NOTCAM OPTICAL DESIGN

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1. **Introduction**

The optical design for the Nordic Telescope Infrared Camera requires to meet the specification defined by the following parameters (see Colin Aspin document: A proposal to design a 1-2.5 μm near -IR camera (NOTCAM) for the NOT):

- wavelength range: 1-2.5 μm .
- detector array: 1024×1024 Rockwell HgCdTe ,18.5 μm square pixel.
- imaging and spectroscopy capability.
- pixel scales and Fields of View:

  Wide-Field (LORES): 0.235"/pixel with a square fov of 3.93 arcmin.

  High-Resolution(HIRES):0.08"/pixel with a square fov of 1.37 armin.
- pupil imaging

2. **Optical concept**

The Nordic Telescope is a Ritchey-Chretien telescope with a 2.56m diameter primary mirror and a combined f/11 giving a plate scale at the telescope focal plane of 7.325"/mm. At the present the average overall image quality is 0.65" FWHM. A plan to improve the telescope to FWHM of 0.38" (Michael Andersen & Anton Norup Sorensen: "Image Quality at the Nordic Telescope") will mean that the instruments using this telescope will have to be of excellent image quality or at least diffraction limited in the K band (0.16"FWHM) or better.

A main feature in the optical design of an infrared camera is its cold aperture stop to reduce the background noise.The entrance pupil or entrance stop is the primary mirror and not the secondary mirror as any Infrared Telescope in which the secondary is undersized . The size of the cold stop is mainly defined by the size of filters used in a standard catalogue (OCLI for example) ,using 1" or 25mm diameter and placed in the optical train closed to the stop. This will minimise cost when a large number of filters has to be purchased (20 or more) and also allow us to work with relatively small optical elements for the camera lenses.

A common refractive collimator is designed to form an image of the primary mirror (cold stop) near the last element and produces a collimated beam where the filters are inserted. The total distance from the cold stop to the detector is fixed for the 3 imaging modes of operation.

The imaging mode consists of 2 separate lens systems which will be alternatively inserted in the collimated beam, keeping the total distance between the cold stop and the detector fixed and equal to 203.3 mm.

The pupil imaging mode will be obtained by inserting in the lens wheel a lens system but keeping as well the total distance cold stop-detector fixed. The cold stop is reimaged into the detector as well as the primary mirror ,allowing a very accurate tool for alignement and accurately defining the size and position of the primary mirror image relative to the cold stop.

For the spectroscopy mode a slit wheel is introduced at the f/11 focal plane and an accessory wheel with grisms is placed near the filter wheels.

A polarimetric mode is also possible using Wollaston prisms in the collimated beam.

The present design will concentrate on the collimator , the imaging modes and the pupil imaging.

3. The Wide -Field Camera .

It is an entirely refractive design and optimized as an integrated system with the telescope and a IR grade Fused Silica window.

It consists of a common collimator with the High-Resolution Camera and a Petzval lens system .

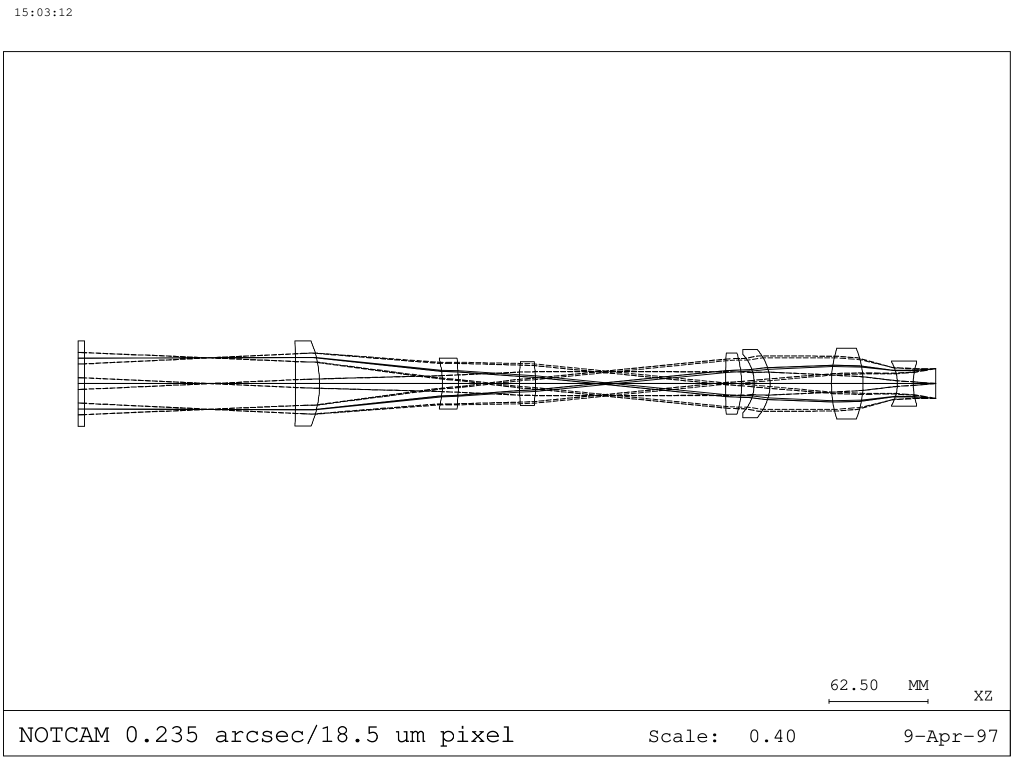
3.1 The Collimator:

