1 COR-1

The SECCHI inner coronagraph is known as COR-1. COR-1 is a classic Lyot internally occulting refractive coronagraph (Lyot, 1939), adapted for the first time to be used in space. The field of view is from 1.4 to 4 solar radii. A linear polarizer is used to suppress scattered light, and to extract the polarized brightness signal from the solar corona.

1.1 Optical Layout

Figure 1 shows the optical layout of the COR1 instrument. Sunlight enters through the front aperture, where the objective lens focuses the solar image onto the occulter. To keep scattering to a minimum, a singlet lens is used for the objective, made of radiation hardened BK7-G18 glass. The primary photospheric light suppression mechanisms in COR-1 are the objective lens to occulter imaging system and the aperture stop to field lens to Lyot stop imaging system. Rather than relying on the out-of-band rejection of the filter, these primary suppression mechanisms are designed to work over the full sensitivity wavelength band of the instrument. The solar image from the objective will be chromatically aberrated, so the occulter must be sized to block all the solar photospheric light from the near UV to infrared (350–1100 nm). The cut-on at 350 nm is set by the transmission of the BK7-G18 glass in the objective lens, and the cut-off at 1100 nm is set by the band gap of the silicon detector. Subsequent lenses in the optical train balance the chromatic aberration from the objective. The narrow bandpass of the instrument also minimizes the effect of chromatic aberration in the final image.

The occulter is mounted on a stem mounted at the center of the field lens (Figure 2). The tip of the occulter is cone shaped, to direct the sunlight into a light trap which surrounds the occulter. The radius was chosen to block all wavelengths (350–1100 nm) out to a radius of $1.1R_\odot$ at orbital perigee. At the design wavelength of 656 nm, the solar image is completely occulted out to 1.30 $R_\odot$, and partially vignetted out to 1.64 $R_\odot$. (When combined with the focal plane mask discussed below, these numbers become 1.4 and 1.9 $R_\odot$ respectively.) The wedge-shaped design of the light trap ensures that any ray entering it must reflect many times, so that the light will be absorbed before it can find its way out again.

Diffracted light from the edge of the front aperture is focused onto a Lyot stop and removed. This eliminates the largest source of stray light in the system. Additional stray light rejection is accomplished by placing baffles at various points between the front aperture and Lyot stop. A Lyot spot is also glued to the front surface of the doublet lens immediately behind the Lyot stop, to remove ghosting from the objective lens.

Two doublet lenses are used to focus the coronal image onto the CCD detector. The first, a positive power achromat, is placed immediately behind the Lyot stop, while the second, a negative power acromat, is placed further down the optical path. Together, these act as a telephoto-lens system, focusing the coronal image onto the detector plane, while maintaining diffraction-limited resolution. A bandpass filter 22.5 nm wide, centered on the Hα line at 656 nm, is placed just behind the first doublet. Thus, the Lyot stop, spot, first doublet, and bandpass filter form a single optical assembly.

A linear polarizer on a hollow core motor rotational stage is located between the two doublets. The polarizing material is Corning's Polarcor, chosen for its uniformity. The placement of the polarizer was chosen to be as close to the first doublet as possible within the dimension constraints

