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Wide-field multispectral imaging system with COTS lenses

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Abstract

Described here is a case-study of a wide-field imaging objective for MWIR bandwidth, fully designed with COTS and optical cage components. Thermal and mechanical tolerancing analysis is included, as well as full system prescription and component list. Simple custom components designed to relax mechanical tolerances are proposed and detailed with CAD drawings.

Contents

1 Introduction

Components Off The Shelves (or COTS) are optical components pre-manufactured and quickly available in small numbers. They are ideal for quick experiments, proof-of-concepts and prototyping. Multiple focal lengths and surface shapes are available for both refractive and reflective components, with coating options that cover most used spectral bandwidths. Uncoated versions are often available.

Due to being pre-manufctured, COTS lack the finer capabilities of custom components and are designed with severe limitations, such as set conjugates, limited spectral bandwidths, apertures and glass materials, and are rarely designed for wider fields of view. Generally, any system can be designed with COTS components, if either field of view, spectral bandwidth or resolution requirements can be relaxed.

In the following sections, a wide-field, multispectral imaging application is designed with COTS components, showing that the limitations of COTS components can be mediated with generic optical design practices and the optimization processes of professional design software. Below is described a diffraction-limited imaging system that surpasses the specifications of the individual components by compensating each others limitations. An optomechanical housing structure was designed using optical cage system parts, also available from the same distributors as the optical COTS components. Prescription, component list and dated prices are found in appendices.

System performance was evaluated using provided error tolerances for both optics and optical cage components, and harsh environment properties were considered.

2 Initial system specifications

A four component MWIR objective was designed using available COTS components. Aim of the design was an imaging system, wide field and well corrected for spherical and chromatic aberrations through the whole bandwidth range and field of view.

System focal length is f = 6.2 mm, and with a system aperture of ⌀4.8 mm, working F-number is F/# = 2.56.

2.1 Layout

The design uses common components for a wide-field imaging object: Element 1 up front is a large-aperture negative power lens, designed to collect light from a wide angle and reduce the angle of incidence of their chief rays. Elements 2 and 3 insert little positive optical power to avoid chromatic aberration, while the bulk of the optical power is carried by element 4 due to it's higher index of refraction.

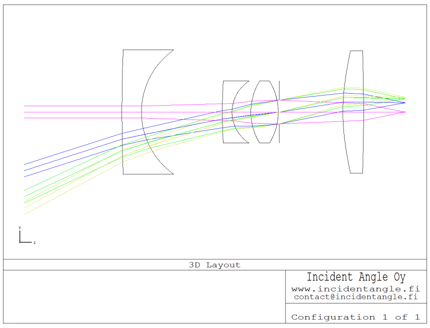


Figure 1: Wide-field MWIR objective made from COTS lenses.

System aperture stop is placed in such manner that the angles of incidence on the sensor are as small as possible to avoid decrease of sensitivity due to the cosine response of the sensor.

2.2 Diffraction effects and resolution

As a very fast objective, only the lower-order aberrations could be compensated, as shown in figure 2. Spot size are well comparable to the Airy disk, which is quite large in the MWIR spectral range.

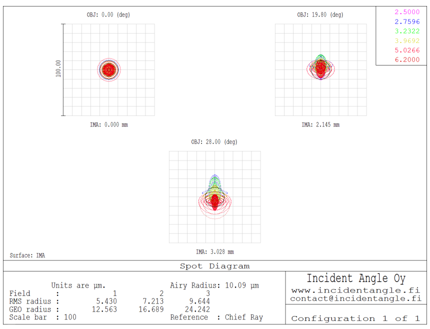


Figure 2: Geometric and RMS spot sizes at 0R, 0.71R and 1R.

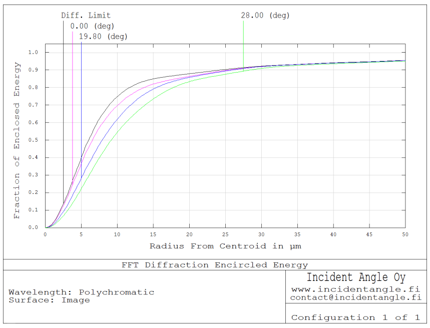


Figure 3: Diffraction encircled energy.

Geometric spot size ignores the effects of diffraction, which are displayed in figure 3. System resolution capablilities are shown by the modulation transfer fucntion curve in figure 4.

