Optical Designs for the Mars ’03 Rover Cameras

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ABSTRACT

In 2003, NASA is planning to send two robotic rover vehicles to explore the surface of Mars. The spacecraft will land on airbags in different, carefully chosen locations. The search for evidence indicating conditions favorable for past or present life will be a high priority.

Each rover will carry a total of ten cameras of five various types. There will be a stereo pair of color panoramic cameras, a stereo pair of wide-field navigation cameras, one close-up camera on a movable arm, two stereo pairs of fisheye cameras for hazard avoidance, and one Sun sensor camera.

This paper discusses the lenses for these cameras. Included are the specifications, design approaches, expected optical performances, prescriptions, and tolerances.

Keywords: optical engineering, lens design, cameras, Mars, JPL

1. INTRODUCTION

The exploration of Mars has become a high-priority goal for the U.S. space agency, NASA. Recent images from the orbiting Mars Global Surveyor spacecraft indicate that liquid water may once have flowed on Mars, and perhaps it still occasionally does. The presence of liquid water suggests the possibility of life, either now or in the past. This exciting prospect has spurred great interest in taking a closer look.

Thus, in June and July of 2003, NASA plans to launch (on separate Delta II rockets) two identical roving science vehicles toward Mars. They are to land using airbags at two different locations on the Martian surface in January and February of 2004. After emerging from their landing enclosures (which will be of no further use), these six-wheeled robotic rovers are to embark on at least three months of exploring and data gathering. Contact with Earth will be limited to daily scheduled radio transmissions (timed near local Martian noon). Operation will thus be a combination of Earth-based target selection and on-board autonomous navigation. The rovers must be smart enough to largely take care of themselves. Crucial for success (even survival) is their being able to see what is out there as they roam by as much as 100 meters per day. Of course, the scientific imaging (photo-electric photography) is a central goal of the mission.

2. THE CAMERAS

A rover's eyes are its cameras, which are a major part of the scientific and engineering equipment. On each rover, there is a total of 10 cameras of five various types. Figure 1 is a schematic drawing of a rover that shows the locations and fields of view of these cameras.

All cameras use the same type of solid-state, silicon-based CCD image detector. This CCD is a 1024×2048 array of 12×12 μm pixels. The top 1024×1024 pixels is the photo-sensitive area, and the bottom 1024×1024 pixels is a covered frame-transfer buffer (there is no shutter). Thus the active imaging area is 12.29 mm square with a diagonal of 17.38 mm. (Relatively speaking, in photography this is not very small. The diagonal of a 16 mm movie camera frame is 12.63 mm, and the original 8 mm movie frame had a diagonal of only 5.95 mm.) The 12 μm pixel separation gives a Nyquist limit for spatial frequency detection of 41.67 cycles/mm. The CCDs themselves are sensitive to wavelengths ranging from about 0.40 μm to 1.1 μm. In most cases, filters plus the CCD response determine the specific wavebands.

The lenses for these cameras have to be small, simple, and effective, and they must survive on Mars. The most has to be done with the least. Thus the fewest number of lens elements are used, all optical surfaces are spherical or flat (no aspheres), and no cemented surfaces are allowed (that could break apart in the Martian cold). Short focal lengths (to match the CCD) and slow focal ratios (to allow great depth of field) make these restrictions realistic. To facilitate polishing, anti-reflection coating, and mechanical mounting, the lens elements have been made somewhat oversized. In no case is any mechanical vignetting (off-axis beam clipping) allowed.

A temperature of 23°C and an air pressure of 0.95 atmosphere were adopted during the optical design process on the assumption that these lenses have to be made, tested, and calibrated here on Earth. However, image quality was reevaluated analytically for the Martian environment of 10°C, -22.5°C, and -55°C, all at 0.01 atmosphere. In no case was a significant change found when going to Mars. Note that nighttime temperatures on Mars can fall to -120°C, but the cameras need only survive, not operate, in these conditions.

3. PANCAMS

The two panoramic cameras (PanCams) are a stereo pair of moderately narrow-field systems located on the top of a mast. The stereo camera separation is 280 mm, which will yield hyper-stereo images (the stereo separation or interpupillary distance between human eyes ranges between about 54 mm and 72 mm). Full 360 degree azimuth and ±90 degree elevation pointing is provided. The lens focal length is 42.97 mm giving a field of view of 16×16 degrees, or 22.5 degrees on the diagonal (the equivalent of a 109 mm lens on a 35 mm camera). In the center of the field, each pixel covers 279×279 microradians in object space (giving 558 microradian limiting resolution on a pair of adjacent pixels). The PanCams operate at *f*/20, view objects in focus whose distances range from infinity to 1500 mm (the depth of field), and are fixed-focused at 3000 mm (the hyperfocal distance). Each carries a filter wheel with 8 interference filters of various wavebands covering the sensitivity range of the CCD to allow multi-spectral imaging and quantitative geological and atmospheric studies. The lens designs are Cooke triplets as shown in the layout in Figure 2.

When constructing the merit function for optimizing the PanCams, the fields and wavelengths were equally weighted on the assumption that all must work well. In addition to correcting the physical and first-order constraints, the merit function minimized the optical path differences (OPDs) in the exit pupil wavefront, which also yielded the best modulation transfer function (MTF) performance. For fine tuning, special optimization operands also exactly corrected longitudinal color, lateral color, and asymmetry of the point spread function (PSF) from coma. In addition, distortion was corrected, and when later evaluated, the lens was found to have residuals of less than 0.01% all across the field. Image irradiance at the edge of the field was found to be 93% of the central value (from "cosine-fourth" falloff).

Figure 3 shows the transverse ray fan plots for diagnosis of residual aberrations, and it illustrates their correction. In the on-axis plot, the wavelengths can be seen to have been selected for their optical properties and to be long-short pairs.

Figure 4 is the polychromatic spot diagram. All the wavelengths are equally weighted. The scale bar length is 24 μm, which is the dimension of one side of a 2×2 matrix of pixels that defines one limiting-resolution detector element. The circles indicate the diameter of the Airy diffraction disk for a wavelength of 0.43 μm.

Figure 5 is an overlay of three sets of MTF curves. Each set gives the monochromatic MTF performance corresponding to the middle of one of the filter wavebands. There is no refocusing; the PanCam is evaluated at the compromise best focus for all wavelengths (as it will be used in practice). The three wavelengths are 0.43 μm (through the shortest-wavelength filter on the filter wheel), 0.75 μm (near the Red Planet's peak reflectance, although Mars really looks yellowish brown), and

0.98 μm (the longest-wavelength filter). For 0.43 μm, the actual MTF values cluster just below the diffraction-limited value of 55% at the Nyquist cutoff frequency of 41.67 cycles/mm. Similarly, for 0.75 μm, the actual curves cluster just below the diffraction limit of 25% at Nyquist. And for 0.98 μm, the curves drop to just below the diffraction limit of 8% at Nyquist.

