Performance Testing of the COR1 Inner Coronagraph for STEREO-SECCHI

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COR1 is a classic Lyot internally occulting refractive coronagraph, adapted for the first time to be used in space. As the inner coronagraph for the SECCHI instrument suite on STEREO, the field of view is from 1.25 to 4 solar radii. A linear polarizer is used to suppress scattered light, and to extract the polarized brightness signal from the solar corona. The optical scattering performance of the coronagraph was first modeled using both the ASAP and APART numerical modeling codes, and then tested at the Vacuum Tunnel Facility at the High Altitude Observatory of the National Center for Atmospheric Research in Boulder, Colorado. Two successive breadboard models of the COR1 instrument have been tested at the HAO facility in the spring and summer of 2001 respectively. We will show how the measured performance improved with the successive breadboard models, and how these results relate to the predicted performance in flight.

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 glass. Thus, the solar image will be chromatically aberrated, so that the occulter must be sized to block all the solar photospheric light from the near UV to infrared (350–1100 nm). Subsequent lenses in the optical train remove the chromatic aberration.

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 design of the light trap is such 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. A Lyot spot is also used to remove ghosting from the objective lens.

Two doublet lenses are used to focus the coronal image onto the CCD detector. Between the two doublets are a bandpass filter (10 nm wide, centered on the Hα line at 656 nm), and a linear polarizer on a rotational stage. Normal operations call for images to be taken with polarizations of $0°$ and $\pm 60°$, to extract the polarized brightness.

A focal plane mask is located between the shutter and the focal plane camera, and is used to remove diffracted light from the edge of the occulter.

COR1 Instrument Layout

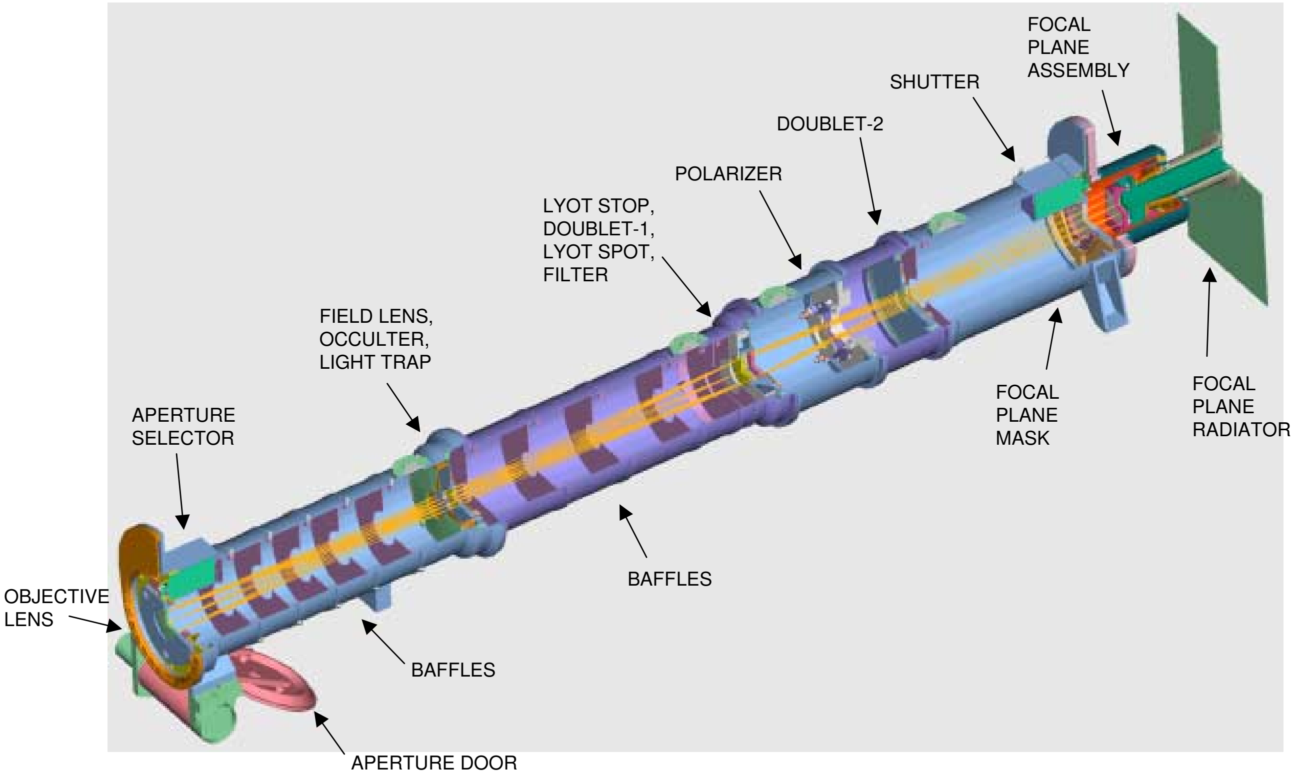

Figure 1: Layout of the COR1 instrument package. Current design does not include an aperture selector.