- Refractive design using 3 lenses made of Baf2 and LiF.
- Focal length: 165 mm.
- Size and position of cold stop : 15 mm diameter at 50 mm from last lens surface.
- Achromatic design from 1-2.5 µm.

3.2 The Petzval camera lens:

- Refractive design using 4 lenses: a BaF2-LiF doublet , a BaF2 singlet and a LiF field lens.
- Focal length: 95.28mm
- F number: 6.35
- fov: ±5.7 degrees
- Entrance stop is the cold stop at 70mm from the first lens.

3.3 Optical Layout



The total length window-detector = 541.82 mm

3.4 Optical data:

3.4.1 Thermal expansion data at cryogenic temperatures :

$\Delta L/L$ is the contraction of the material from room temperature to 60K.

Optical material	$-\Delta L/L$
Baf2	0.0039
LiF	0.0050
Al-Alloy	0.0040

3.4.2 Indices of refraction at 60K

Wavelength (µm)	BaF2	LiF
1.0	1.471490	1.389700
1.1	1.470767	1.387747
1.175	1.470398	1.387412
1.250	1.470082	1.387182
1.325	1.469790	1.386872
1.40	1.469513	1.386455
2.0	1.467539	1.381247
2.2	1.466902	1.379158
2.5	1.465908	1.375709

3.4.3 Definition of OCLI filters I, J, H, K used in the optical design:

OCLI filters	I	J	H	K
λ(Blue) in µm	0.950	1.089	1.490	1.969
λ(central)	1.040	1.228	1.643	2.182
λ(red)	1.120	1.370	1.782	2.388

3.4.4 Lens parameters :

	Radius of curvature (mm) (60K)	Thickness (mm) (60K)	Material	Clear Aperture Diameter (mm)
pole primary mirror	plano	880.69		
Window	plano plano	4.00 78.78	IR grade Fused Silica	56.0 54.0
F/11 focal plane	plano	54.54	Air	47.0
Lens 1	-727.45 -70.25	15.00 77.45	BaF2	54.0 54.0
Lens 2	-64.49 -190.07	10.00 38.75	LiF	38.0 38.0
Lens 3	210.98 -116.67	10.00 50.00	BaF2	35.0 35.0
Cold Stop	plano	70.00	Air	15.0
Lens 4	544.27 -66.11	10.00 8.00	BaF2	43.0 43.0
Lens 5	-27.497 -32.612	10.00 38.66	LiF	43.0 48.0
Lens 6	73.795 -60.114	20.00 21.64	BaF2	47.0 47.0
Lens 7	-27.451 41.349	10.00 15.00	LiF	29.0 29.0
Detector	plano		Air	square: ±9.472 mm sides

The radii of curvature and thicknesses of the lenses in table 1 are given at 60K ,working temperature of Notcam. For the manufacturing and assembly , those parameters have to be replaced by warm parameters ,using the thermal expansion coefficients defined in 3.1.1, giving the following parameters in table 2:

Component	Radius of curvature (mm) warm	Thickness (mm) warm
pole primary mirror	plano	880.69
Window	plano	4.0
	plano	79.095
F/11 focal plane	plano	54.76
Lens 1	-730.29	15.06
	-70.52	77.76
Lens 2	-64.81	10.05
	-191.02	38.91
Lens 3	211.80	10.04
	-117.13	50.20
Cold stop	plano	70.28
Lens 4	546.39	10.04
	-66.368	8.03
Lens 5	-27.634	10.05
	-32.775	38.81
Lens 6	74.083	20.08
	-60.348	21.73
Lens 7	-27.588	10.05
	41.556	15.06

3.5 Image Quality

3.5.1 Encircled Energy Diameters (µm)

Each number in the tables represent the 50% , 80% and 100% eed for 9 positions in the detector array.