For object distances other than 3000 mm, the images formed by this fixed-focus lens will become defocused to some degree, and they will often be not so diffraction limited. Relative to longer wavelengths, the MTFs for shorter wavelengths are initially higher (again see Figure 5), but they degrade more with defocus. Even so, for objects between infinity and 1500 mm, the MTFs for shorter wavelengths are at worst about the same as the MTFs for longer wavelengths. For all these object distances and through all the filters, the images will look nearly in-focus to within the resolving capability of the CCD.

Listing 1 is the PanCam optical prescription. As a place holder, a similar optical glass has been substituted for the filter glass type. A sapphire window seals against dust and protects the filter wheel mechanism.

4. NAVCAMS

The two navigation cameras (NavCams) are a stereo pair of moderately wide-angle systems. They are also mounted on top of the mast with the PanCams and point in the same direction. The stereo separation is 200 mm. The lens focal length is 14.67 mm giving a field of view of 45×45 degrees, or 60.7 degrees on the diagonal (the equivalent of a 37 mm lens on a 35 mm camera). In the center of the field, each pixel covers 818×818 microradians in object space. The NavCams operate at *f*/12, view objects whose distances range from infinity to 500 mm, and are fixed-focused at 1000 mm. They are monochrome (black-and-white) systems; a pair of absorption filters (Schott OG590 and KG5) working in series gives a reddish waveband extending from roughly 0.60 μm to 0.80 μm. The lens design is a cross between a Hologon and a Biogon and is shown in the layout in Figure 6.

Like the PanCams, the fields and wavelengths for the NavCams were equally weighted during optimization, and the merit function minimized OPDs plus correcting constraints and first-order properties. Distortion was corrected, and when later evaluated, the lens was found to have residuals of less than 0.03%. Image irradiance at the edge of the field was found to be 63% of the central value.

Figure 7 shows the transverse ray fan plots. Note on the on-axis plot that primary longitudinal color has not been corrected. This is because the lens has insufficient degrees of freedom to do so (more elements in the central group, some typically cemented together, would be required). But image quality is easily good enough, given the slow *f*/number and short focal length. Note on the off-axis plots that lateral color is virtually zero.

Figure 8 is the polychromatic spot diagram. Wavelengths within the waveband are equally weighted. Again the scale bar length is 24 μm. The circles indicate the diameter of the Airy diffraction disk for a wavelength of 0.70 μm.

Figure 9 is the polychromatic MTF plot. Here, wavelengths are weighted according to the combined filter-detector response curve. The small departures of the off-axis curves from the on-axis diffraction-limited curve are caused, not by aberrations, but by the Airy disk becoming slightly elongated. Strehl ratio is nearly flat across the field and remains above 97%. Clearly, the NavCam lenses are diffraction limited at best focus. At other object distances between infinity and 500 mm, the images remain nearly diffraction limited.

Listing 2 is the NavCam optical prescription. Note the wavelengths and their weights.

5. MICRO-IMAGER

The single Micro-Imager camera on each rover is a close-up system that is located on the end of a movable arm. The camera can be maneuvered to get a detailed look at rocks and other nearby objects of interest. Stereo is possible by taking one picture, shifting the camera sideways a bit, and taking a second picture. The lens focal length is 20.14 mm. Optical magnification is 2.5-to-1 (or 1-to-0.4). Thus a 30.7 mm square object area is imaged onto the 12.29 mm square CCD, and a 30 μm square is imaged onto each 12 μm pixel (giving 60 μm limiting object resolution on a pair of adjacent pixels). The object is larger than the image, and thus the lens is what photographers would call a macro lens. At these finite conjugates, the Micro-Imager forms an image having an *f*/15 cone of light (if the object were moved to infinity, the image focal ratio would become *f*/10.4). The system is monochrome with an absorption filter (Schott BG40) giving a waveband (width and shape) very similar to the human visual response. A sapphire window protects the lens in case it accidentally bumps against anything during its Martian explorations. The in-focus working clearance between object and window is 63 mm, and the total length between object and image is 100 mm. The lens design is a Cooke triplet and is shown in the layout in Figure 10.

Like the previous lenses, the fields and wavelengths for the Micro-Imager were equally weighted during optimization. Distortion was corrected, and when later evaluated, the lens was found to have residuals of less than 0.01%. Image irradiance at the edge of the field was found to be 89% of the central value.

Figure 11 shows the transverse ray fan plots. A special optimization operand corrected the longitudinal color. A fine tuning operand for lateral color was not needed; lateral color was made small by just minimizing polychromatic OPDs.

Figure 12 is the polychromatic spot diagram. Wavelengths within the waveband are equally weighted. Again the scale bar length is 24 μm. The circles indicate the diameter of the Airy diffraction disk for a wavelength of 0.54 μm.

Based on the object distances at which the calculated spots begin to go appreciably out-of-focus, depth of field is estimated to be at least 3 mm on each side of best focus. In practice, the usable field depth may be considerably greater. When in use on Mars, multiple images at various object distances will be taken of rough surfaces to ensure that all parts are imaged in good focus.

Figure 13 is the polychromatic MTF plot for wavelengths weighted according to the system response curve. The lens is diffraction limited at best focus, which is confirmed by Strehl ratios remaining above 82% across the field.

Listing 3 is the Micro-Imager optical prescription.

6. HAZCAMS

In the lower part of both ends of the rover, there are stereo pairs of hazard avoidance cameras (HazCams). One pair faces forward, and one pair faces rearward. The stereo separation is 100 mm. These cameras are part of the on-board autonomous navigation system; their purpose is to reveal dangerous objects in the path of the rover as it drives in either direction. The diagonal field of view of each camera is 180 degrees, a full hemisphere. For such an extremely wide field, conventional f-tanθ distortion correction is impossible. Thus, the HazCam lenses are full-frame fisheye lenses.

In a fisheye lens, the image geometry is of the f-θ type, that is, equal meridional angle increments in the object scene are mapped (ideally) as equal linear increments on the image plane. When looking at the whole scene, a fisheye lens unavoidably produces a great amount of barrel distortion. This distortion is actually just the consequence of projecting a hemisphere onto a plane. Of course, the projection function can be calibrated. But of more practical importance, small parts of the scene, even those near the field edge, are imaged quite accurately without needing a lot of subsequent image processing. For the HazCams, f-θ mapping will be very effective.

The usable field coverage of the HazCam lenses is 180 degrees across the diagonal of the square CCD format, and 124 degrees from side to side. The lens focal length is 5.58 mm in the center of the field. The HazCams operate at f/15, view objects whose distances range from infinity to 200 mm, and are fixed-focused at 400 mm. They are monochrome systems; as with the NavCams, a pair of absorption filters (Schott OG590 and KG5) working in series gives a reddish waveband extending from roughly 0.60 μm to 0.80 μm. With their internal location, absorption filters rather than quasi-reflective interference filters were selected to reduce stray light. The lens design is shown in the layout in Figure 14.

The fields and wavelengths for the HazCams were equally weighted during optimization, and the merit function minimized OPDs. When later evaluated, the departures from perfect f-θ mapping were found to be less than 3%. Image irradiance at the edge of the field was found to be 36% of the central value (off-axis pupil growth plus the large barrel distortion prevent it from going to zero).

Figure 15 shows the transverse ray fan plots. Primary longitudinal color has not been corrected, but it is small enough to not matter. Lateral color is virtually zero.