Image of Sun Reflects off Occulter into Light Trap

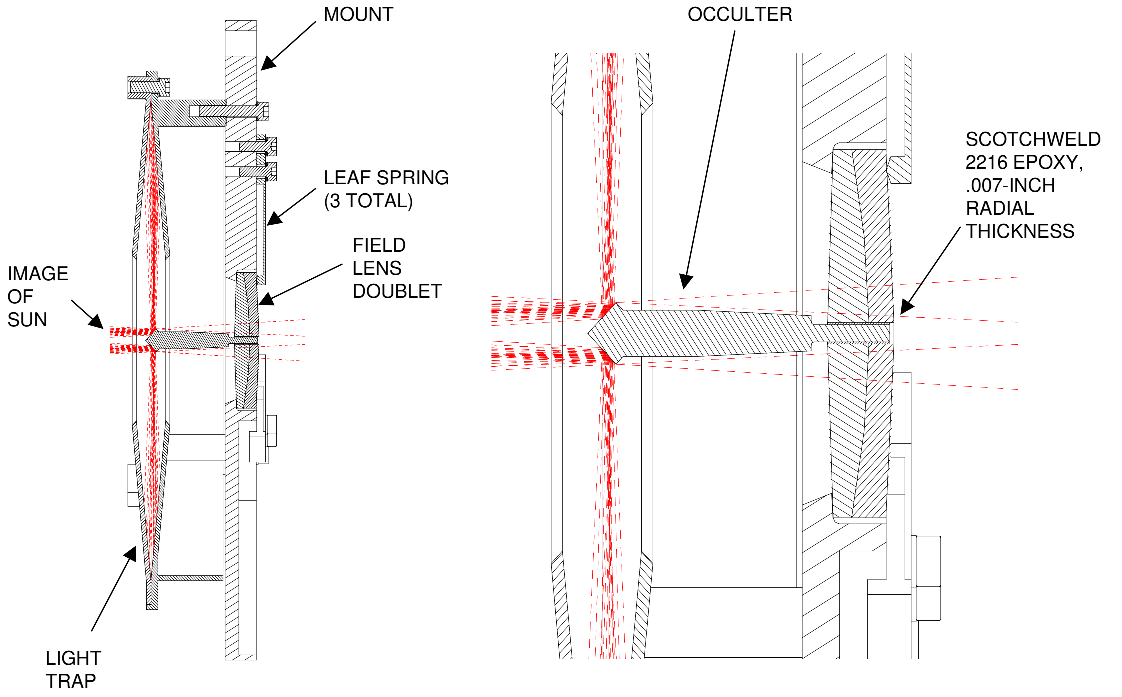

Figure 2: The conical occulter and light trap. (The final design of the lens mount is slightly different than shown.)

Testing at the HAO Facility

Testing was done at the High Altitude Observatory Vacuum Tunnel Facility at the National Center for Atmospheric Research in Boulder, Colorado (Figure 3). A heliostat is used to feed sunlight into one end of a 100 foot evacuated tunnel. A Fresnel lens concentrates this light onto a diffuser window mounted inside the vacuum chamber. The light from the diffuser is then directed down the tunnel axis by a plano-convex lens. An adjustable iris is mounted just past the lens, and forms the target for the instrument chamber at the other end of the tunnel.

A large instrument chamber sits at the other end of the tunnel (Figure 4), within a class 10,000 cleanroom. The tunnel and instrument chamber are evacuated to $\sim$40 μm (0.04 Torr), to remove atmospheric scattering, and to allow the CCD detector to be cooled. The primary cooling was provided by a chilled glycol/water mixture pumped from outside the chamber—the coolant lines are visible in Figure 4. A TEC mounted between the CCD and coolant reservoir provided additional cooling and temperature control.

The COR1 breadboards were mounted so that they could be steered in pitch and yaw. They were supported at their center of mass by a cradle arrangement, while the back end was mounted to two crossed linear motion controllers. This allowed precise control of the alignment of the instrument to the source while the chamber was under vacuum.

A photodiode was mounted alongside the front aperture of the breadboard, to monitor the brightness of the source. This photodiode was equiped with a bandpass filter identical to the one incorporated in the breadboard design.

