

# SOBER, the SOAR BEam simulator

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This document describes the design goals, the optical design, the image quality, and optical tolerances of SOBER.

## 1 Design Goals

SOBER is a device designed to simulate the light beam of the SOAR telescope for aligning the Spartan IR Camera. The design goals are:

- To produce an  $f/16$  beam similar to the one produced by SOAR.
- To produce image quality similar to SOAR, to align the IR camera.
- To minimize cost and assembly difficulty.

## 2 Optical Design

We developed a design utilizing two off-the-shelf lenses and an LED mounted on a stage and optical rail. The advantages of this design are:

- Diffraction limited images at 660 nm.
- Rotational motion of SOBER can be used to easily find the center-of-field.
- Low cost. The most expensive items are stages and rails, not the optics.
- Easy manufacture and assembly. All optics are on-axis with no tilts or decenters.

In the optical design (Figure 1), a star is simulated by an LED behind a pinhole. A plano-convex lens, a double-convex lens, and an aperture stop convert this light into an  $f/16$  beam.

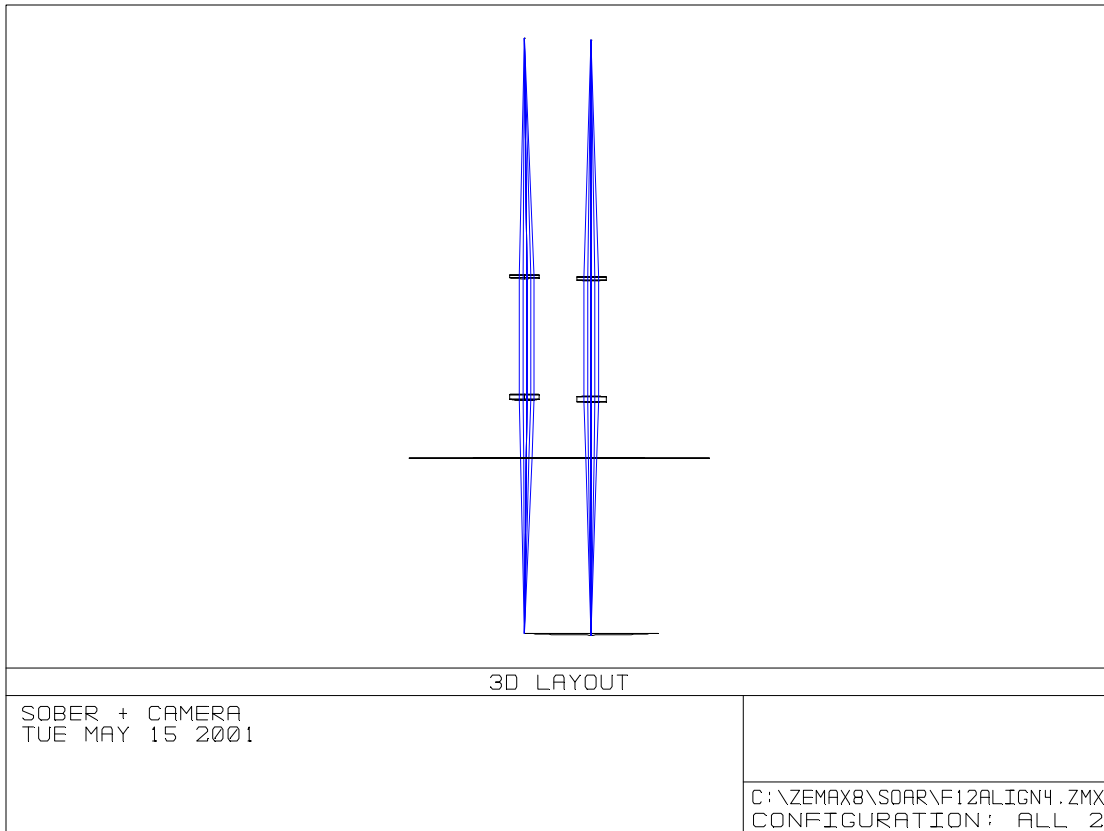


Figure 1 – SOBER placed for the central and an edge field. The LED is at the top of the assembly, followed by a plano-convex lens, a double-convex lens followed directly by the aperture stop, and the mounting plate.