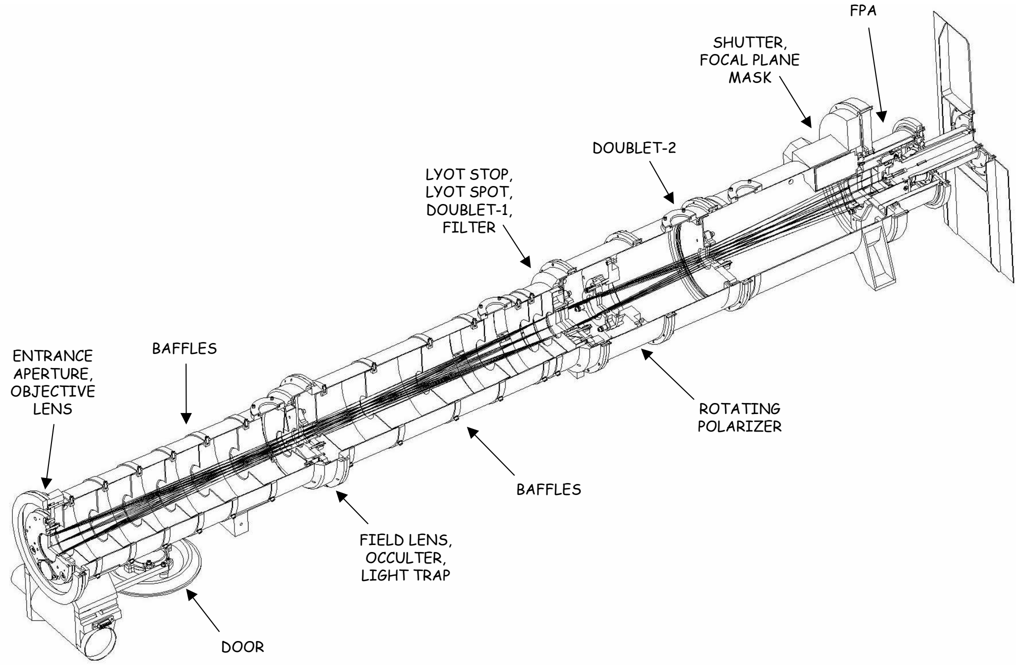

Figure 1: Layout of the COR1 instrument package.

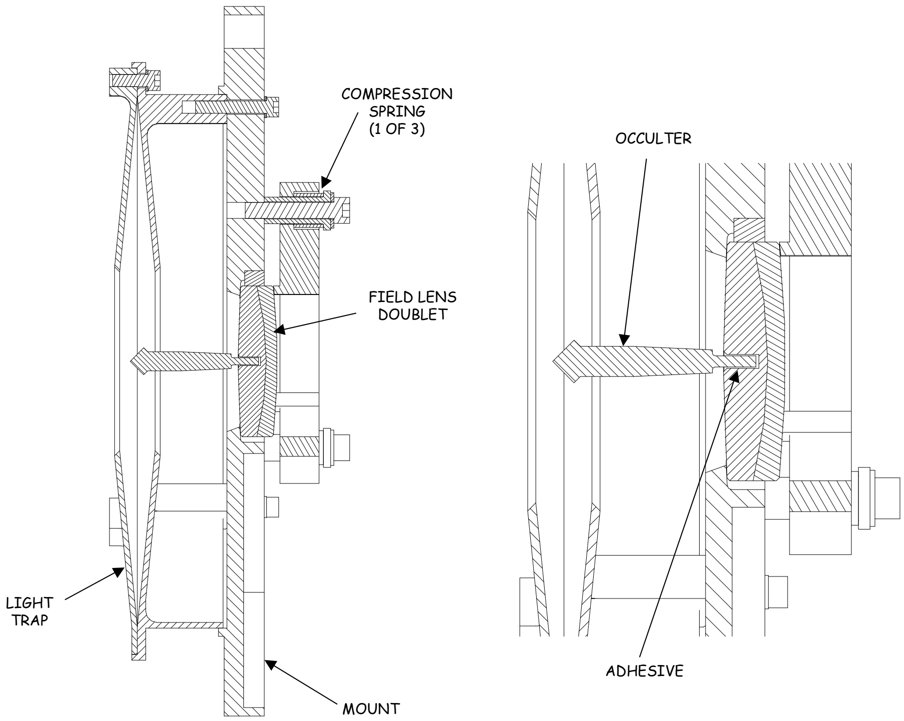

Figure 2: The conical occulter mounted at the center of the field lens, and surrounded by the light trap. Hashed regions show the presence of material at the central plane in this cutaway view.

of the largest diameter piece of Polarcor that can be obtained (33 mm clear aperture). Normal operations call for three sequential images to be taken with polarizations of 0° and ±60°, to extract the polarized brightness.