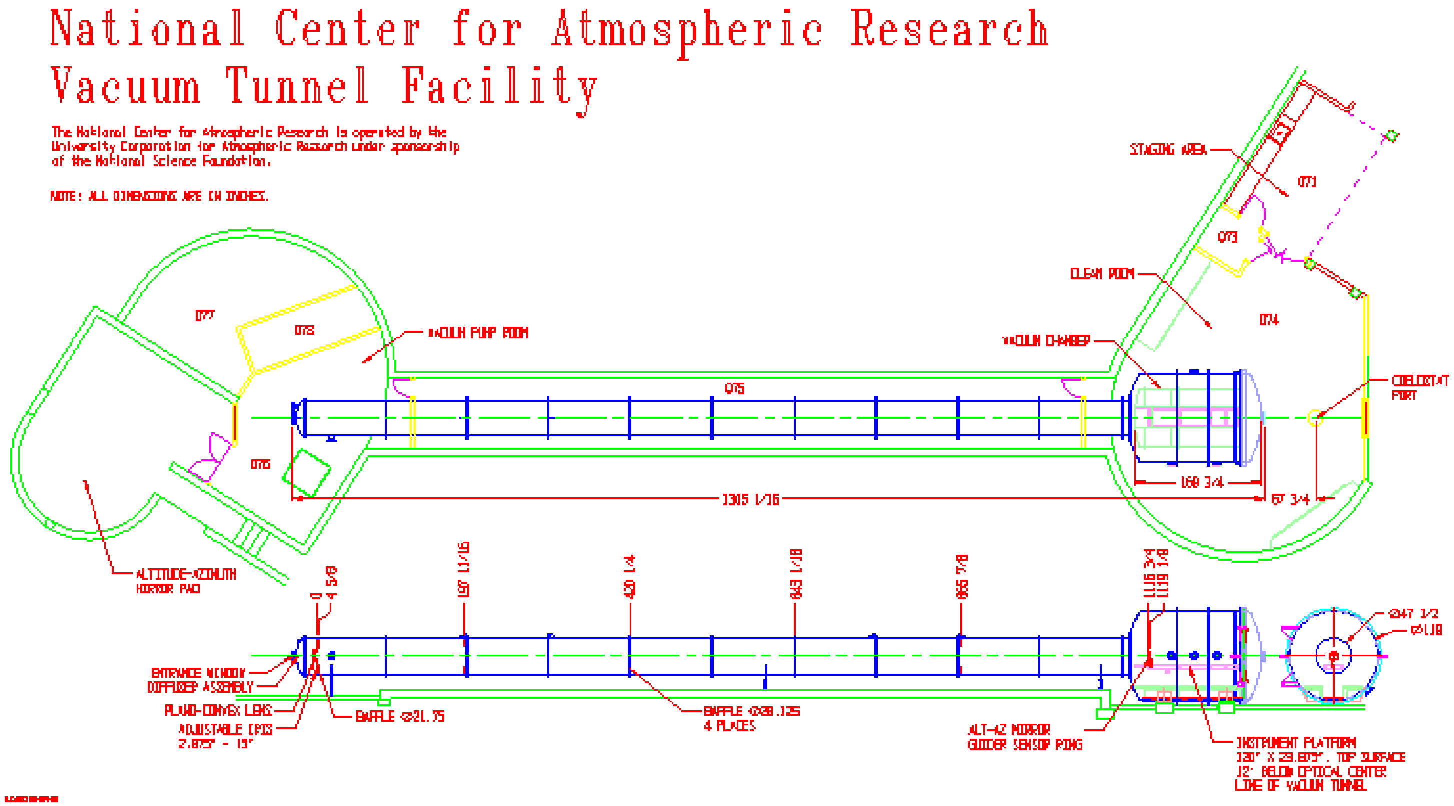

Figure 3: Plan of the NCAR/HAO Vacuum Tunnel Facility

Figure 4: The instrument chamber at the far end of the 100 foot tunnel.

COR1 Breadboard Results

Two successive versions of the breadboard were tested, with increasing fidelity to the flight design. The first version used commercial mounts for all the optical elements. It also used an earlier 45° flat occulter design instead of the final conical occulter. The second version introduced a flight-like tube section containing the objective lens, occulter, and field lens, with flight-like lens mounts and baffling, a conical occulter and the corresponding light trap. Both breadboards were designed for a source at a finite 100 foot distance, rather than at infinity.

Significant improvement seen between the first and second breadboards (Figure 7). This can be attributed to

- Improved handling procedures for the objective lens
- Baffles between the objective and occulter/field lens assembly
- Conical occulter

Additional improvement was realized by adding a Lyot spot (Figure 8). The best performance in the final breadboard configuration goes from 10^{-6} $B_\odot$ near the edge of the occulter to 2×10^{-7} $B_\odot$ at the edge of the detector ($\sim$4 $R_\odot$)