Figure 16 is the polychromatic spot diagram. Wavelengths within the waveband are equally weighted. The scale bar length is 36 μm, the size of a 3×3 matrix of pixels. The circles (which are radially stretched into ellipses off-axis) indicate the size of the Airy diffraction disk for a wavelength of 0.70 μm.

Figure 17 is the polychromatic MTF plot for wavelengths weighted according to the response curve. The substantial departures of the off-axis curves from the on-axis diffraction-limited curve are caused, not by aberrations, but by the elongation of the Airy disk. Strehl ratio is actually nearly flat across the field and remains above 87%. Thus, over the whole field of view, the HazCam lenses are diffraction limited at best focus. At other object distances between infinity and 200 mm, image quality is almost unchanged.

Listing 4 is the HazCam optical prescription.

7. SUNCAM

It is necessary that the absolute three-axes orientation of the rover be known to enable the high-gain radio antenna dish to be accurately pointed at Earth. The north heading must also be known while driving on the Martian surface. With no global magnetic field on Mars that can activate a compass, this information will be derived from the rover's location on the Martian surface, the time of day, the apparent angular direction of the Sun relative to the rover, and a vertical-direction sensor.

The direction of the Sun will be measured by a special camera called the SunCam. Originally, the SunCam was to be equipped with a classical fisheye lens that covered a full 180 degrees across the width (not diagonal) of the CCD. It was to be located on the deck of the rover out in the open pointing straight up. However, this idea was abandoned for three reasons. First, Mars is a dusty place. Even if there is no dust storm during the mission, dust would settle out of the atmosphere and soon partially cover the lens, thereby degrading performance. Second, the rover will flex as it moves, thereby introducing orientation differences between the deck and the antenna. And third, the SunCam requires a strong neutral density filter (ND ~6.5). For the fisheye lens, this filter must be built into the optics and would not be removable. Consequentially, such a tiny fraction of the light would be transmitted that laboratory calibration of the imaging properties of the lens would be difficult.

The solution to the first two problems was to move the SunCam and mount it instead up with the antenna dish. The two will be next to each other and point in the same direction. For much of the time, the dish and SunCam will be turned to point down and thus be protected from falling dust. However, shortly before a radio transmission, they will be turned together to point at the Sun to get a precise orientation measurement. This updated orientation will also be used to recalibrate the fiber-optics laser gyro in the inertial navigation system.

The solution to the third problem was to make the lens for the SunCam the same type as the lens for the NavCam, with one difference. The difference is that a third filter, the neutral density filter, will be included out front ahead of the two waveband filters. During calibration here on Earth, this neutral density filter can be removed. When in the center of the 45×45 degree field of view, the diameter of the Sun's image on the CCD will be 89 μm on Mars.

8. TOLERANCES

To properly model the lenses for the tolerance analyses, several dummy surfaces had to be added to each lens. In the computer, these extra constructional surfaces (with air on both sides) allow the lens elements to be tilted, decentered, and despaced in the most physically realistic way. However, they do complicate both the optical prescription and the merit function. To avoid possible confusion here, they have not been included in the prescription listings given on the following pages.

Fairly standard opto-mechanical fabrication tolerances were specified to the optical and machine shops. For surface power error, ±3 fringes, and for surface irregularity, ±0.5 fringes, are allowed (double-pass at the 0.5461 μm mercury green wavelength). Airspace thickness errors of ±0.025 mm and glass center-thickness errors of ±0.050 mm are allowed. Measured by total-indicator-runout (TIR), element tilt errors of 0.0127 mm and element wedge errors of 0.010 mm are allowed with any axial orientation. Element decentration errors of ±0.025 mm are allowed in any direction. Schott grade 3 optical glass was specified having refractive index held to ±0.0005 and reciprocal dispersion (Abbe number) held to ±0.5%.

Image quality was found to remain high with these tolerances, as calculated using the changes both in RMS wavefront error and in diffraction MTF at 30 cycles/mm.

9. GLASS DIFFICULTIES

Now a note from the real world. Originally, the flint glass type for all these lenses was chosen to be Schott SF4. But the optical shop suggested changing to the newer Schott SFL4 glass, which stained less. So the lenses were reoptimized for SFL4. Then they were fitted to test plates, the thicknesses were reoptimized again to correspond to the test plate radii, these lenses were toleranced, and finally the opto-mechanical design was begun. But when the glass was to be purchased, it had become SFL4A, a still newer glass similar to the now discontinued SFL4. (Incidentally, Schott says they will soon replace SFL4A by NSF4.)

It was noted that the nominal refractive index of SFL4A is nearly identical to that of SFL4 (n_d of 1.75520 for both glass types), and the Abbe number dispersions are different by only 0.19, or 0.70% (ν_d of 27.40 for SFL4A versus 27.21 for SFL4). This Abbe number departure is close to the ±0.5% error assumed during the tolerance runs (which predicted excellent as-built performance). Thus, to save time (the launch date cannot be postponed) and to save the work already done on the mechanical designs, the new glass was directly substituted in with no optical reoptimization.

However, for the purposes of this paper, it was felt that optimized designs should be given. Thus, the nominal, test-plate-fitted, SFL4 designs with reoptimized thicknesses have been presented and evaluated here. Nevertheless, these are not the versions actually built to go to Mars, although they are close. If you wish to model these lenses using the lens prescription listings, and if you wish to know what was *really* done, then replace all the SFL4 glass with SFL4A glass. You will see a difference, especially on the ray fan plots for the two Cooke triplets.

Of course, there will be numerous additional small fabrication errors that will cause the as-built lenses to again depart from their nominal designs. So substituting in SFL4A glass will still not exactly model the flight hardware. The important thing is that all these errors become small when the effects of diffraction are included. In any case, the actual lenses when fabricated should give excellent images on Mars.

ACKNOWLEDGMENTS

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FOR FURTHER READING

Gregory Hallock Smith, *Practical Computer-Aided Lens Design,* Willmann-Bell, Richmond, 1998.
Rudolf Kingslake, *A History of the Photographic Lens,* Academic Press, San Diego, 1989.