A focal plane mask is located between the shutter and the focal plane detector, and is used to remove diffracted light from the edge of the occulter. This circular mask, mounted on a plane of BK7 glass, is sized to be slightly larger than the occulter image at that location. Without the mask, the image on the detector would be dominated by bright rings at the umbral and penumbral edges of the occulter shadow. The addition of the focal plane mask removes these bright rings.

The focal plane assembly is discussed in Section ...

1.2 Mechanical and thermal design

The COR1 mechanical structure is designed as a series of tube sections (Figure 1), which are bolted and pinned together for stability. The individual optics are aligned, mounted, and pinned within these tube sections. COR1 assembly starts from the front tube section, with the objective, occulter, light trap, and field lens, and then each subsequent section is added, together with its associated optical or mechanical components. Because the individual tube sections are pinned together, sections can be taken off and back on again without changing the optical alignment.

Three mechanisms are included in the COR1 instrument package. At the front of the instrument is a door, supplied by the Max-Planck-Institut für Aeronomie in Lindau, Germany, to protect the instrument before and during launch, and during spacecraft maneuvers. On the front of this door is a diffuser so that the operation of the instrument can be tested when the door is closed, and to provide a flat-field calibration signal. The diffuser is sized to completely illuminate the objective over all angles within the field-of-view.

The other two mechanisms are the hollow core motor to rotate the linear polarizer, and a rotating blade shutter mounted just in front of the focal plane detector assembly, both supplied by Lockheed Martin. All the mechanisms, together with the focal plane CCD detector, will be operated from a centralized control system for all the SECCHI instruments.

Because the two STEREO spacecraft are in elliptical orbits about the Sun, the COR1 instruments will experience considerable variation in solar load, from 1264–1769 and 1068–1482 W/m^2 for the Ahead and Behind spacecraft respectively. When these loads are combined with the modeled changes in the material thermal properties from beginning to end of life, and with the most extreme differences in the thermal loads from the surrounding structure, the worst-case temperature variation in the COR1 instrument is from 2.5 to 30 °C. There's also an axial gradient in temperature from the front to the back of the instrument, varying from 3 °C in the cold case, to 7 °C in the hot case. Strategically placed software controlled proportional heaters with programmable set points, are used to keep the instrument within the 0–40 °C operational temperature range. There are also survival heaters on mechanical thermostat control to keep the instrument within the -20 to +55 °C non-operational range.

Specialized composite coatings of oxides over silver are used to help manage the intense solar fluxes which COR1 will be experiencing. The oxide coatings are deposited onto many of the exposed surfaces around the aperture area, such as the objective lens holder assembly and door assemblies. This coating exhibits very low solar absorbtivities, is very stable, and has relatively high IR emissivity values depending on the thickness of the deposited oxide layers. Silver teflon is used for the front layer of the multilayer insulation.

The majority of the solar load collected by the front objective is concentrated on the occulter tip (Figure 2). In the worst-case analysis, the tip can reach a temperature of 125 °C. This tip is made of titanium, and is diamond turned to direct the sunlight into the light trap. It is coated with a Goddard composite silver coating for high reflectivity. The occulter shaft is coated with black nickel to radiate away the heat. A thin cross-section titanium shaft is used to thermally isolate the occulter from the field lens.

1.3 Performance testing

Before building the COR-1 flight units, an extensive test program was carried out on a series of breadboards and engineering test units, using the Vacuum Tunnel Facility at the National Center for Atmospheric Research in Boulder, Colorado (Thompson *et al.*, 2003). These tests were used to demonstrate the instrument concept, and to improve the design for flight. One result of this testing was the addition of a focal plane mask to remove diffracted light from the edge of the occulter.

Characterization of the COR-1 flight units was carried out in a similar vacuum tank facility at the Naval Research Laboratory in Washington, D.C. The instrument was installed in a large vacuum chamber within a class 10,000 cleanroom. A long vacuum tunnel extended out from one end of the vacuum chamber to a window, where an entrance aperture was mounted to simulate the size of the Sun at perigee. The total distance between the source aperture and the COR-1 front aperture was 11 meters. A partially collimated Xenon arc lamp was used to illuminate the source aperture, with the degree of collimation chosen to direct the light onto the COR-1 objective and heat shield. Different aperture sizes were used for the Ahead and Behind instruments, because of the different orbital perigees of the two spacecraft.

