# Refractive IR Objective Optical Design Operating in LWIR band For Military Observation Applications

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Abstract: IR objective is a very essential component of infrared imaging system that plays an important role in the performance of overall system. In this paper, a design of objective operating in (8-12μm) spectral band is done using ZEMAX software. The refractive design is chosen since reflective one provides smaller FOV. In order to get high resolution we picked up a detector with pixel pitch of 25 μm with a high MTFA value of .6 at spatial frequency resolution boundary (Nyquist frequency) of 20 cycle/millimeter, in order to cover wide FOV this detector pixel pitch and small focal length value provides so. This high resolution and wide FOV make this design suitable for the observation applications.

Keywords: Infrared imaging system , Objective design , Thermal IR Materials ,Long wavelength infrared (LWIR) , Average modulation transfer function (MTFA) , Nyquist frequency, RMS spot radius.

## 1-INTRODUCTION

The use of infrared cameras is common in all fields ofindustry. Applications such as non-destructive testing,monitoring and security in public places such asairports has made infrared cameras one of the mostpopular instruments in these fields **[1]**.

Thermal imagers are imaging systems that generate images of the observed scenery using thermal radiation emitted by the scenery In **.**TIS from images of the observed field of view (FOV) by detecting scene radiated thermal energy from objects overcomes their reflected energy since the reflected energy is low to be detected over this wavelength portion**[2]**.

Objects of typical earth temperatures emit radiation mostly in the spectral region from about 3 μm to about 15 μm. Thermal radiation emitted by these objects dominate over the radiation reflected by them at this spectral range because the radiation emitted by sun, moon, stars and typical artificial sources is weak for wavelengths over 3 µm. There are two „atmospheric windows" in the above mentioned range: the 3-5-µm window and the 8-12-µm window. Therefore there are two main types of thermal imaging systems: the middle-wave MW systems using the 3-5-µm win-dow and the long-wave LW systems using the 8-12-µm window and rarely available commercially SW systems of spectral band located within 1-3-µm range**[3].**

The optical system has no reflective surface and formed from IR transparent elements.Germanium is a versatile infrared material commonly used in imaging systems, but in the mid infrared region, large dispersion of the germanium causes high chromatic aberration **[4].**

IR objective job is gathering most thermal radiation from target and background and delivers it to the detector. Getting High image performance from IR objective affects directly to overall IR imaging system characteristics **[5].**

Compact high resolution wide field of view IR objective in (8-12 µm) spectral band for different observation applications was introduced as a reference in this paper **[6].**

There are alot of studies and researches worked on IR objectives and their structures, specifications and analysis.

In **[1-5],** researches are worked on thermal objective design but in the mid wave band 3-5µm.In **[6]**, we increased the resolution with became better also a wider field was introduced by this paper. In (4), study worked on dual optical bands system in mid and long bands, but it is notices that this design has small FOV.

So this paper provides high resolution wide FOV operation in 8-12 µm spectral band for different military observation applications.

## II. DESIGN THEORY

This design is expected to have high performance optically and compactness mechanically. So from optics point of view high resolution is achieved with MTFA equal to .6 and RMS spot radius centered at the pixel pitch of the detector. From mechanics point of view it should have small dimension and weight as much as possible in order to lower the cost of manufacturing and production.

For our objective detector model (U6010) may be used. This detector dimension is 640*480 pixel, with pixel dimension 25 µm. using detector dimensions and required specifications for our objective such as focal length, characteristics of used materials some calculations were done to get the total FOV and the radius of curvature value for each surface in our objective design. According to these calculations and requirements design parameters such as F/#. Entrance Pupil Diameter and spectral band, ZEMAX software optimization were done by adding some restricted operands and freedom degrees to realize the limitations in our design process**[6].**

Table 1 show our objective required specifications and detector characteristics used in design calculations.

TABLE1. REQUIRED SPECIFIFCATIONS AND USED DETECTOR FOR OUR IR OBJECTIOVE

| | |
|---|---|
| Spectral wave band | 8-12µm |
| Effective focal length (EFFL) | 35 mm |
| Entrance Pupil Diameter | 25mm |
| F/# | 1.4 |
| Detector type | 640*480 uncooled VOxMicrobolometer |
| Detector model | U6010 |
| Pixel pitch | 25 µm |

## III-DESIGN CALCULATIONS

In this section design calculations containing the field of view (FOV) with start point calculations are shown.