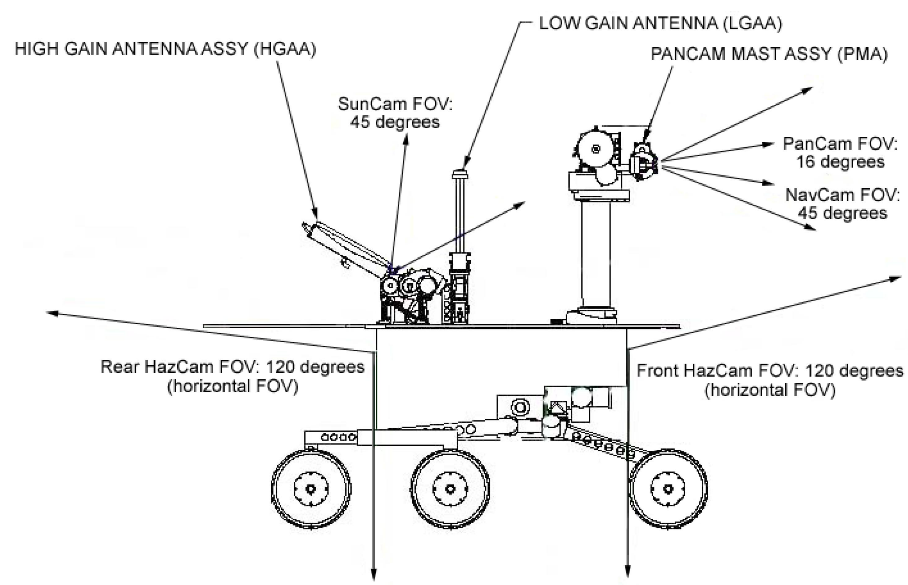


Figure 1. Schematic drawing of a rover

Figure 3

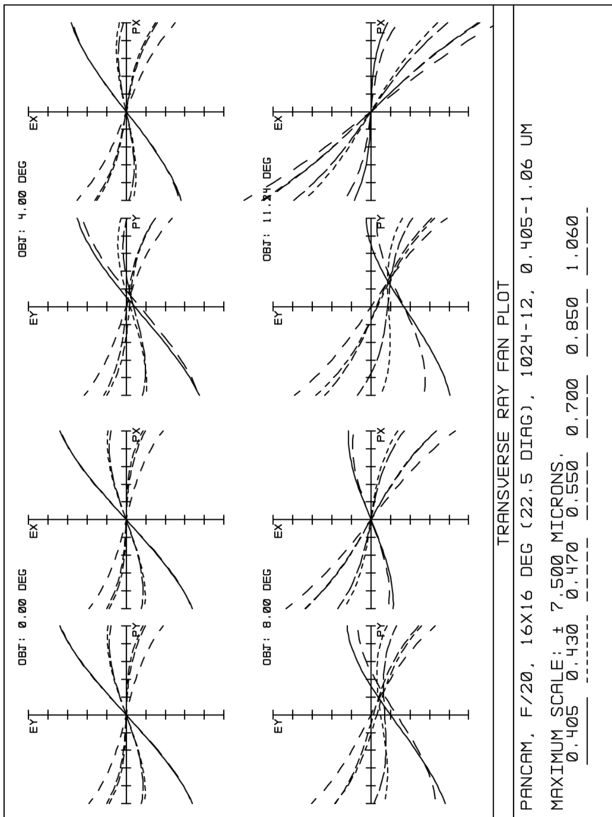
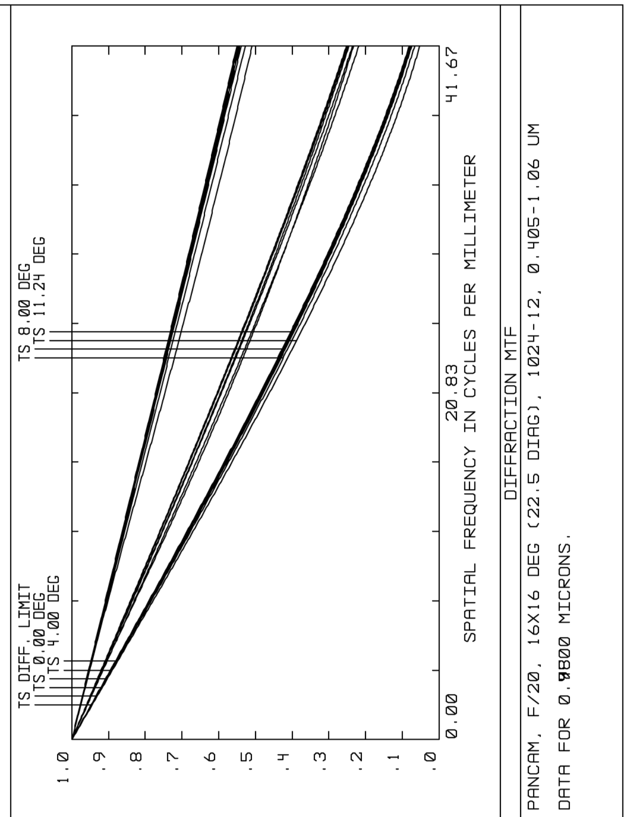


Figure 5



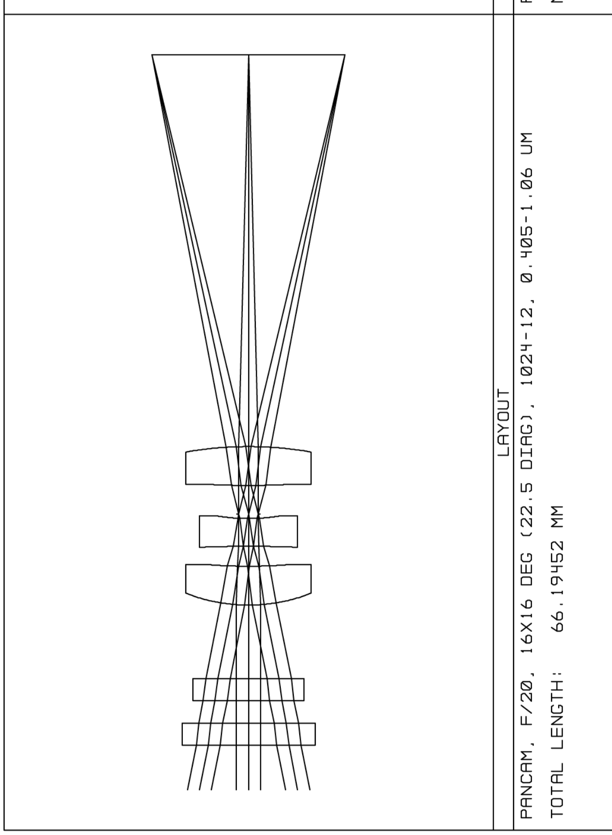


Figure 2

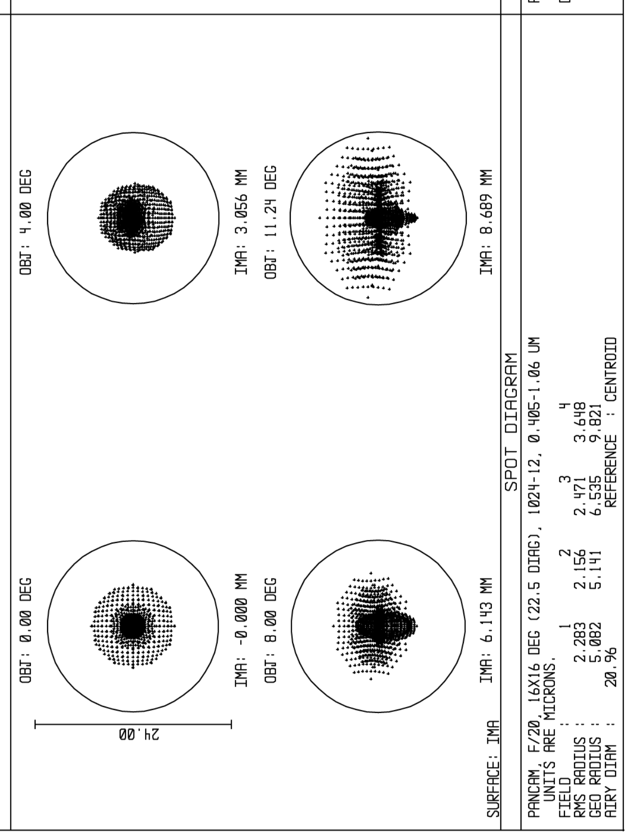


Figure 4

PANCAM, F/20, 16X16 DEG (22.5 DIAG), 1024-12, 0.405-1.06 UM

GENERAL LENS DATA:

Temperature (C)	23
Pressure (ATM)	0.95
Effective Focal Length	42.97357
Back Focal Length	34.6005
Paraxial Working F/#	20
Entrance Pupil Diameter	2.182744
Entrance Pupil Position	22.32985
Exit Pupil Diameter	2.022109
Exit Pupil Position	-40.49783
Reference Wavelength	0.55
Lens Units	Millimeters

Fields: Angle in degrees

#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.000000	4.000000	1.000000
3	0.000000	8.000000	1.000000
4	0.000000	11.24400	1.000000

Wavelengths: Microns

#	Value	Weight
1	0.405000	1.000000
2	0.430000	1.000000
3	0.470000	1.000000
4	0.550000	1.000000
5	0.700000	1.000000
6	0.850000	1.000000
7	1.060000	1.000000

SURFACE DATA SUMMARY:

Surface	Type	Radius	Thickness	Glass	Diameter
OBJECT	STANDARD	Infinity	3000		1201.7
1	STANDARD	Infinity	4		0
2	STANDARD	Infinity	2	SAPPHIRE	12
3	STANDARD	Infinity	2		12
4	STANDARD	Infinity	2	BAK2	10
5	STANDARD	Infinity	6.625		10
6	STANDARD	15.673	3.5	LAFN21	11.3
7	STANDARD	45.954	1.8		8
8	STANDARD	-109.408	2.5	SFL4	8.8
9	STANDARD	17.602	0.38454		6
STOP	STANDARD	Infinity	2.59767		1.743924
11	STANDARD	70.226	3.5	LAFN21	11.3
12	STANDARD	-32.864	35.28731		11.3
IMAGE	STANDARD	Infinity			17.39269

Listing 1. PanCam optical prescription

Figure 7

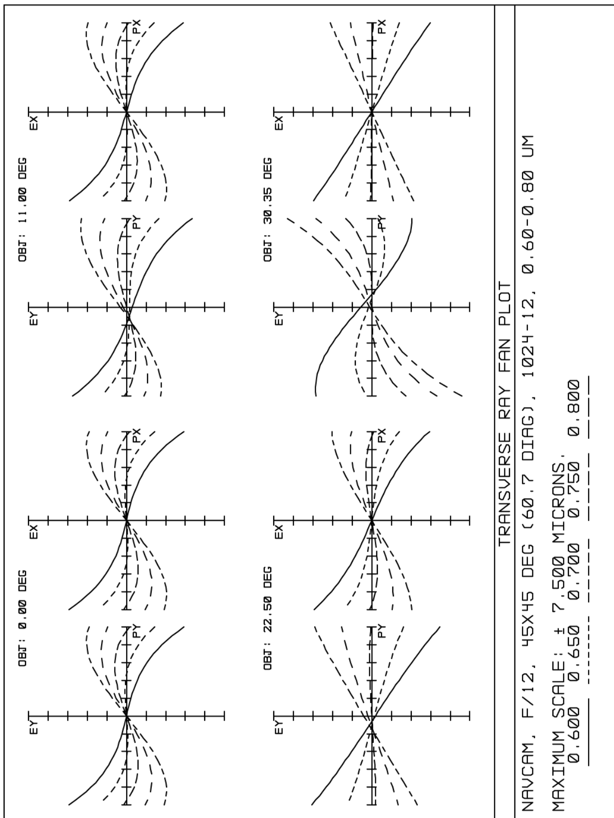
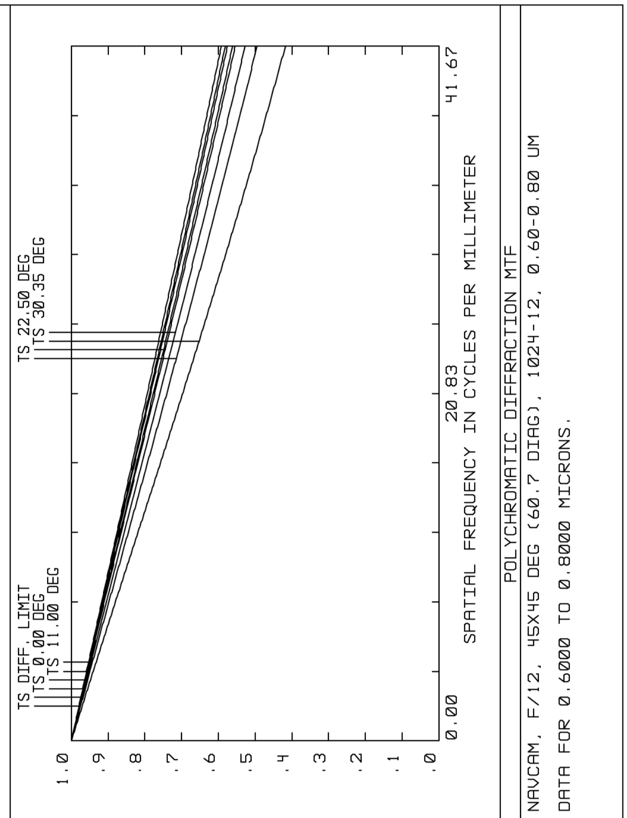