- Filter I : detector position : 14.22 mm
  plate scale: 0.237 "/ pixel

50% eed			80% eed			100% eed		
11	6	11	30	9	30	84	17	84
6	14	6	9	19	10	17	24	17
11	6	11	30	9	30	84	17	84

- Filter J : detector position: 14.46 mm
  plate scale: 0.236 "/ pixel

50% eed			80% eed			100% eed		
19	7	19	37	20	37	120	43	120
7	13	7	19	21	19	43	31	43
19	7	19	37	19	37	120	43	120

- Filter H : detector position: 14.82 mm
  plate scale: 0.235 "/ pixel

50% eed			80% eed			100% eed		
9	4	9	17	8	17	58	22	58
4	9	4	8	13	8	22	16	22
9	4	9	17	8	17	58	22	58

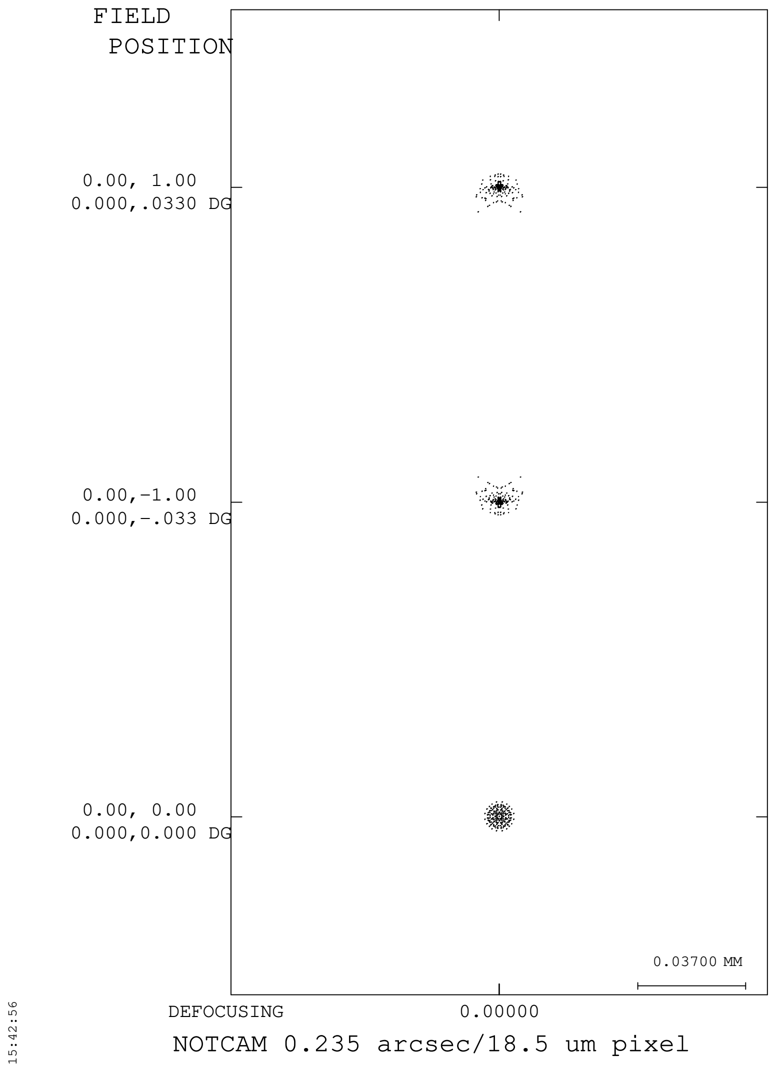
- Filter K : detector position: 15.00mm
  plate scale: 0.235"/ pixel

50% eed			80% eed			100% eed		
9	3	9	13	8	13	31	21	31
3	6	3	8	8	8	21	10	20
9	3	9	13	8	13	31	21	31