### 1-Field of view :

For the calculations of FOV using the selected detector dimensions and focal length of the objective the Horizontal, Vertical dimension of the detector (HD),(VD) are calculated successively from equations (1) and (2). And the Horizontal, Vertical field of view (HFOV),(VFOV) of the camera are calculated from equations (3) and (4) respectively.

$$\text{HD=number of horizontal pixels * pixel pitch} \qquad (1)$$

$$\text{VD= number of vertical pixels * pixel pitch} \qquad (2)$$

$$\text{HFOV}=2\tan^{-1}\left(\frac{\text{HD}}{2*EFFL}\right)$$

$$\text{VFOV}=2\tan^{-1}\left(\frac{\text{VD}}{2*EFFL}\right)$$

Then HD, VD , HFOV and VFOV are about 16mm, 12mm, $26^{\circ}$, $20^{\circ}$respectively. According to these results, our IR objective design is analyzed at three fields of view on axis FOV, .5FOV=$8^{\circ}$ , Full FOV=$16^{\circ}$.

2. Start design calculations :

We used the Cooke triplet to design the refracting telescope as shown in fig1.

The Cooke Triplet is the first and simplest design form that is capable of correcting all the first- and third-order aberrations over a medium field-of-view. The Cooke Triplet consists of three elements. The two elements on the outside are positive crowns and the middle element is a negative flint as shown in fig2. The aperture stop is located either in front of the middle element or behind it.

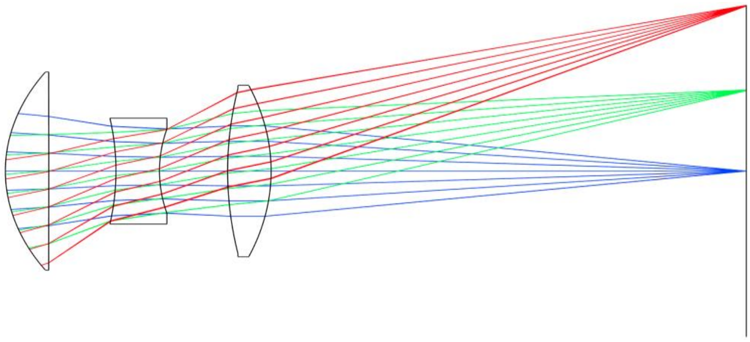

Fig1.The Cooke Triplet design

In this post I will walk through the procedure for designing a Cooke Triplet from scratch using first-order thin lens calculations, then optimizing it with real thicknesses in ZEMAX **[7].**

- **System Specs:**

1-Focal length of (EFFL) = 35mm

2-Entrance pupil diameter which is found to be (d)= 25 mm

Glass: GERMANIUM (nd=4.0032, V=1501.6) and KRS5 glass (nd=2.37069, V=165.14).

Field angles: $0^{\circ}$, $8^{\circ}$,$16^{\circ}$.

Wavelengths: (8µm), (10µm), and (12µm) wavelengths.

Paraxial F/#: 1.4

**The Starting Point :**

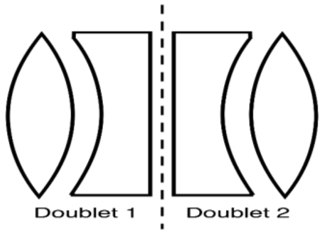

fig2.IR objective layout design

The starting point of the first-order design is to imagine the Cooke Triplet as a pair of air spaced achromatic doublets.
The second achromatic doublet (Doublet 2) has exactly the same radii of curvatures as the first except with opposite signs.
The Gaussian reduction equation for total power of two elements is:
$\phi_E=\phi_1+\phi_2-\phi_1\phi_2 t$

If we approximate the airspace as zero $t\approx0$ and assume Doublet 1 & 2 have the same focal length, then each doublet has half the power of the total system power:
$\phi_E=\phi_1+\phi_2$ such that $\phi_1=\phi_2$

Thus the power of each air spaced achromatic doublet is:
$\phi_1=\phi_2=0.01428$ mm−1

Now we need to solve for the powers of the positive and negative elements of one achromatic doublet. Again assume no air gap.
Using the Gaussian reduction equation again, the power of the positive lens plus the power of the negative lens is the power of the doublet:
$\phi_{11}+\phi_{12}=0.01428$ mm−1

