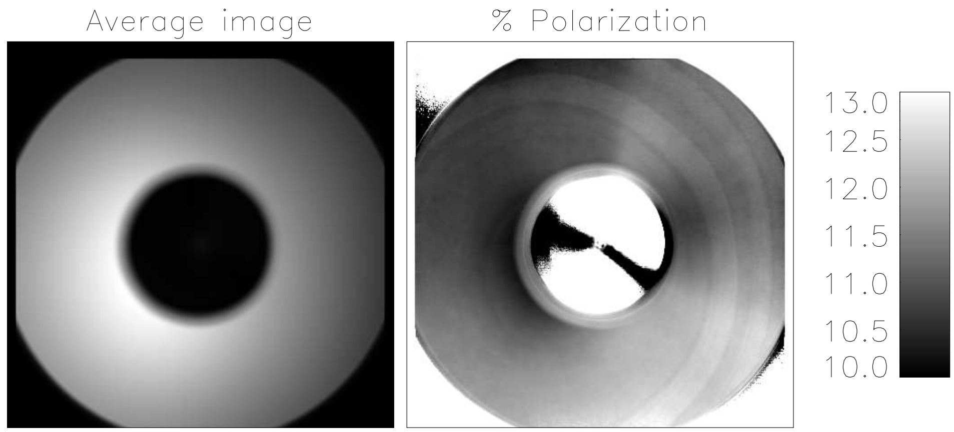

Figure 7: Variation of fractional polarization over the field of view. On the left is the average image—the B and pB images derived from these data are visually equivalent to this average image.

respectively. The small discrepency between these two numbers are probably due to alignment errors of the polarizers within the filter wheels. These results are consistent with the value of $0.^\circ79 \pm 1.^\circ01$ found during final assembly. Given the intrinsic uncertainties in these measurements, they're all consistent with zero.

An additional filter wheel position held a circular polarizer. Unfortunately, the quarter-wave plate portion of this circular polarizer was tuned to a shorter wavelength than the COR-1B bandpass, so it was not a valid test of the system. For what it's worth, when observed with COR-1B, the light was seen to be $\sim$14% partially polarized at a phase angle of about -40°.

6.1 Partial polarization

A diffuser and two plates of glass, held at opposing 45° angles to the optical axis, were used to create partially polarized light in front of the instrument. The measured signal was polarized by $11.37\% \pm 0.63\%$, at a phase angle of $0.^\circ93 \pm 1.^\circ94$. Figure 7 shows the variation in the fractional polarization over the field of view. It's not clear what causes the weak banding in the fractional polarization image. The banding follows the contours of the average image, and may be optical in nature, or caused by electronic effects within the detector. For example, it may be related to the non-linearity discussed in Section 7.

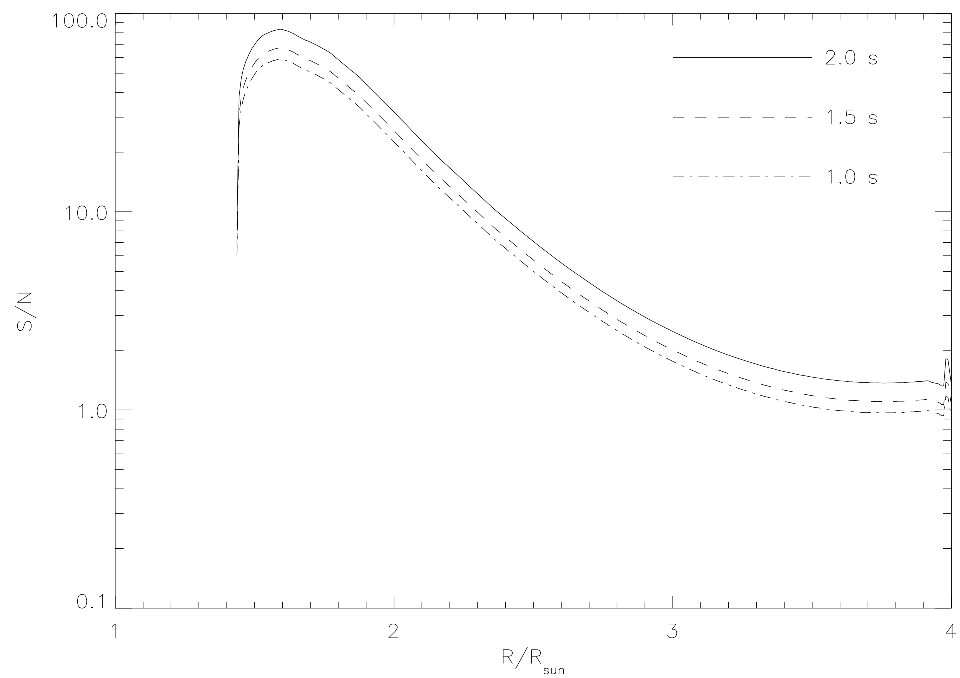

Figure 8: Average signal-to-noise ratio as a function of radial distance from the center of the focal plane mask for exposure times of 2 seconds (solid), 1.3 seconds (dashed), and 1 second (dash-dot).