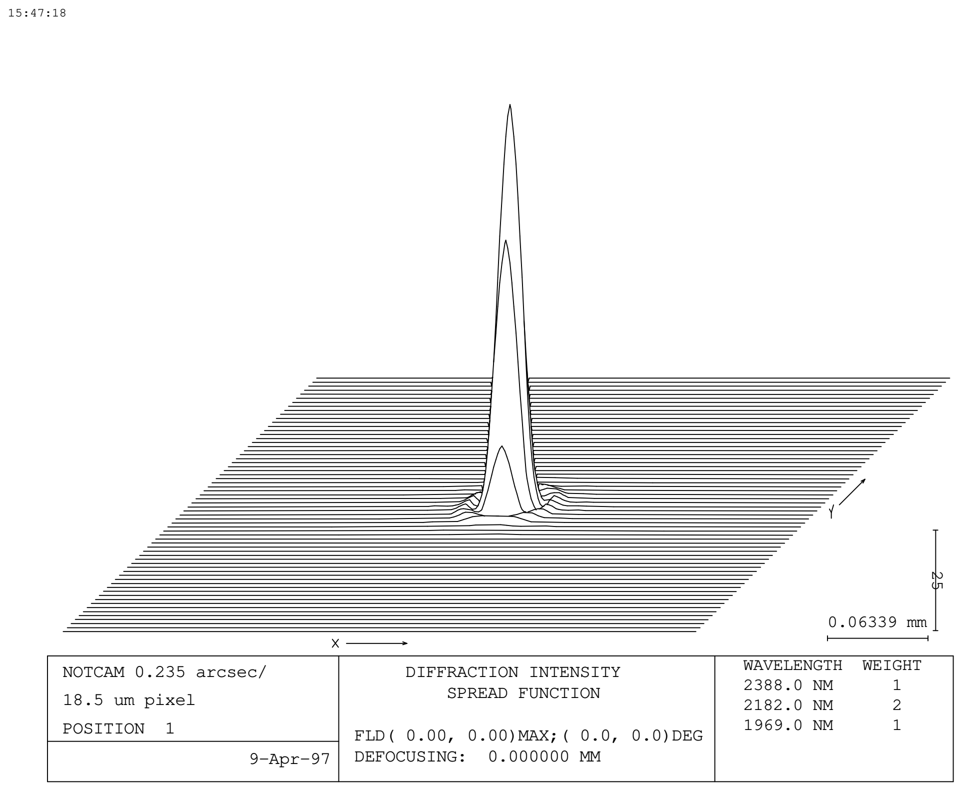
3.5.2 Strehl ratios :

K			H			I		
0.95	0.99	0.95	0.74	0.94	0.74	0.22	0.75	0.22
0.99	0.97	0.99	0.94	0.86	0.94	0.75	0.39	0.75
0.95	0.99	0.95	0.74	0.94	0.74	0.22	0.75	0.22