As well as stray light, this vacuum tunnel facility was also used to measure other performance characteristics, such as resolution, polarization, and photometric response. The photometric calibration of the instrument was measured by illuminating the aperture at the end of the tank with a diffuse unpolarized light source of known intensity. Placing a sheet polarizer in front of this source allowed us to test the polarization response. Focus was tested by projecting an Air Force 1951 resolution test target through a collimator onto the instrument. The instrumental flat field was tested using both the diffuser mounted in the door, and with an external double-opal source mounted in front of the instrument, with identical results.

The vignetting function and flat field response of the instrument is demonstrated in Figure 3. The field is unvignetted except for a small area around the edge of the occulter, and near the field stop in the corners of the image. (The dim spot in the center of the occulter shadow is caused by scattering within the instrument.) Only the Ahead data are shown—the Behind response is virtually identical.

Figure 4 shows the measured COR-1 scattered light performance for the Ahead and Behind instruments. The average radial profile is well below $10^{-6}B/B_\odot$ for both instruments. There are discrete ring-shaped areas of increased brightness, which can climb to as high as $1.4 \times 10^{-6}B/B_\odot$ for the Behind instrument. It has been determined that these are caused by features on the front surface of the field lens.

Some contamination was found on the COR-1 Behind objection after thermal vacuum testing of the STEREO spacecraft. The objective has been cleaned and re-installed, and may no longer

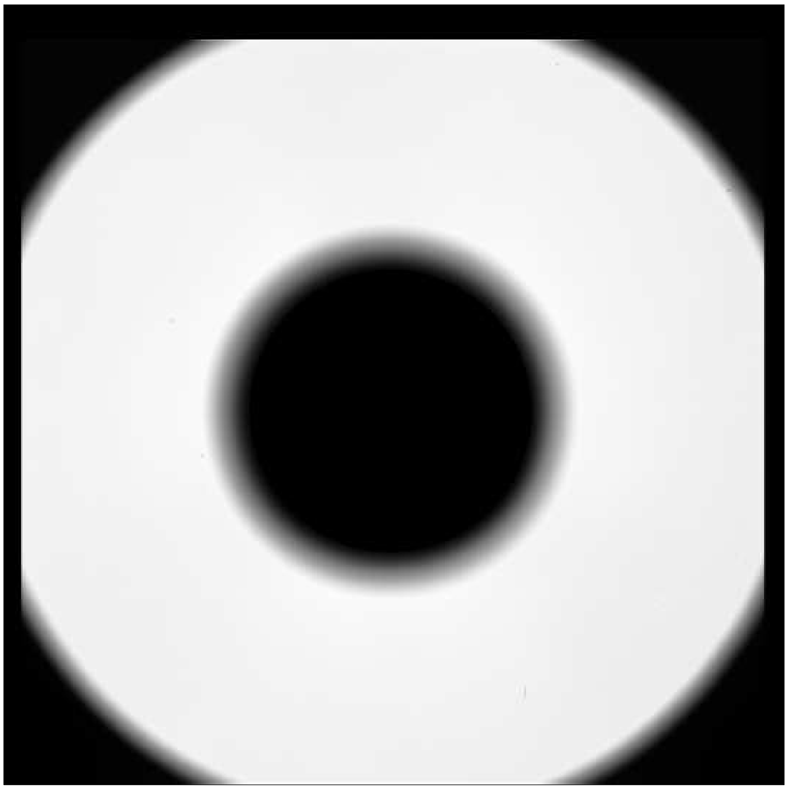

Figure 3: Flat field response of the COR-1 Ahead instrument.