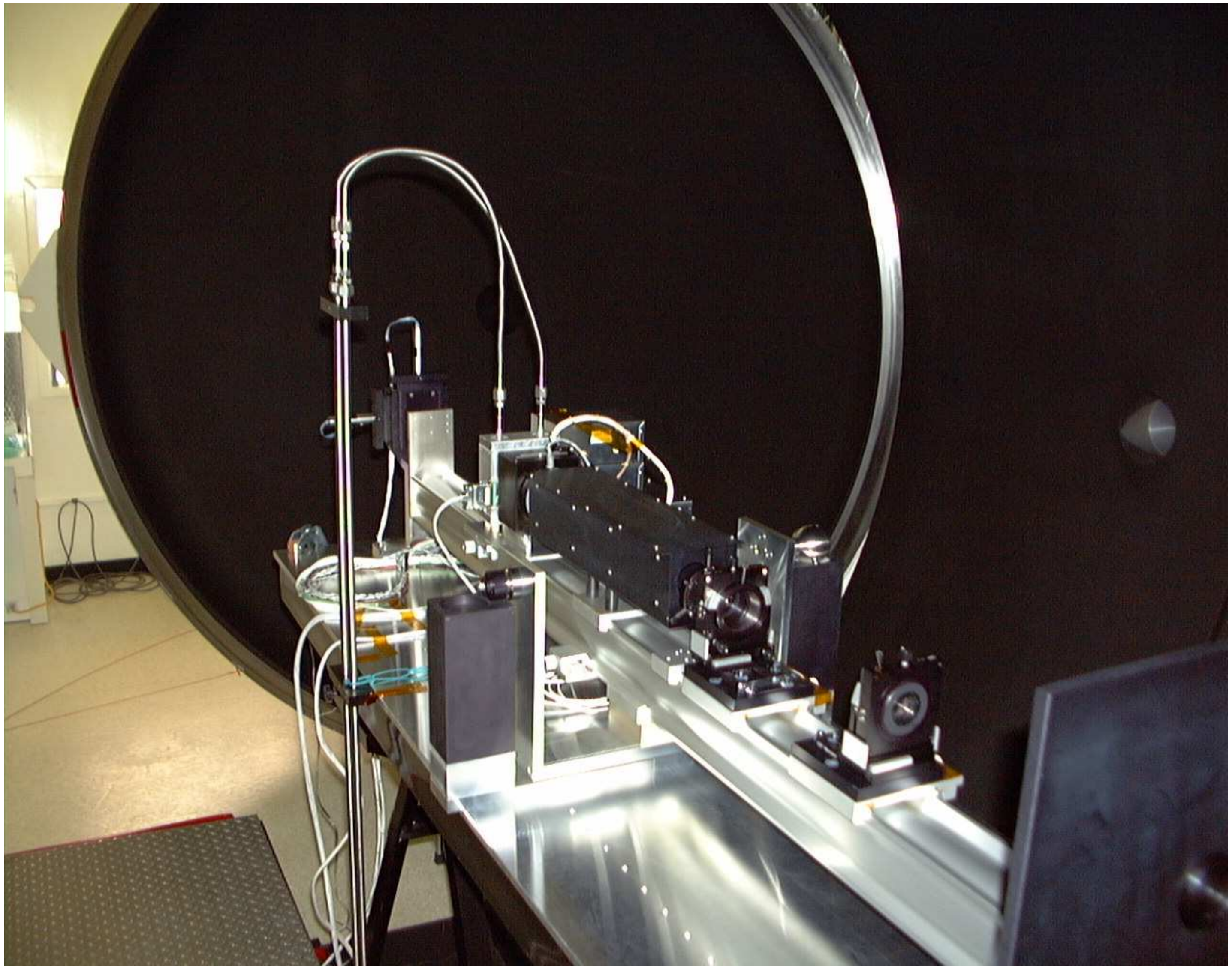

Figure 5: Photo of the first breadboard, with all optics on commercial mounts. The objective lens is in the extreme lower right corner. The next optic along the rail is the field lens with the occulter extending out from the middle of the lens. After that is the Lyot stop/field lens assembly, baffling, and finally the detector. The support cradle at the center of the rail, and the steering mechanism at the back is also visible.