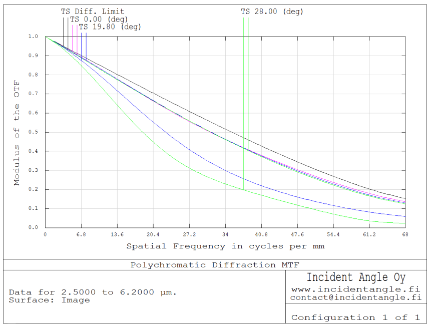


Figure 4: Modulation transfer function demonstrates the resolution capabilities.

2.3 Field of view response

Field of view is effectively controlled by the diameter of the first meniscus element and location of the system aperture stop. Considering allowances for the mechanical structures, widest angle with no vignetting is $FFOV = 56°$. This assumption ignores some persistent surface quality issues that COTS components might manifest in the outer half of the surface area.

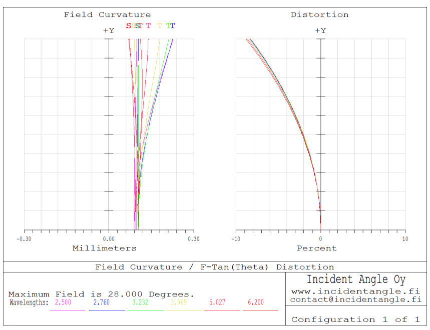


Figure 5: Flat field curvature. Distortion is comparable to other wide-field applications.

Field curvature shows a flat image field, but due to aberration compensations, the image plane deviates from the plane of the smallest RMS spot size (positioned at the +Y axis in left side of figure 5).

Pillow distortion is less than 10% and like with any machine vision application, easily enough corrected in image post-processing.

2.4 Chromatic aberration withing the bandwidth

The index of refraction typically decreases as the wavelength increases as a downwards sloping curve. At the selected range of 2.6$\leq\lambda\leq$6.0 µm the drop isn't as pronounced as i.e. in the visual range, making colour correction much easier. The Airy disk also affects the aberrations by growing to quite manageable size, obscuring most aberrations inside the diffraction limit. The system displays apochromatic colour correction within the bandwidth range, as can be seen in figure 6.

2.4.1 V-number

Abbe number generally describes the chromatic dispersion of an optical glass, but the definition only applies in the visual range. For the MWIR range, V-numbers must be calculated for the desired range and reference points using the Abbe formula

$$V = \frac{n_{center} - 1}{n_{short} - n_{long}}, \tag{1}$$

where the n_{center} is set at 4 µm, n_{short} at 2.6 µm and n_{long} at 6.0 µm.

The indices of refraction for reference points can be calculated from the Sellmeier equations

$$n^2(\lambda) = 1 + \frac{0.69913\lambda^2}{\lambda^2 - 0.09374} + \frac{0.11994\lambda^2}{\lambda^2 - 21.18} + \frac{4.35181\lambda^2}{\lambda^2 - 0.85417} \tag{2}$$

for the CaF2 glass, and

$$n^2(\lambda) = 1 + \frac{0.80687\lambda^2}{\lambda^2 - 0.71816} + \frac{0.74799\lambda^2}{\lambda^2 - 0.85417}, \tag{3}$$

for the germanium glass.

The difference in number of terms in the Sellmeier equations stem from the wider and more complex dispersion behaviour of the CaF2 glass.

By inserting values from equations 2 and 3 into 1, we get

$$V_{CaF2} = \frac{1.4058 - 1}{1.4196 - 1.4017} = 22.67 \tag{4}$$

and

$$V_{Ge} = \frac{4.0170 - 1}{4.0535 - 4.0103} = 69.84 \quad (5)$$

With a V-number difference of 47.17, the glass pair CaF2/Ge is found more than suitable for compensating chromatic aberrations in the MWIR range.

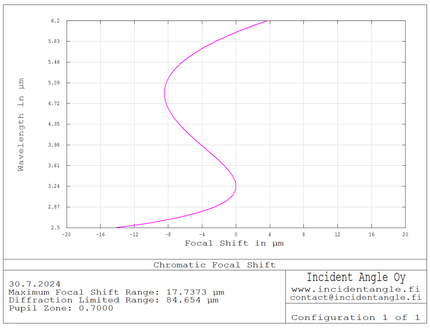


Figure 6: Chromatic focal shift between 2.6≤λ≤6.0 µm wavelength band. A focal shift range of 9µm contains focal points for three wavelengths, making the system apochromatic.