There are a few disadvantages with this design. First is that the simulator does not reproduce the entire field of view of the telescope at once. The tube must be moved about the field. Second, this simulator only works at 660 nm, not all wavelengths like the telescope.

The final problem is that the exit pupil is 175 mm from the focus for SOBER and 10 m for SOAR. For the on-axis field point, the exit pupil of SOBER images onto the Lyot stop of the instrument. For off-axis field points, the aperture stop must be decentered.

These disadvantages could have been corrected with an alternate design based on an Offner system. This design (Figure 2) reproduces the entire field of view of the telescope and the pupil at all wavelengths. This design was abandoned for the following reasons. First, both mirrors and the source would have been tilted with respect to the image plane, making alignment and assembly more difficult. Second, it requires a large mirror.

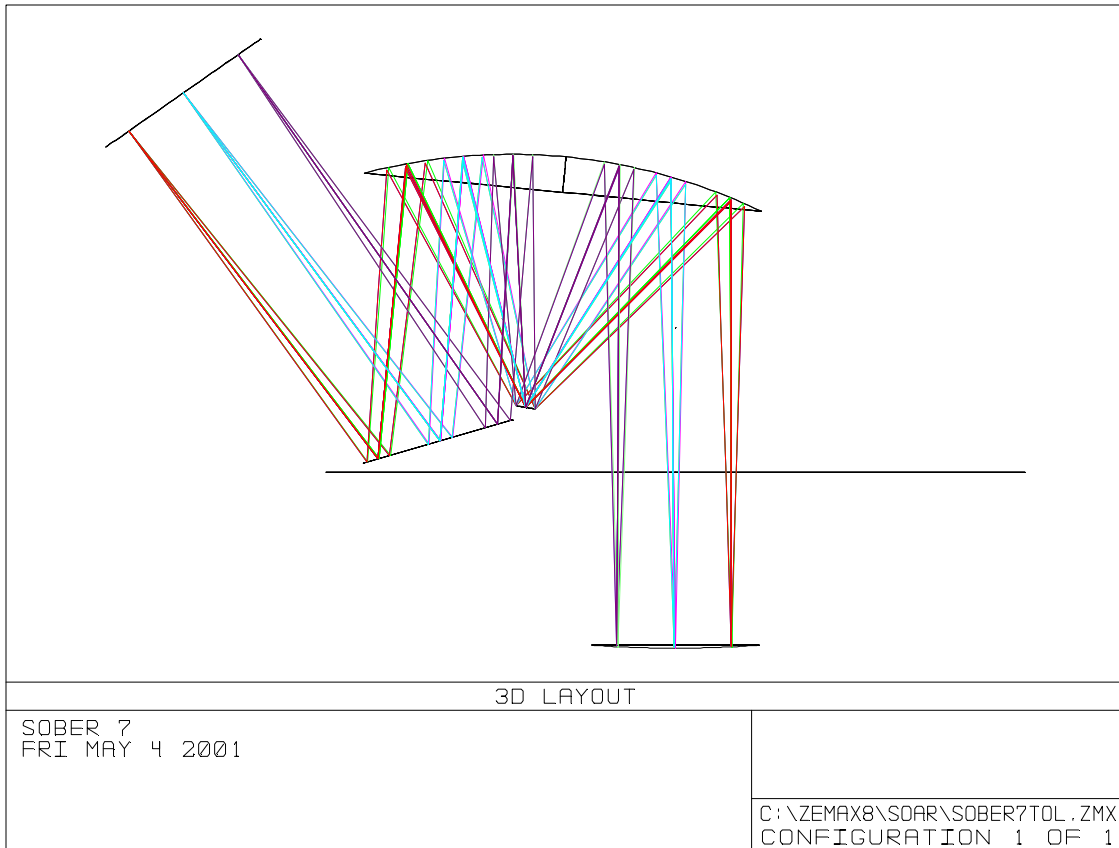


Figure 2 – The rejected SOBER design. The primary mirror is 350 mm in diameter. Note the tilt of the elements with respect to the image plane.