6.2 Signal-to-noise ratio

To calculate the expected signal-to-noise ratio, the first step is to model the expected pB signal from the corona. This was modeled using the formula

$$\log_{10}(pB) = -2.66 - 3.55r + 0.460r^2 \tag{1}$$

where r is the distance in solar radians. The modeled k-corona polarized brightness thus ranges from $2 \times 10^{-7}\ B/B_\odot$ at the inner edge of the field of view to $3 \times 10^{-10}\ B/B_\odot$ at the outer edge. The flat field of Figure 6 is applied to this brightness distribution, which is then combined with the scattered light pattern of Figure 4. Assuming that the CCD is digitized at 15 e^-/DN, and that the pixels are binned 2×2, one can calculate the ratio between the signal and the Poisson noise. The average signal-to-noise ratio is shown in Figure 8 for an exposure time of 2 seconds, where some of the small bright features may saturate, at 1.3 seconds, where all but one of the features should be below saturation, and at 1 second, which is the design goal, and where the brightest point in the image should be just at saturation. The S/N peaks at around 55–85 near 1.6 $R/R_\odot$, depending on the exposure time, and drops to unity at around 4 $R/R_\odot$. There are small drops in S/N associated with the discrete scattered light features in Figure 4, on the order of 30–60%.

7 Exposure time test

The linearity of the instrumental exposure time had been tested during final assembly, but thermal effects caused it to saturate at the highest exposure times. Running the instrument cold allowed this

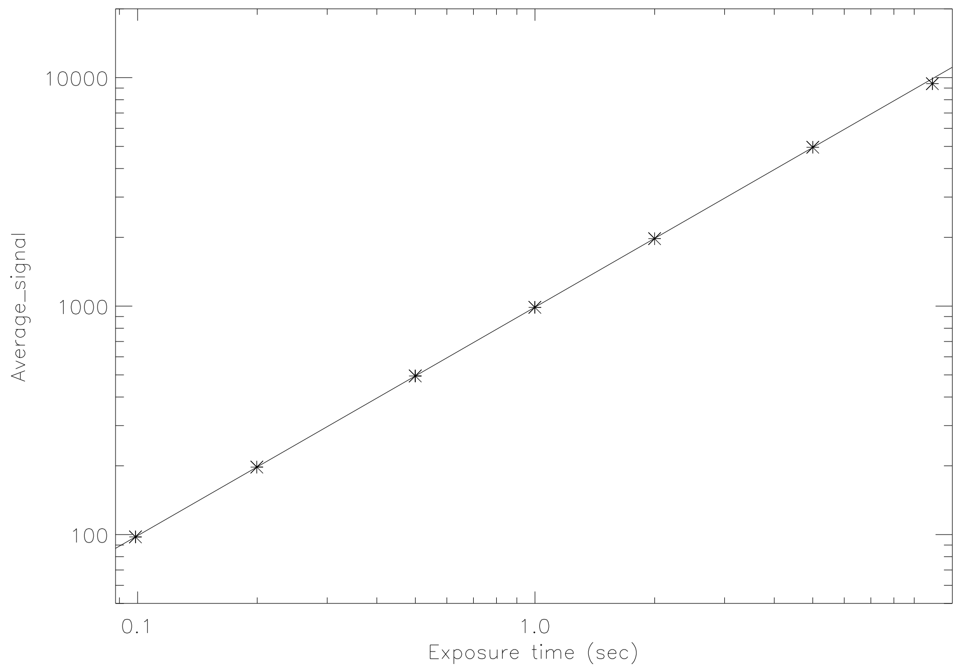

Figure 9: Comparison between measured signal and exposure time.

test to be carried out at greater accuracy. The result is shown in Figure 9. There is a discrepancy at the longest exposure time of 10 seconds, where the signal is 5% lower than would be expected based on the other exposure times. It turns out that this is a known non-linearity problem with the GSE electronics above ∼60% of full well, which is fixed in the flight electronics. The other exposure times are all consistent with each other.

8 Conclusions

The COR-1B instrument meets all of its performance goals for scattered light, resolution, sensitivity, and polarization response.

The overall level of scattered light is about half that of COR-1A. However, the small bright features associated with the field lens are brighter, by as much as 50%, and appear more numerous. One spot exceeds the $10^{-6}B/B_\odot$ scattered light requirement over an area of approximately 10×40 pixels, reaching $1.4 \times 10^{-6}\ B/B_\odot$. However, the requirement to be applied to this feature is the same as for the bright rings around the edge of the occulter, which is to be less than $10 \times 10^{-6}\ B/B_\odot$.

There's some question about what correction factor to apply to adjust for the COR-1 bandpass. During the COR-1A calibration, a factor of 18% was determined, and was also used in the present analysis. With that correction, the calibration to be applied to COR-1A and B would be 1.20×10^{-10} and 1.09×10^{-10} $B_\odot$/DN respectively. However, the same measurement made during the COR-1B calibration suggested a correction factor of only 5%. Averaging these two measurements together, for a correction of 11%, implies that the calibrations should be 1.13×10^{-10} and

1.03×10^{-10} $B_\odot$/DN for COR-1A and B respectively. (The calibration to be used when multiple polarizations are used to derive B and pB are half of the above values, to take the internal polarizer into account.)