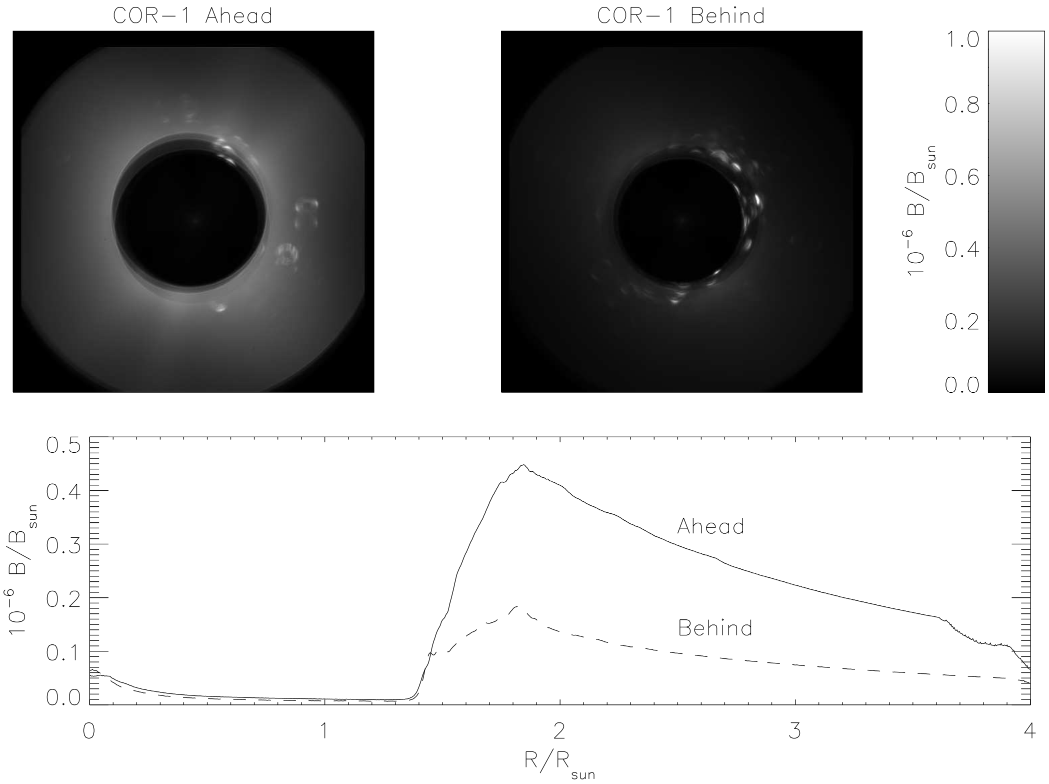

Figure 4: Measured scattered light images and average radial profiles for the COR-1 Ahead (solid) and Behind (dashed) instruments.