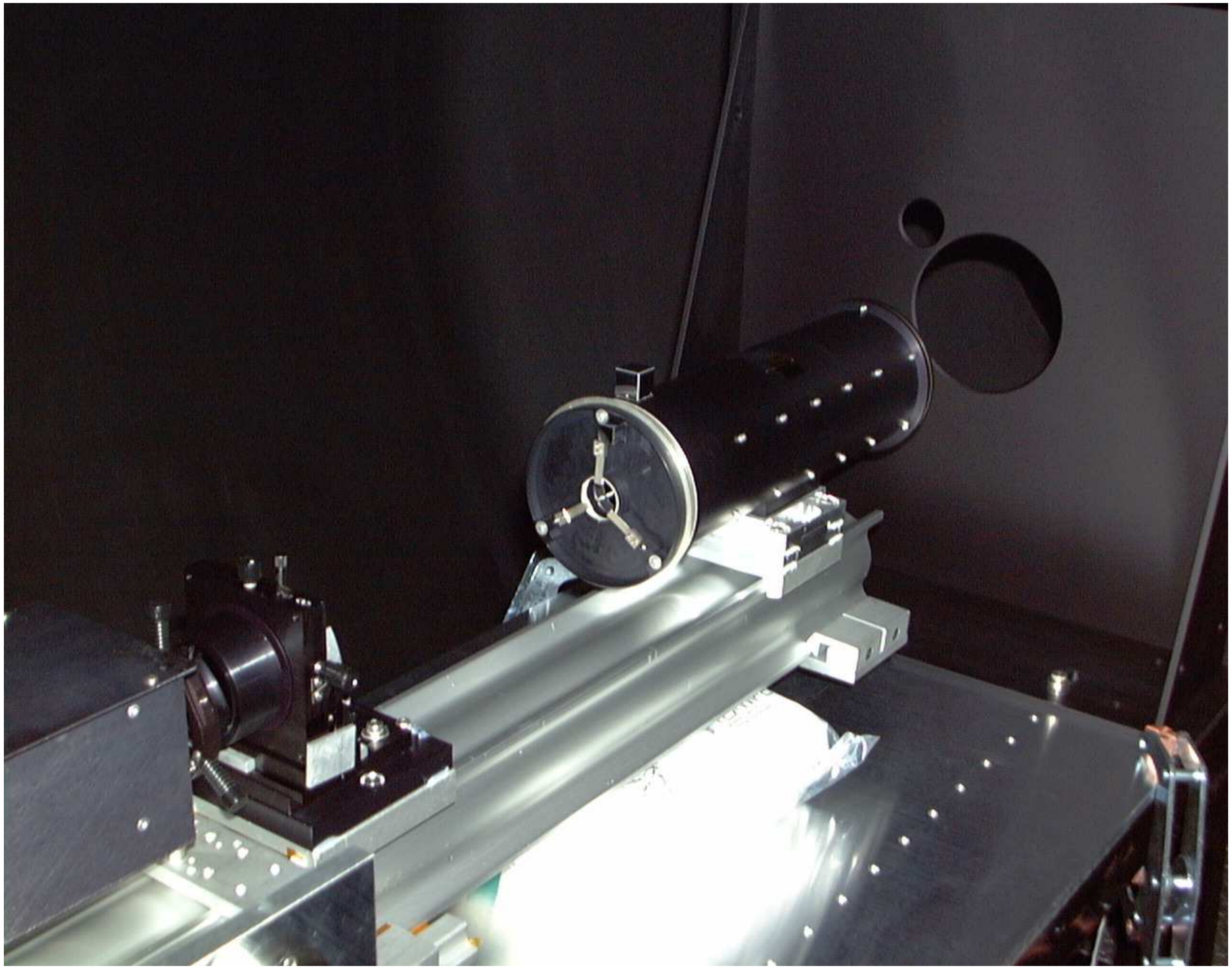

Figure 6: Photograph of the front cylindrical section of the second breadboard. The near side of the cylinder contains the field lens, with the embedded occulter on the interior side. The objective lens is mounted on the far side. Also visible on the left side of the photograph is the focusing lens assembly in the Newport LP-2 mount, the bandpass filter, and the baffling which extends back to the detector.