The selected MWIR bandwidth contains several key emission lines for PAHs, hydrogen and carbon monoxide, to mention a few.

2.5 Thermal evaluations

Optical system has an ambient design temperature and pressure setting in the design software. Regardless of application, these settings are often set to standart temperature and pressure for prototype testing purposes. In different thermal conditions, the thermal expansion coefficients would cause the dimensions and surfaces to vary, affecting the focal distance, aberration control etc. of an optical system. A thermal analysis will re-analyze the performance at selected temperatures, and when necessary, also enables re-optimization for handling the thermal effects.

Thermal analysis of the MWIR objective, with it's aluminium optical cage structures, proved very resilient to temperature changes between -40°C≤T≤55°C, a temperature range often experienced by MLI-insulated satellite instruments. Affecting mainly the longer wavelengths, the RMS spot radius within the inner half area (71% pupil radius) expanded beyond the diffraction-limited radius only at the low end of the temperature range.

Having very similar thermal coefficients, the aluminium structure compensated the distortions in the CaF2 lens material well enough. With a thermal coefficient of roughly fourth of that of aluminium, the deformations in the germanium lens weren't properly compensated, adding spherical aberration to the final image. With an introduction of a focal shift of 60 µm, the spherical aberration could be corrected. A custom-built piezoelectric refocusing mechanism could prove beneficial to the design.

3 Optomechanical housing

The optomechanical structures of the objective utilizes mainly optical cage system parts, available from the same sources as the COTS components. A few simple custom components were designed in order to improve the mounting options. System aperture was also a customized. If not used, similar function can be achieved with COTS retaining rings.

Custom components are all rotationally symmetric, designed mainly CNC machining in mind, because recommended material is aluminium for the thermal expansion control. 3D-printing is not recommended for the temperature range in question due to the glass transition effects in plastics.

3.1 Optical Cage systems

Optical cage systems provided ample mounting and housing options for the 25.4/25 mm as well as 12.7/12.5 mm optics. Construction material is aluminium, which has a thermal expansion coefficient close to that of CaF2. Connection method was SM1[1] and SM05[2] threading. These components have an error tolerance of ±0.1 mm, which was used for the tolerance analysis, compounded where applicable.

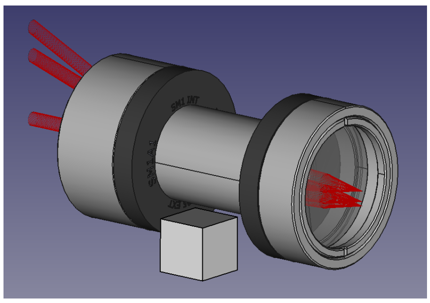


Figure 7: CAD image of the optomechanical setup, with a 10x10x10 mm cube as a size reference.

[1]SM1: (1.035"-40)
[2]SM05: (0.535"-40)

3.2 Custom components for auto-centering

For auto-centering concave optical surfaces to mechanical apertures, a custom method was used. A convex surface is automatically centered to a mechanical aperture slightly smaller in diameter than the surface being centered, but an concave surface requires an additional component to create a biconvex surface between the aperture and concave surface. Examples of such components, suitably designed O-rings, are shown in figure 8 and in appendix C.1.

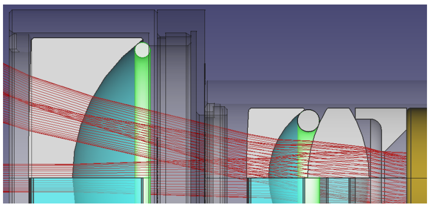


Figure 8: Section cuts of customized O-rings (in green) placed against a concave surface and the aperture of a mount, and another connecting and centering back concave surface of a negative lens to the front convex surface of positive lens.

Figure 8 and appendix C.2 shows the section cut of a customized system aperture stop element, which incorporates an optic spacing and auto-centering functions in a simple axially rotational element. An adjustable COTS iris would also be sufficient, but available models lacked proper dimensions for accurate placement.

3.3 Tolerancing analysis

A standard sensitivity analysis was re-run once the optomechanical layout was concluded. The manufacturers tolerance limits for the optical and optomechanical components were introduced, with cumulative error values applied where pertinent. Layout was considered stacked with spacers, with a compensating dimension at the back focus.