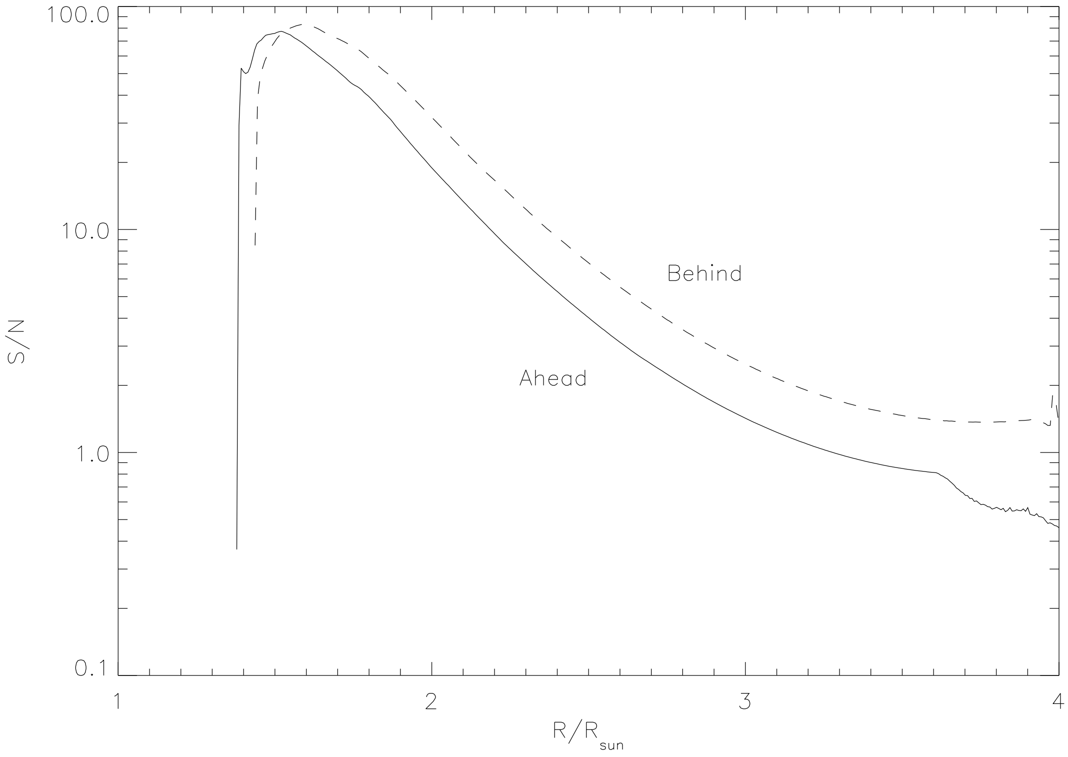

Figure 5: Estimated signal-to-noise ratios for a modeled K-corona for an exposure time of 1 second, with 2×2 pixel binning.

have the performance shown in Figure 4.

Combining the data from Figures 3 and 4, together with a model of the K corona polarized brightness, allows one to estimate the signal-to-noise ratios that will be seen during flight. The results are shown in Figure 5 for an exposure time of 1 second. The coronal model used is based on Gibson (1973), and has the functional form:

$$\log_{10}(pB) = -2.65682 - 3.55169(R/R_\odot) + 0.459870(R/R_\odot)^2, \tag{1}$$

and is valid between 1.4 and 4 solar radii.

The overall performance characteristics of the COR-1 instruments are summarized in Table 1.

1.4 Concept of operations

Like all coronagraphs, COR1 is designed to measure the weak light from the solar corona in the presence of scattered light from the much brighter solar photosphere. The COR1 signal will be dominated by instrumentally scattered light, which must be removed to measure the underlying coronal signal. To build up enough signal to make this happen, the 3.75 arc second square pixels will be summed together into 2×2 bins, to form larger pixels 7.5 arc seconds on a side.

The design goal for the root-mean-square spot size on the detector was chosen to be 15 μm (4.17 arcsec), somewhat larger than the 13.5 μm size of a single CCD pixel, but well within the

Table 1: COR-1 performance characteristics

Parameter	Units	Ahead	Behind
Pixel size, full resolution	arcsec	3.75	3.75
Pixel size, 2×2 binned	arcsec	7.5	7.5
RMS spot size (design)	arcsec	4.17	4.17
Planned exposure time	sec	1	1
Polarizer attenuation	-	10^{-4}	10^{-4}
Photometric response	$B_{\odot}/DN$	7.1×10^{-11}	5.95×10^{-11}
Time to complete pB sequence	sec	11	11
Image sequence cadence	min	8	8

27 μm size of a 2×2 binned pixel. The largest contribution to the optical error budget comes from thermal changes on orbit, which can be as large as 12 μm.

COR1 will measure both the total brightness B, and the polarized brightness pB, of the solar K corona. This is done by taking polarizer measurements at angles of -60° (I_a), 0° (I_b), and +60° (I_c), and combining them using the following equations (Billings, 1966):

$$B = 2(I_a + I_b + I_c) \tag{2}$$

$$pB = (4/3)\sqrt{(I_a + I_b + I_c)^2 - 3(I_a I_b + I_a I_c + I_b I_c)} \tag{3}$$

The three images will be taken in sequence, as quickly as possible, so that changes due to evolution of the corona will be minimized. Each set of three images makes up a complete observation, and the cadence of observations is the time between one three-image set and the next.

References

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