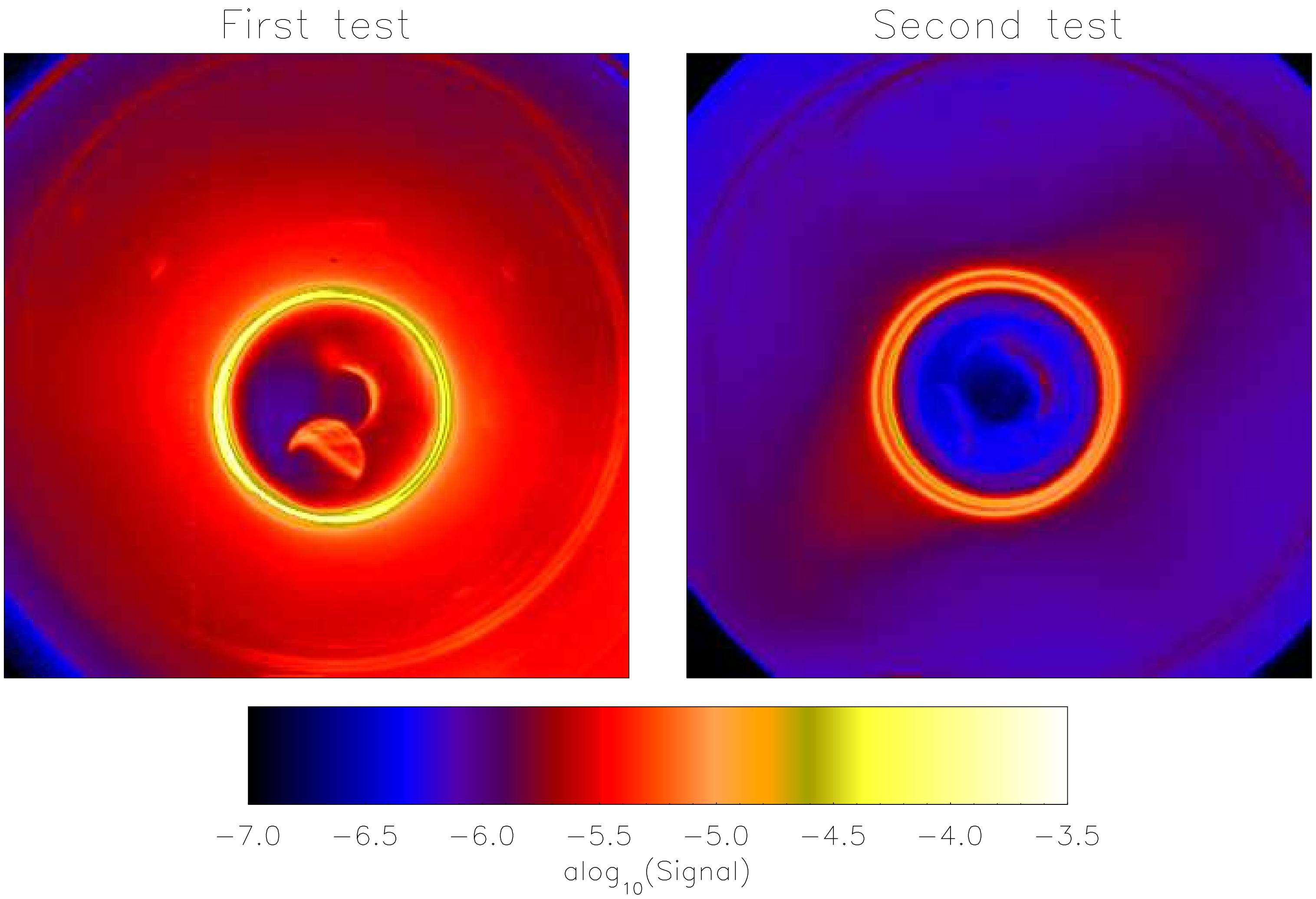

Figure 7: Comparison of the scattered light profile from the two versions of the breadboard.

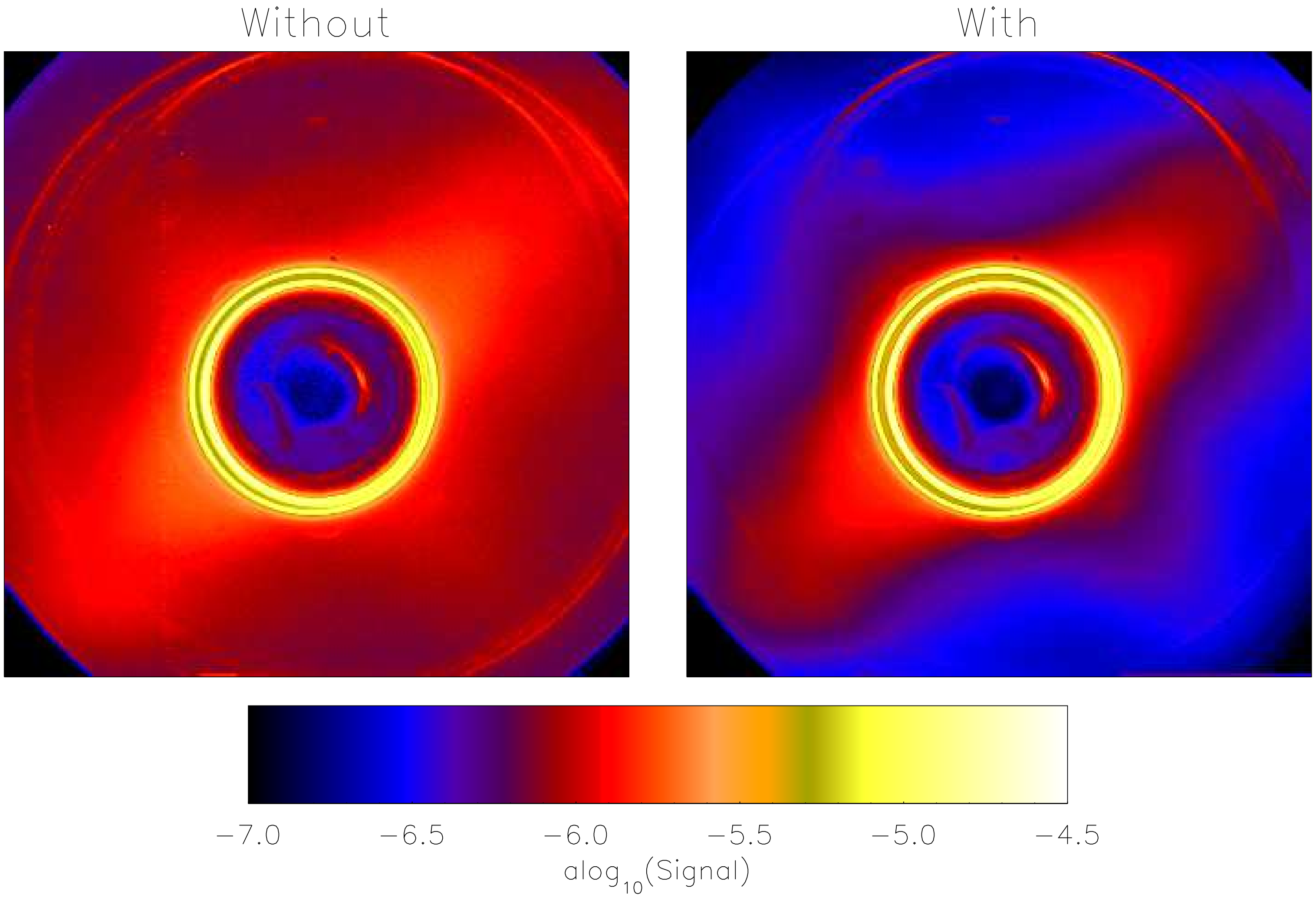

Figure 8: Comparison of the scattered light profile from the second breadboard, with and without a Lyot stop. The image on the left is the same as the right hand image in Figure 7, using a different color table.