The auto-centering effect of the O-ring was introduced to the tolerancing, as well as the similar effect from threading. Figure 9 displays the overlapped polychromatic RMS spot radii vs field as a result of over 3000 Monte Carlo simulations utilizing a normal distribution within a span of five standard deviations.

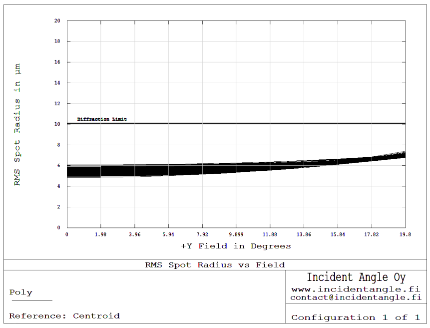


Figure 9: Superimposed polychromatic RMS radii within manufacturers error tolerance limits.

4 Conclusion

Described here is a wide-field apochromatic imaging objective for the MWIR bandwidth range designed with components off the shelf. Optical analysis shows that the image quality is stable throughout the full field of view between temperature range $-40°$C≤T≤$55°$C with the designed mechanical mounting.

Tolerance analysis showed that the housing structure can be constructed with optical cage systems, enabling fast prototyping and testing. Some custom components were designed to ease tolerancing sensitivities and to assist in centering the optical components inside the COTS tubes, but they were not critical in nature.

5 Discussion

Operating temperature range is suitable for an MLI-insulated orbital instrument, but associated ruggedizations and their effects on housing structure were not explored.

A System prescription

```
GENERAL LENS DATA:
Surfaces                    :                  11
Stop                        :                   8
System Aperture             : Float By Stop Size = 2.4
Glass Catalogs              : INFRARED
Ray Aiming                  : Real Reference, Cache On
X Pupil Shift               :                  0
Y Pupil Shift               :                  0
Z Pupil Shift               :                  0
X Pupil Compress            :                  0
Y Pupil Compress            :                  0
Apodization                 : Uniform, factor =   0.00000E+000
Temperature (C)             :    2.00000E+001
Pressure (ATM)              :    1.00000E+000
Adjust Index Data To Environment  : Off
Effective Focal Length  :        6.211536 (in air at system temperature and pressure)
Effective Focal Length  :        6.211536 (in image space)
Back Focal Length       :        8.688503
Total Track             :        78.01307
Image Space F/#         :        2.540383
Paraxial Working F/#    :        2.540383
Working F/#             :        2.558867
Image Space NA          :       0.1931158
Object Space NA         :    1.222559e-010
Stop Radius             :             2.4
Paraxial Image Height   :        3.302732
Paraxial Magnification  :               0
Entrance Pupil Diameter :        2.445118
Entrance Pupil Position :        37.86213
Exit Pupil Diameter     :        51.19373
Exit Pupil Position     :         130.155
Field Type              : Angle in degrees
Maximum Radial Field    :              28
Primary Wavelength      :        3.232166 µm
Lens Units              :   Millimeters
Angular Magnification   :     -0.04776208
```

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Diameter	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
1	STANDARD	Infinity	20		45.6	0	
2	STANDARD	308.3	4	CAF2	25.4	0	LF5469
3	STANDARD	15.5	16.532		25.4	0	
4	STANDARD	95.6	2	CAF2	12.7	0	LF5067
5	STANDARD	7.5	3.848		12.7	0	
6	STANDARD	12.1	5.6	CAF2	12.7	0	LB5766-E1
7	STANDARD	-12.1	0.215		12.7	0	
STO	STANDARD	Infinity	13.013		4.8	0	
9	BINARY_2	41.851	4.22	GERMANIUM	25	0	68259
10	STANDARD	-440.2	8.585		25	0	
IMA	STANDARD	Infinity			6.088	0	