3.5.3 Spot diagram for K:



3.5.4 PSF

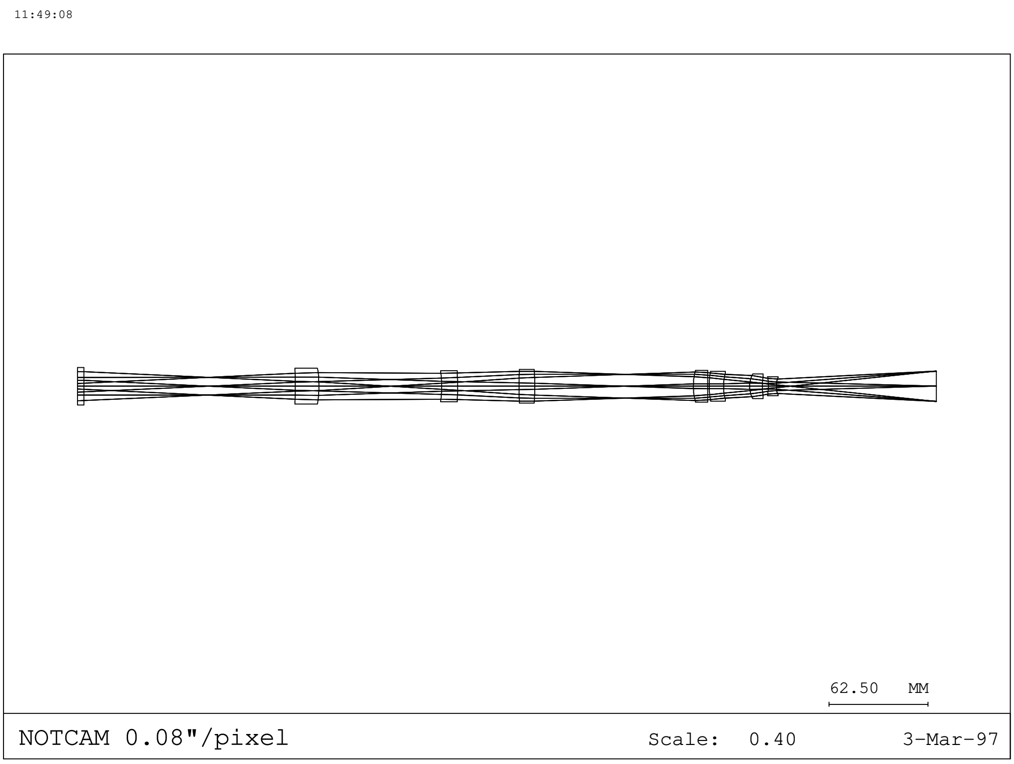

15:47:18
Y
25
0.06339 mm
X
NOTCAM 0.235 arcsec/
18.5 um pixel
POSITION 1
9-Apr-97
DIFFRACTION INTENSITY
SPREAD FUNCTION
FLD(0.00, 0.00)MAX;(0.0, 0.0)DEG
DEFOCUSING: 0.000000 MM
WAVELENGTH WEIGHT
2388.0 NM 1
2182.0 NM 2
1969.0 NM 1

4. High Resolution Camera

It shares the same collimator optics as for the wide-field camera but the lenses in front of the detector are replaced by a new set of 4 lenses: a BaF2-LiF doublet and 2 BaF2 singlets .

- Focal length: 279.5 mm
- F number: 18.63
- FOV: ± 1.94 degrees
- Cold stop at 50 mm from the first lens

4.1 Optical Layout



4.2 Optical Data

	Radius of curvature (mm) (60K)	Thickness (mm) (60K)	Material	Clear Aperture Diameter (mm)
pole primary mirror	plano	880.69		
Window	plano plano	4.00 78.78	IR grade Fused Silica	56.0 54.0
F/11 focal plane	plano	54.54	Air	47.0
Lens 1	-727.45 -70.25	15.00 77.45	BaF2	54.0 54.0
Lens 2	-64.49 -190.07	10.00 38.75	LiF	38.0 38.0
Lens 3	210.98 -116.67	10.00 50.00	BaF2	35.0 35.0
Cold Stop	plano	50.00	Air	15.0
Lens 4	36.87 526.61	9.00 1.00	BaF2	24.0 24.0
Lens 5	51.98 31.61	9.00 16.48	LiF	23.0 23.0
Lens 6	16.46 35.68	8.00 3.86	BaF2	20.0 20.0
Lens 7	-33.33 14.896	5.00 100.87	BaF2	15.0 15.0
Detector	plano		Air	square: ±9.472 mm sides

The radii of curvature ,thicknesses and separations of the lenses in table 3 are given at 60K . In order to get those parameters for manufacturing and assembly at room temperature, we use the thermal expansion coefficients defined in 3.3.1.

Component	Radius of curvature (mm) warm	Thickness (mm) warm
Window	plano plano	4.0 79.095
F/11 focal plane	plano	54.76
Lens 1	-730.28 -70.52	15.06 77.76
Lens 2	-64.81 -191.02	10.05 38.91
Lens 3	211.80 -117.126	10.04 50.20
Cold stop	plano	50.20
Lens 4	37.02 528.66	9.04 1.00
Lens 5	52.24 31.76	9.045 16.54
Lens 6	16.52 35.81	8.03 3.87
Lens 7	-33.46 14.95	5.02 101.27
Detector	plano	

4.3 Image Quality

4.3.1 Encircled Energy Diameters (µm)

Each number in the tables represent the 50% ,80% and 100% eed for 9 positions in the detector array.