### 3 Image Quality and Camera Alignment

SOBER can be used to align the Spartan IR Camera. The procedure is described in detail in the document “Alignment of the Spartan IR Camera,” but can be summarized as follows. The encircled energy of a point image is greatest when the optics are best aligned. A misalignment in the optics produces known image degradation. The IR camera can be aligned by measuring the encircled energy of field points in a 3 \* 3 grid. These measurements can be used to determine which camera parameters need to be moved. When the encircled energy of these field points is maximized, the camera is aligned.

The images produced by SOBER are diffraction limited. The spot diagrams in Figures 3 and 4 compare images produced by SOAR and the camera at 660 nm to images produced by SOBER and the camera. Table 1 shows a comparison between the Strehl ratios of the two sources.

Table 1 – Strehl ratios of SOAR and SOBER. The measurements are taken with the f/11 channel at 660 nm. The fields are as they would appear in the sky.

	SOAR			SOBER		
	Left	Center	Bottom	Left	Center	Bottom
Top	0.794	0.732	0.794	0.881	0.759	0.881
Center	0.804	0.800	0.804	0.868	0.842	0.868
Bottom	0.876	0.980	0.871	0.946	0.920	0.946

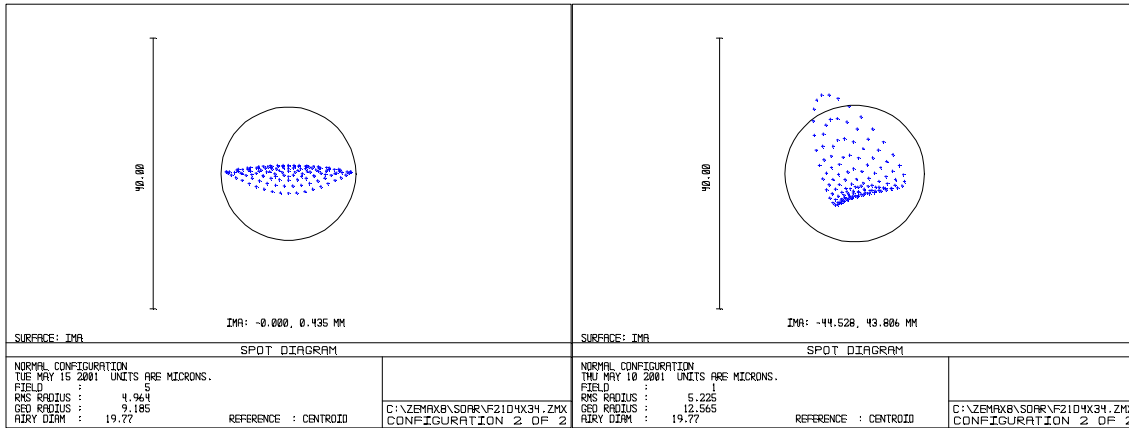


Figure 3 – (left) Center of the field for SOAR + the f/11 channel at 660 nm. (Right) Corner of the field for SOAR + the f/11 channel at 660 nm. The scale is given by the 20- $\mu$ m Airy disk.