Figure 9



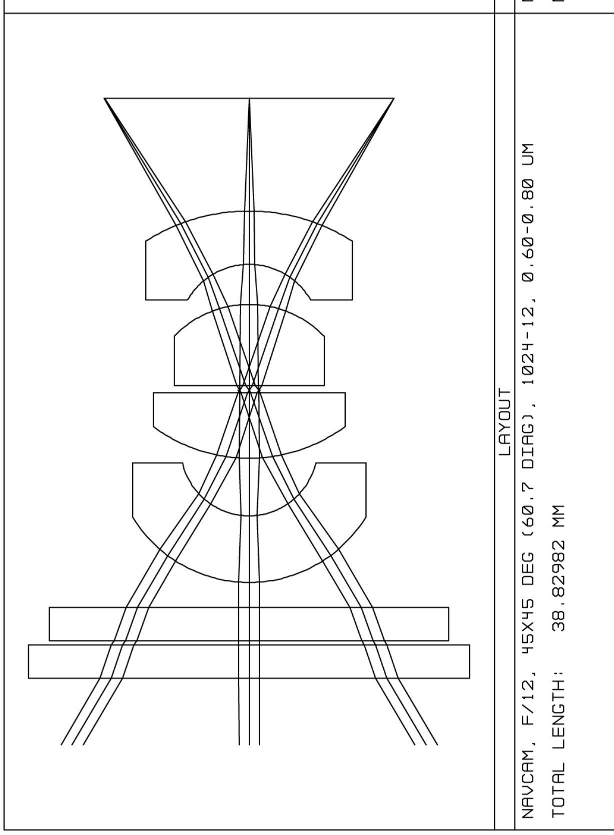


Figure 6

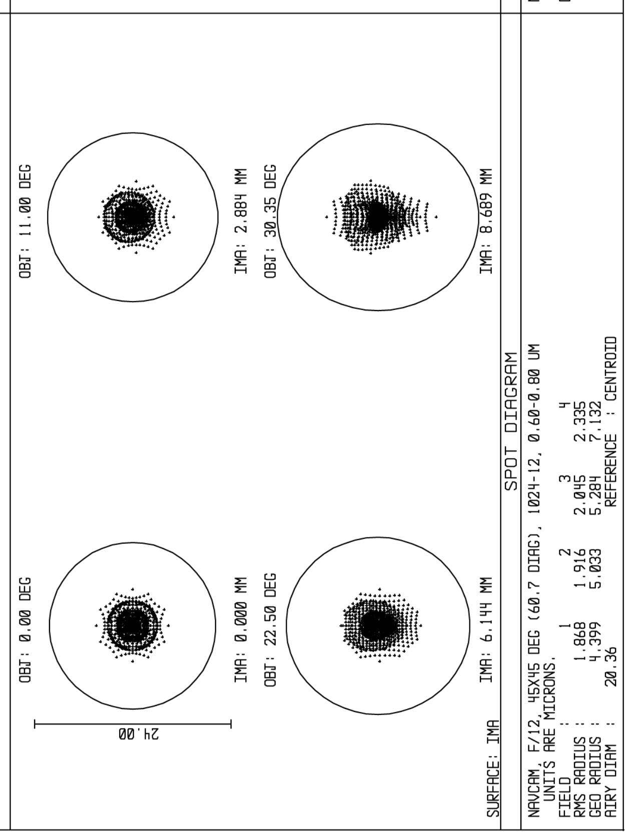


Figure 8

NAVCAM, F/12, 45X45 DEG (60.7 DIAG), 1024-12, 0.60-0.80 UM

GENERAL LENS DATA:

Temperature (C)	23
Pressure (ATM)	0.95
Effective Focal Length	14.67204
Back Focal Length	6.609621
Paraxial Working F/#	12
Entrance Pupil Diameter	1.244116
Entrance Pupil Position	18.38886
Exit Pupil Diameter	1.19291
Exit Pupil Position	-14.22556
Reference Wavelength	0.70
Lens Units	Millimeters

Fields: Angle in degrees

#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.000000	11.00000	1.000000
3	0.000000	22.50000	1.000000
4	0.000000	30.35000	1.000000

Wavelengths: Microns

#	Value	Weight
1	0.600000	0.270000
2	0.650000	0.250000
3	0.700000	0.160000
4	0.750000	0.060000
5	0.800000	0.020000

SURFACE DATA SUMMARY:

Surface	Type	Radius	Thickness	Glass	Diameter
OBJECT	STANDARD	Infinity	1000		1192.582
1	STANDARD	Infinity	4		0
2	STANDARD	Infinity	2	BAK2	26.5
3	STANDARD	Infinity	0.254		26.5
4	STANDARD	Infinity	2	K7	24
5	STANDARD	Infinity	1.5		24
6	STANDARD	8.211	4	SFL4	14
7	STANDARD	4.108	3.4601		8
8	STANDARD	9.674	3.95146	LAFN21	11.5
9	STANDARD	Infinity	0.127		11.5
STOP	STANDARD	Infinity	0.273		1.140495
11	STANDARD	Infinity	4.88702	LAFN21	9
12	STANDARD	-6.251	2.41023		9
13	STANDARD	-4.252	3.2	SFL4	7.4
14	STANDARD	-11.507	6.76701		12.4
IMAGE	STANDARD	Infinity			17.39096

Listing 2. NavCam optical prescription

Figure 11

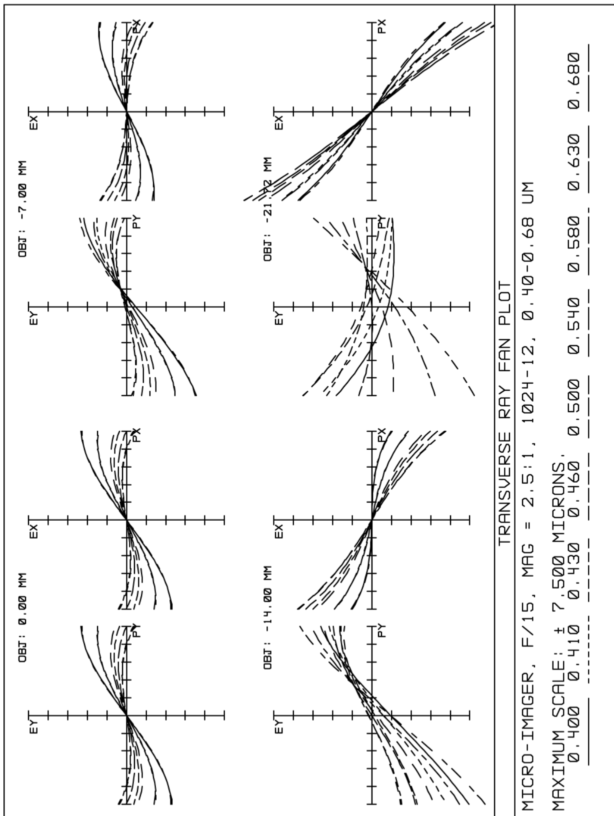
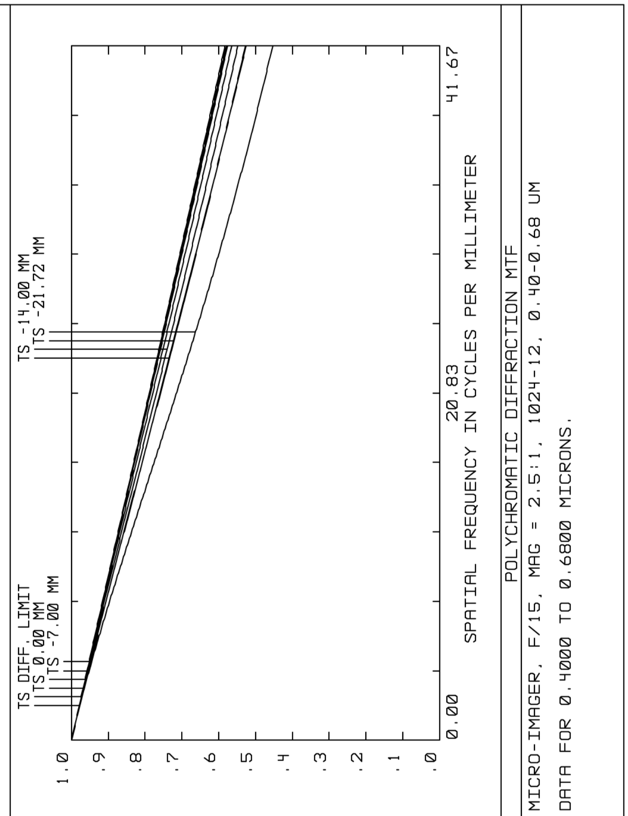