- Filter I : detector position : 95.21 mm
  pfov : 0.0837 "/ pixel

50% eed	80% eed	100% eed
18 13 18	27 21 27	40 34 40
13 10 13	21 23 21	34 31 34
18 13 18	27 21 27	40 34 40

- Filter J : detector position : 96.87 mm
  pfov: 0.0824 "/ pixel

50% eed	80% eed	100% eed
22 18 22	50 50 50	83 85 83
18 17 18	49 50 49	87 74 87
22 18 22	50 50 50	83 87 83

- Filter H : detector position : 99.53 mm
  pfov : 0.0808 " / pixel

50% eed	80%eed	100% eed
19 14 19	27 22 27	45 48 45
14 12 14	22 21 21	48 38 48
19 15 19	27 22 27	45 48 45

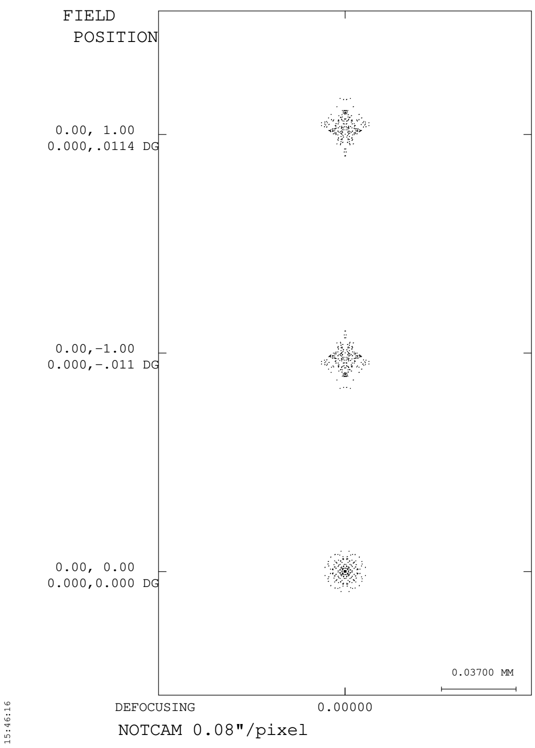
- Filter K : detector position : 100.87 mm
  pfov : 0.0800 " / pixel

50% eed	80% eed	100% eed
17 13 17	22 20 22	39 38 39
18 27 18	33 27 33	38 29 38
24 18 24	41 33 41	39 38 39

4.3.2 Strehl ratios :

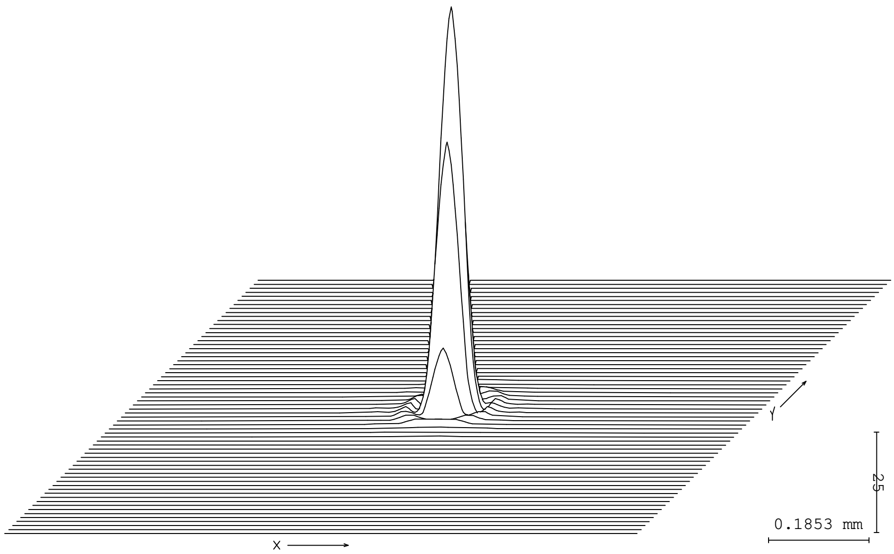
K			H			I		
0.97	0.99	0.97	0.94	0.96	0.94	0.84	0.92	0.84
0.97	1.0	0.99	0.96	0.98	0.96	0.92	0.96	0.92
0.97	0.99	0.97	0.94	0.96	0.94	0.84	0.92	0.84