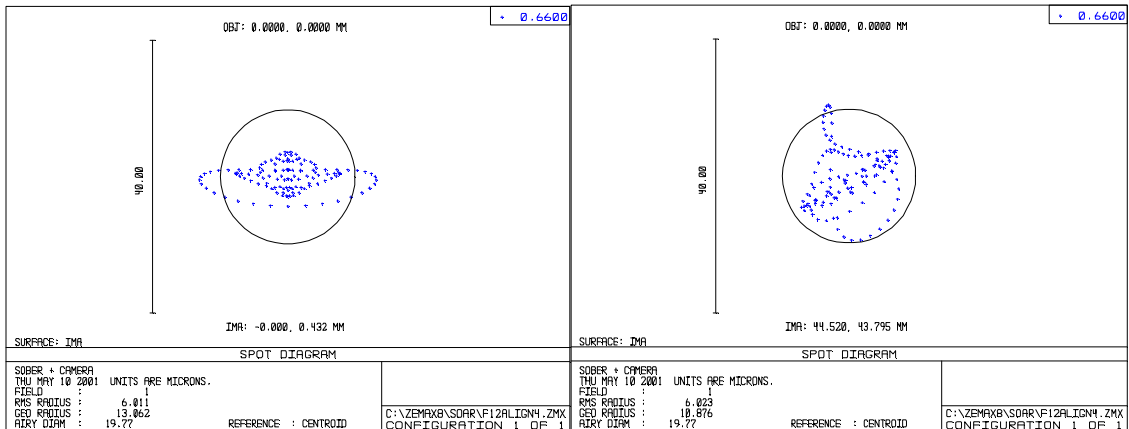


Figure 4 – (left) Center of the field for SOBER + the f/11 channel at 660 nm. (Right) Corner of the field for SOBER + the f/11 channel at 660 nm. The scale is given by the 40- $\mu$ m Airy disk.

The difference between the Strehl ratio of SOBER plus the camera and the Strehl ratio of SOAR plus the camera ranges from -6% to +10%, depending on the field point. On average, SOBER and the camera has a Strehl ratio 6% greater than that for SOAR plus the camera. This Strehl ratio is good enough to align the camera using our alignment procedure. The alignment procedure relies most heavily on measuring the encircled energy difference between field points on the left and right of the image. SOBER and the camera gives the same values for these points due to field symmetry, so the alignment procedure will work. The exact values listed in the alignment procedure document may change, but the procedure itself will still work.

While this SOBER design will not produce diffraction limited IR images, it can be used in the IR. Figure 5 shows a J-band image taken with SOBER and the camera. While the chromatic aberration present means image quality is not good enough for alignment, this design can be used to ensure that the IR detector works. The image size should be roughly twice the Airy disk in the J-band.