B Optical cage components

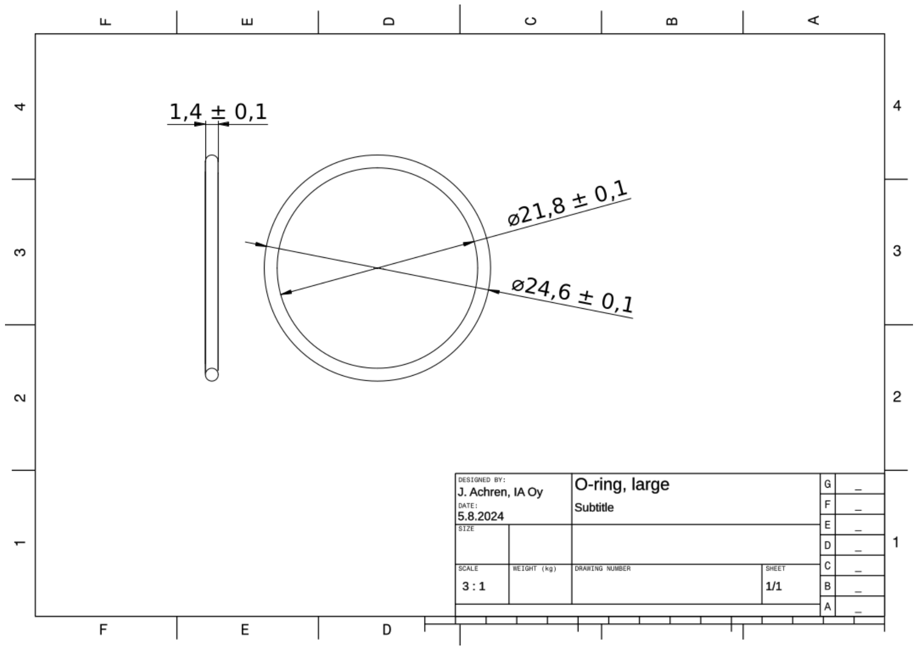
Product numbers and unit prices are collected from Thorlabs and Edmund Optics online catalogues on 31.7.2024. Incident Angle or the author in not responsible for any changes in naming, pricing, availability or otherwise during or since the collection date. Below list does not contain the custom components.

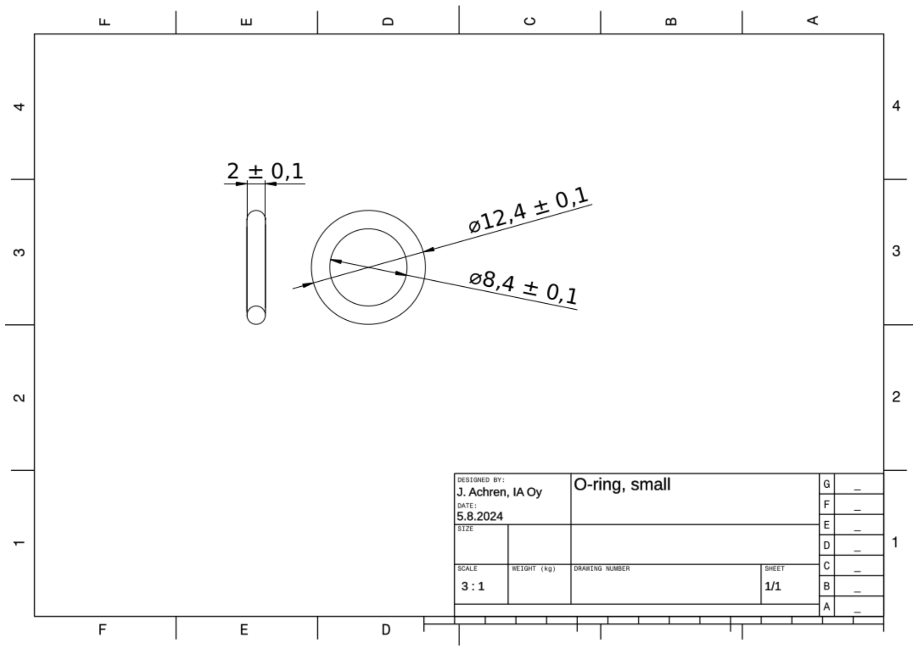
Component name	Product number	Unit price
SM1 lens tube	SM1L10	€14,01
Negative CaF2 meniscus lens	LF5469-E	€385,50
Thread adapter	SM1A1	€21,28 (x2)
SM05 lens tube	SM05M10	€17,13
Negative CaF2 meniscus lens	LF5067-E	€308,82
Bi-convex lens	LB5766-E1	€204,08
Optic spacer	SM05S5M	€7,73
SM1 lens tube	SM1L03	€11,95
Hybrid aspheric germanium lens	68-259	€1150,00
	Total cost	€2141,78

http://www.thorlabs.com
http://www.edmundoptics.eu

C Custom components

C.1 O-rings





C.2 System aperture stop structure