Two bright rings appear around the edge of the occulter. We spent some time after the HAO tests characterizing these rings, and found that both rings are associated with the occulter. One follows the edge of the umbra and the other the penumbra of the occulter shadow. When the occulter is in perfect focus, the two rings merge into a single ring right at the edge of the occulter. We interpret these rings as diffraction effects occuring at the edge of the occulter, and tied to the diffraction from the aperture. A focal plane mask will be introduced into the optical path just in front of the detector to remove these two rings.

Two sets of bars radiate from the source image at 45°, with one set much stronger than the other. By changing the pointing of the instrument relative to the source, it was found that these bars are centered on the source rather than on any feature of the instrument. The most likely source is scattering from the objective lens.

There are several artifacts appearing inside the occulter shadow. These have been traced to light hitting a chamfer in the field lens at the end of the occulter stem. In the flight design, the stem will not go all the way through the field lens, so there will not be a chamfer to be illuminated.

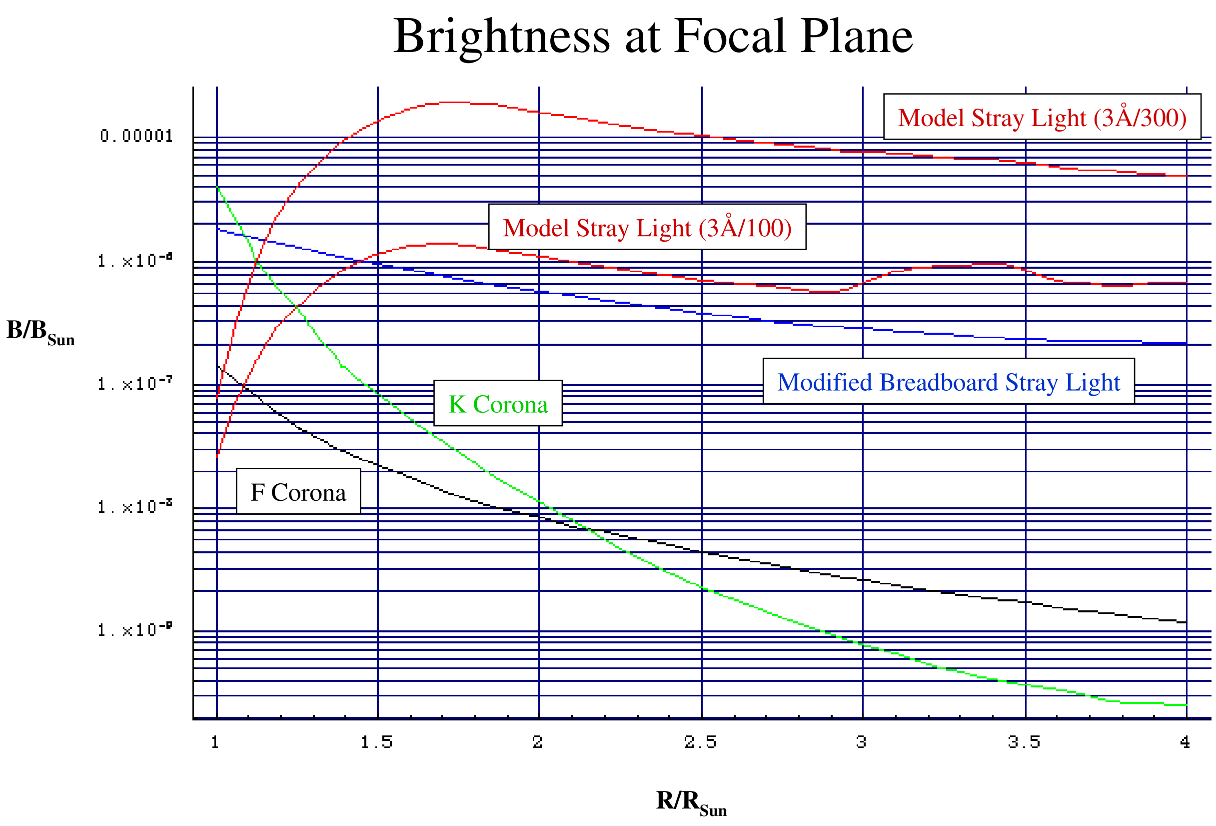

Figure 9: Comparison of the modeled and measured instrumental scattered light to the anticipated background F and K coronae.