Figure 13



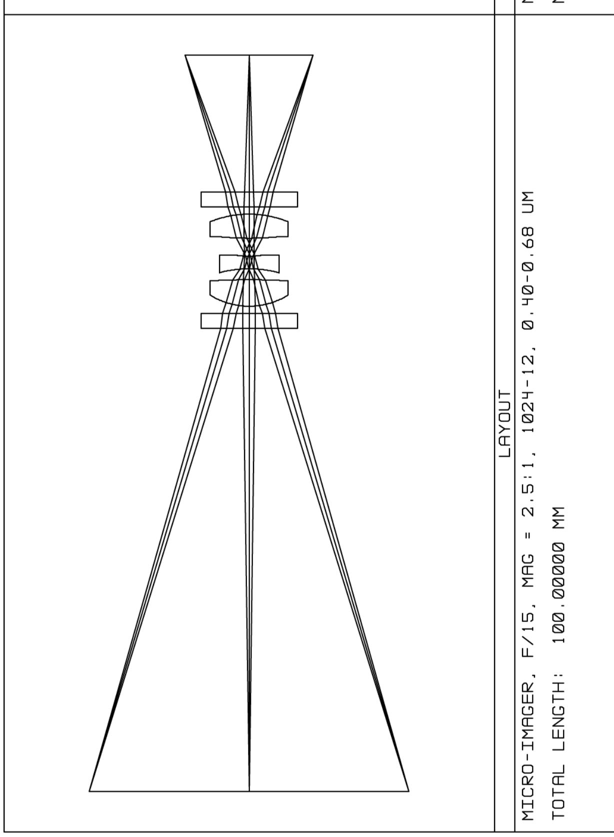


Figure 10

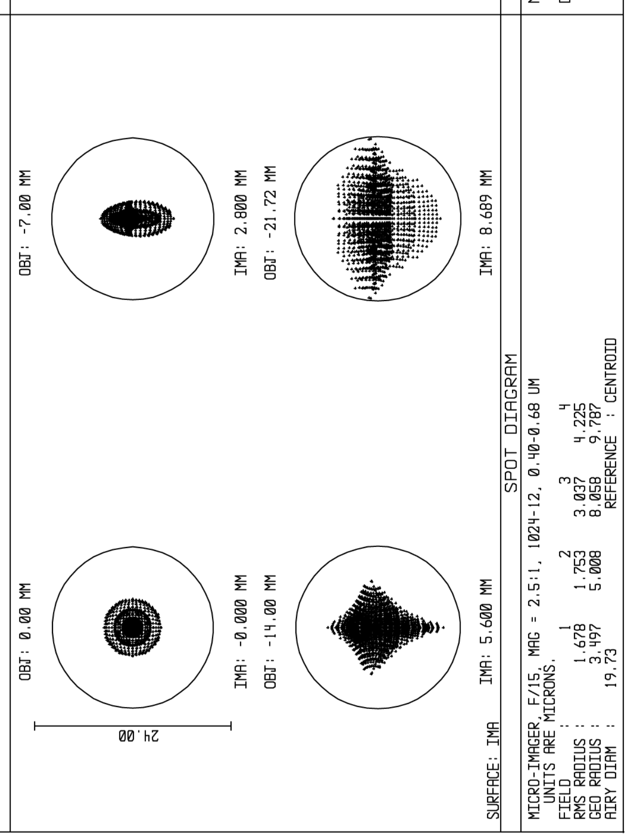


Figure 12

MICRO-IMAGER, F/15, MAG = 2.5:1, 1024-12, 0.40-0.68 UM

GENERAL LENS DATA:

Temperature (C)	23
Pressure (ATM)	0.95
Effective Focal Length	20.13672
Back Focal Length	10.55737
Total Track	100
Image Space F/#	10.36836
Paraxial Working F/#	15
Image Space NA	0.03333445
Object Space NA	0.01336515
Entrance Pupil Diameter	1.942131
Entrance Pupil Position	72.65004
Exit Pupil Diameter	1.745668
Exit Pupil Position	-26.12037
Reference Wavelength	0.54
Lens Units	Millimeters

Fields: Object height in Millimeters

#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.000000	-7.000000	1.000000
3	0.000000	-14.00000	1.000000
4	0.000000	-21.72230	1.000000

Wavelengths: Microns

#	Value	Weight
1	0.400000	0.030000
2	0.410000	0.040000
3	0.430000	0.070000
4	0.460000	0.130000
5	0.500000	0.200000
6	0.540000	0.270000
7	0.580000	0.270000
8	0.630000	0.130000
9	0.680000	0.020000

SURFACE DATA SUMMARY:

Surface	Type	Radius	Thickness	Glass	Diameter
OBJECT	STANDARD	Infinity	0		43.4446
1	STANDARD	Infinity	62.91163		43.4446
2	STANDARD	Infinity	2	SAPPHIRE	13.1
3	STANDARD	Infinity	1		13.1
4	STANDARD	10.127	3.60518	LAFN21	10.6
5	STANDARD	-86.017	1.47879		10.6
6	STANDARD	-15.881	1.7	SFL4	8.1
7	STANDARD	10.012	0.32879		4
STOP	STANDARD	Infinity	2.13542		1.291679
9	STANDARD	42.005	3.26217	LAFN21	10.6
10	STANDARD	-14.006	1		10.6
11	STANDARD	Infinity	2	BAK2	13.1
12	STANDARD	Infinity	18.57802		13.1
IMAGE	STANDARD	Infinity			17.38835