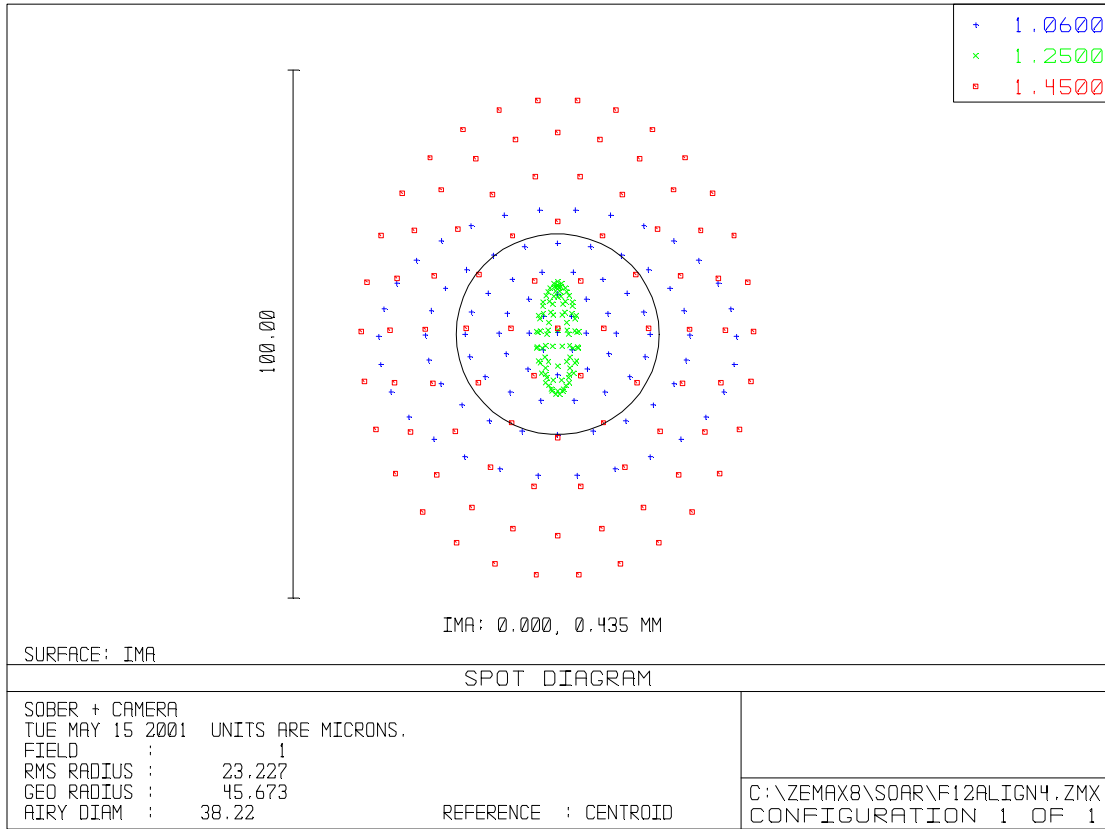


Figure 5 – Chromatic aberration of SOBER + the IR Camera in the J-band at 1.06, 1.25, and 1.45 $\mu$ . Chromatic aberration prevents alignment at this wavelength.

## 4 Optical Tolerances

SOBER must meet alignment and manufacturing tolerances to produce sharp images. The instrument has a total of 21 degrees of freedom. There are 16 positional degrees of freedom: five degrees of freedom for each optic plus positions of the source and whole instrument. There are five manufacturing degrees of freedom: three curvature radii and two lens thicknesses.

### 4.1 Alignment Tolerance

The Strehl ratio is allowed to fall by 1% at 660 nm. Simulations have shown that allowing a 1% drop in the beam simulator's Strehl ratio results in a 0.08% drop in the camera's Strehl ratio in the H-band after alignment. By Maréchal's formula (Born & Wolf 1970), the RMS error is  $(\ln(1/0.99))^{1/2}/(2\pi)=0.016$  waves. The errors for the degrees of freedom are assumed to add in quadrature. Therefore each degree of freedom is allowed  $0.016/(21)^{1/2}=0.0035$  waves.

All of the alignment tolerances (Table 2) can be achieved by machining, so no optical alignment is required. The tolerances assume SOBER can be focused after assembly.

Table 2 Alignment tolerances. The z-direction is along the optic axis, perpendicular to the mounting plate. PCX is short for “plano-convex,” while DCX is short for “double-convex.”

Element	Positional Tolerance			Angular Tolerance		
	x mm	y mm	z mm	x mrad	y mrad	z mrad
Source	3.12	3.12	1.59	NA	NA	NA
PCX	1.07	1.07	5.00	18.8	18.8	NA
DCX back	1.19	1.19	5.00	13.5	13.5	NA
Mounting plate	3.12	3.12	5.00	15.5	15.5	NA

## 4.2 Manufacturing Tolerance

Except for the surface irregularity, the manufacturing tolerances were calculated in the same way as the alignment tolerances. Each degree of freedom is allowed 0.0035 waves.

The tolerances of the radii of curvature of the lenses are looser than 1%, which is the capability of Edmund Optics for off-the-shelf lenses. The tolerances of the thickness of the lenses are looser than 0.1 mm, which also is the capability of Edmund Optics (Edmund Industrial Optics, 2001).

Table 3 Manufacturing Tolerances

Element	Thickness mm	Radius of Curvature mm
Source	NA	
PCX	3.2 ± 2.4	-104.60 ± 1.55
DCX front	5 ± 3	208.34 ± 3.25
DCX back		-208.34 ± 3.30
Mounting plate	NA	

## 4.3 Surface Irregularity

The surface irregularities of the lenses are not a concern. Edmund Optics can manufacture lenses with a surface irregularity of  $\lambda/4$  (Edmund Industrial Optics, 2001). This irregularity will cause the Strehl ratio to drop slightly at the alignment wavelength. Since irregularities are not likely to mimic alignment errors, they will not cause the camera to be misaligned.

## 5 References

Born, M., & Wolf, E. 1970, *Principles of Optics*, Pergamon, New York, p. 468.

Edmund Industrial Optics 2001, <http://www.edmundoptics.com>