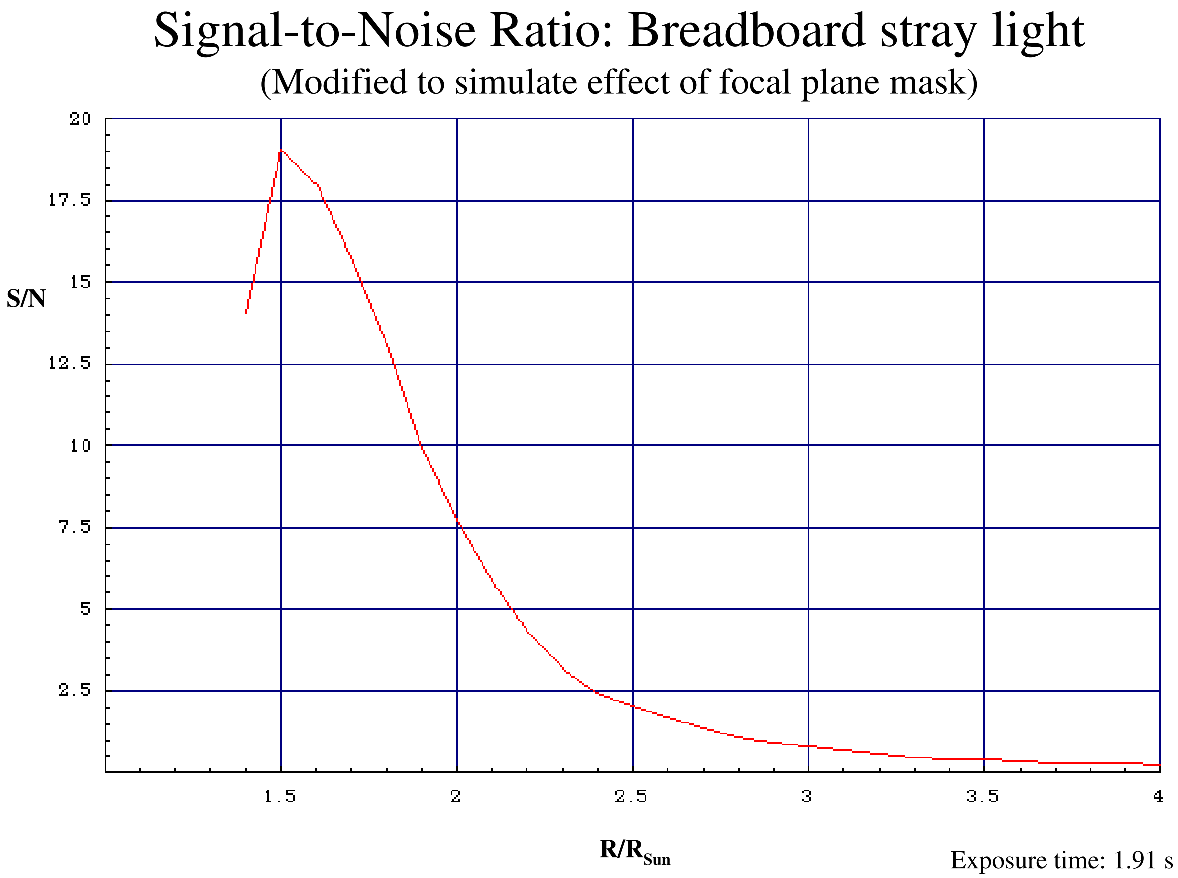

Figure 10: Calculated signal-to-noise ratio for the anticipated background K corona.

Future plans

An Engineering Test Unit (ETU) is currently under development. Two configurations are planned for the ETU. One configuration, for vibration testing, will be a complete instrument built to the flight design, but with simulated mechanisms and detector. Some of the optics will also be simulated. The second configuration, for performance testing, will retain the first two tube sections from the first, which will have flight-like optics installed, up to the bandpass filter (see Figure 1). The remaining optics will be mounted on commercial mounts as in the two breadboards.

The ETU will encompass a number of significant improvements over the previous breadboard models

- Assembly will be performed in the higher quality cleanroom that will be used for the flight instruments.
- Two doublets will be used, as in the flight design, to focus the image onto the detector. This will improve the resolution to flight standards.
- A polarizer will be inserted into the optical path, to characterize the polarization properties of the instrument.
- The focal plane mask concept will be tested.

Calibrating the Flight Instrument

- The flight models will be calibrated at a similar vacuum facility at NRL.
- Calibration will be done in flight by observing stars and planets. We will also cross-calibrate the overlapping field with COR2. During the early mission phases, we will also be able to cross-calibrate with the Mauna Loa Solar Observatory Mark IV Coronameter.
- A diffuser window will be mounted in the door, to monitor the instrument calibration and flat-field during flight. This can also be used on the ground for monitoring the alignment of the occulter and focal plane mask.