Listing 3. Micro-Imager optical prescription

Figure 15

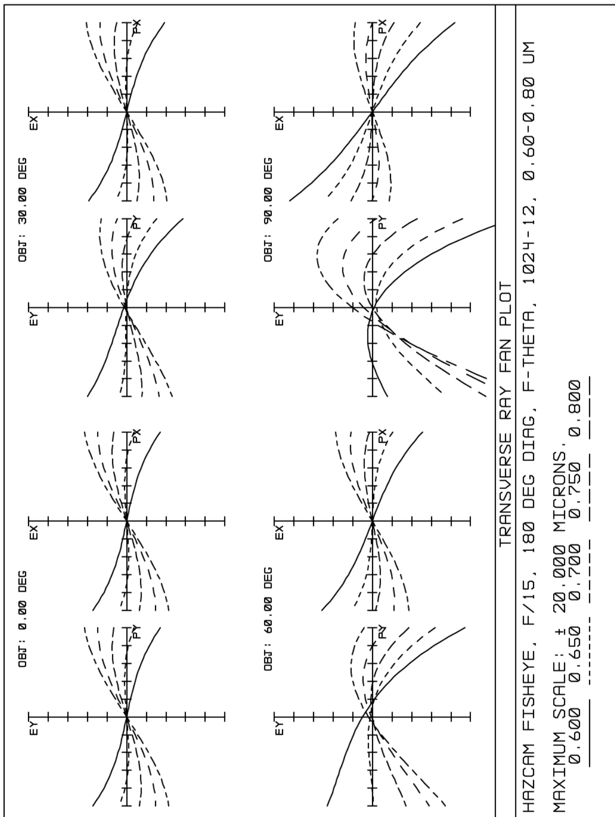
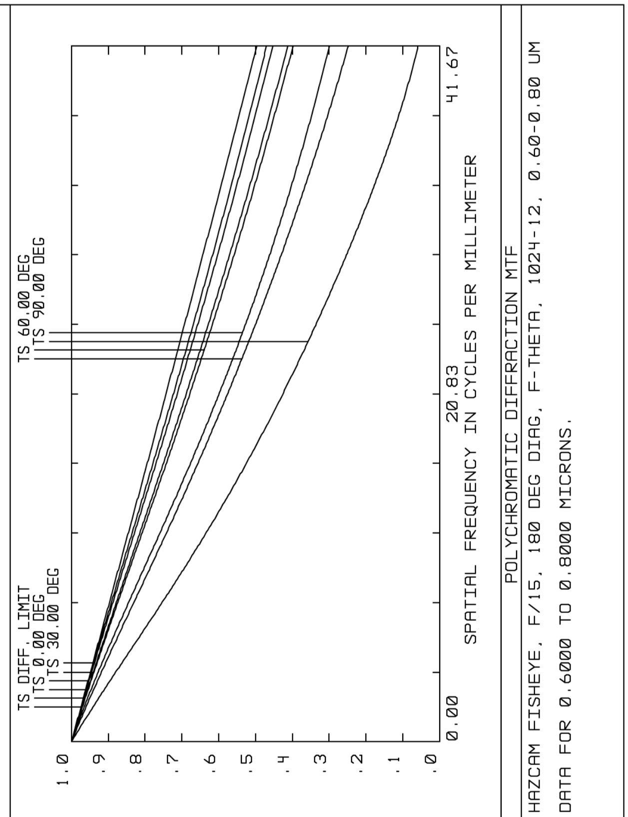


Figure 17



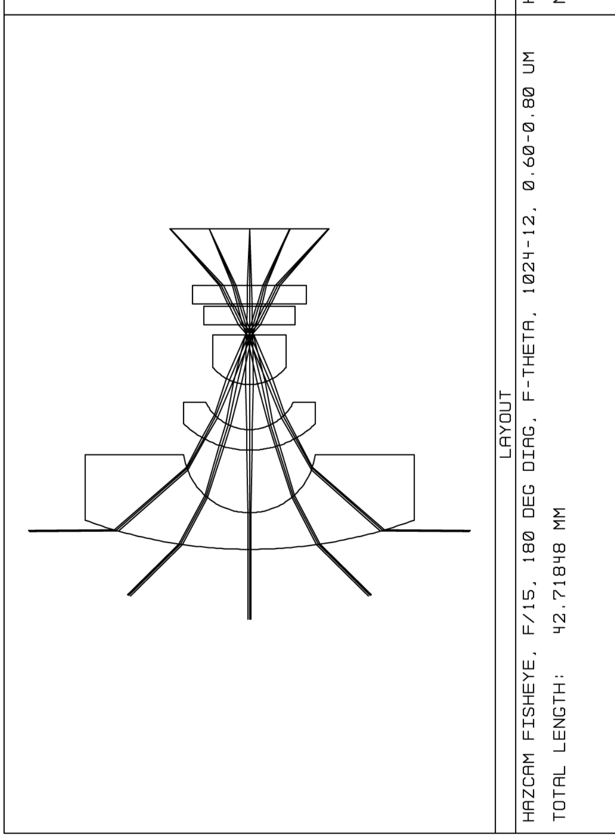


Figure 14

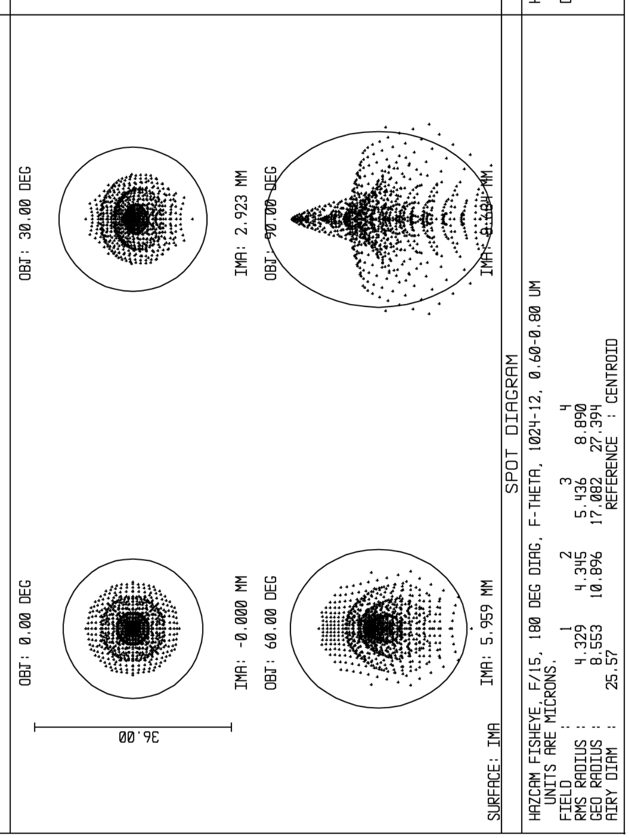


Figure 16

HAZCAM FISHEYE, F/15, 180 DEG DIAG, F-THETA, 1024-12, 0.60-0.80 UM

GENERAL LENS DATA:

Temperature (C)	23
Pressure (ATM)	0.95
Effective Focal Length	5.584007
Back Focal Length	6.309354
Image Space F/#	15
Entrance Pupil Diameter	0.3722671
Entrance Pupil Position	17.0834
Exit Pupil Diameter	0.6794979
Exit Pupil Position	-10.09887
Reference Wavelength	0.70
Lens Units	Millimeters

Fields: Angle in degrees

#	X-Value	Y-Value	Weight
1	0.000000	0.000000	1.000000
2	0.000000	30.00000	1.000000
3	0.000000	60.00000	1.000000
4	0.000000	90.00000	1.000000

Wavelengths: Microns

#	Value	Weight
1	0.600000	0.270000
2	0.650000	0.250000
3	0.700000	0.160000
4	0.750000	0.060000
5	0.800000	0.020000

SURFACE DATA SUMMARY:

Surface	Type	Radius	Thickness	Glass	Diameter
OBJECT	STANDARD	800	400		1391.299
1	STANDARD	35	7.65077		0
2	STANDARD	52.484	4	LAFN21	36
3	STANDARD	7.257	6.84923		14.4
4	STANDARD	10.437	2.25	BK7	14.4
5	STANDARD	5.339	4.93072		9.6
6	STANDARD	5.203	5.441	SFL4	8
7	STANDARD	Infinity	0.127		8
STOP	STANDARD	Infinity	1		0.6799867
9	STANDARD	Infinity	2	K7	10
10	STANDARD	Infinity	0.254		10
11	STANDARD	Infinity	2	BAK2	12.5
12	STANDARD	Infinity	6.21576		12.5
IMAGE	STANDARD	Infinity			17.39186

Listing 4. HazCam optical prescription