4.3.3 Spot Diagram for K



4.3.4 PSF

15:50:18

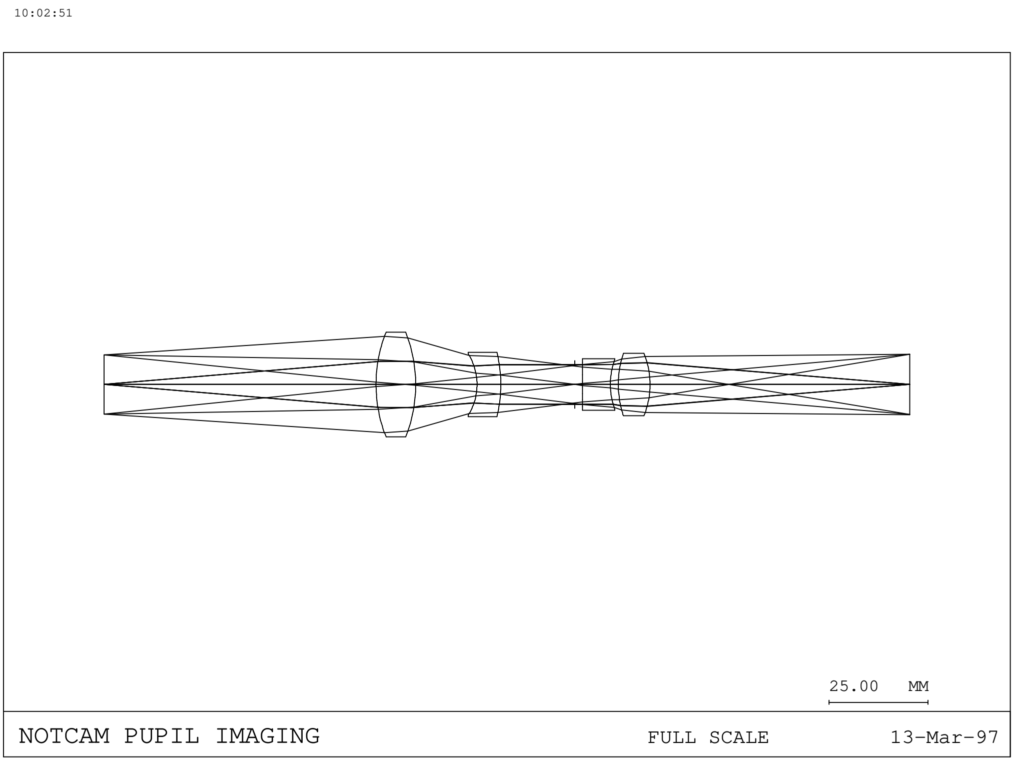


NOTCAM 0.08"/pixel	DIFFRACTION INTENSITY SPREAD FUNCTION	WAVELENGTH WEIGHT
		2388.0 NM 1
		2182.0 NM 2
POSITION 1	FLD(0.00, 0.00)MAX;(0.0, 0.0)DEG	1969.0 NM 1
3-Mar-97	DEFOCUSING: 0.000000 MM	

5. **Pupil Imaging Lens**

This lens reimages the cold stop to the detector array. It's in fact a 1:1 relay optical system. It consists of 4 lenses inserted between the cold stop and the detector .

5.1 Optical Layout



5.2 Optical Data

	Radius of Curvature (mm) at 60K	Thickness (mm) at 60K	Material	Clear Aperture Diameter (mm)
Cold Stop	plano	68.63		15.0
Lens 1	35.834 -35.912	10.00 15.47	BaF2	30.0 30.0
Lens 2	-14.818 -33.634	6.00 18.655	LiF	20.0 20.0
Stop	plano	2.00		10.0
Lens 3	-282.787 18.025	7.00 2.00	BaF2	15.0 15.0
Lens 4	24.864 -21.158	8.00 65.54	BaF2	20.0 20.0

5.3 Image Quality

The main purpose of this lens is to align the instrument relative to the telescope and particularly to align the physical cold stop inside the camera to the image of the telescope pupil. Each point in the cold stop is reimaged in the detector and the encircled energies in microns across the array are expressed in the following table for the K filter:

50% eed (µm)			80% eed (µm)			100% eed (µm)		
	15			24			51	
15	7	15	24	11	24	51	14	51
	15			24			51	

6. **Throughput:**

6.1 Basic Data for the system throughput calculation:

- Non-coated BaF2 lens transmission: 93.5 % average for all the filters.
- Coated BaF2 with AR coatings on both sides: 98 %.
- Non-coated LiF lens: 95%.
- Non-coated IR fused silica window: 94%
- Coated IR fused silica window: 96%
- Filters : 95%
- Detector: 90%

6.2 Total Transmission (%) including Filters and Detector:

	non-coated	coated
Wide-Field Camera	53	65
High-Resolution Camera	52	67
Pupil Imaging	52	67