Since we have two equations and two unknowns we can solve for the power of the positive and negative element:
$\phi_{11}=.016$ mm−1
$\phi_{12}=-0.00176$ mm−1

We can use the thin lens equations to solve for the radii of each element in the achromatic doublet:
$(N_{d2}-1)(C_3-C_4)=\phi_{12}$
$(N_{d1}-1)(C_1-C_2)=\phi_{11}$

For an achromatic doublet the following formula must hold to put the F and C wavelengths at the same focus:
$\phi_{11}V_1+\phi_{12}V_2=0$
Since the fourth surface is flat:
$C_4=0$
Assume the second and third have the same radii of curvature:
$C_2=C_3$
Which produces
$C_1=0.0040493$ mm−1 and $R_1=246.954$ mm
$C_2=-0.001284$ mm−1 and $R_2=-778.801$ mm
$C_3=-0.001284$ mm−1 and $R_3=-778.801$ mm
$C_4=0.0$ mm−1 and $R_4=\infty$ mm

The second achromatic doublet will have the same radii with opposite signs.

$C_5$=0.0 mm−1 and $R_1$=∞mm
$C_6$=0.001284 mm−1 and $R_2$=778.801 mm
$C_7$=0.001284 mm−1 and $R_3$=778.801 mm
$C_8$=0.0040493 mm−1 and $R_4$= -246.954 mm

We input these into ZEMAX without any airspaces, which collapses into five surfaces.

## 3-Optimization:

For our IR objective we used the start point mentioned before and by making right constraints and operands in the default merit function we reach our goal of high wide FOV relying on different figures of merit such as RMS spot diagram and MTF plot.

## IV-Construction and Layout

We will present the construction of our design with used materials and also the layout on ZEMAX software.

### 1. Objective construction:

Our IR objective consists of two external positive elements which are made of GERMANIUM . The center element is negative KRS5.

This objective consists of three elements ( six spherical surfaces )

with small pupil diameter=25mm and short length 92.4mm.

### 2. Objective Layout:

We present the layout at three FOV selected for this design (on axis FOV, .5 FOV , full FOV) is shown in figure.3. The objective shaded model layout displaying the used material for each lens in our objective design is represented in Fig.4.

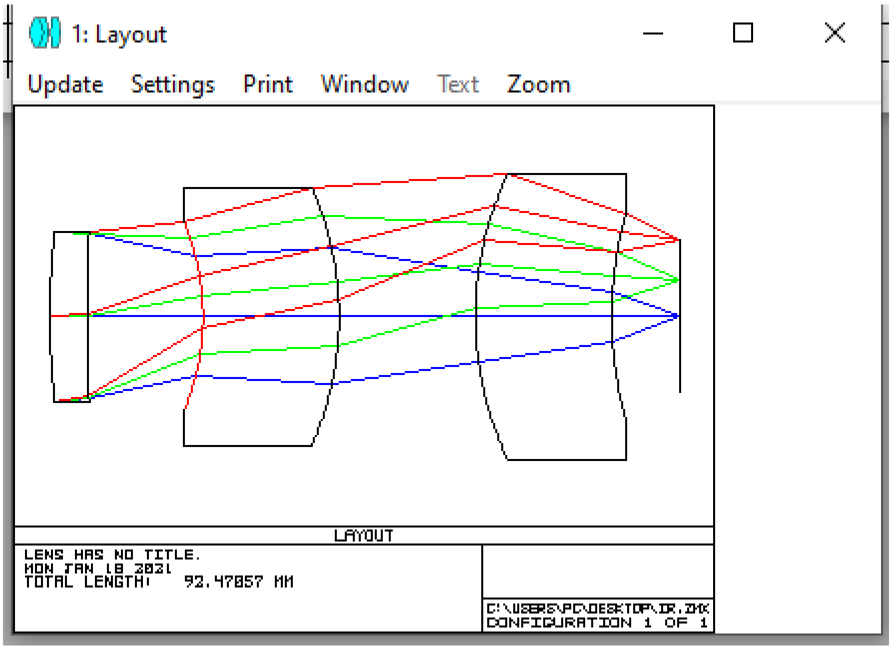


Fig.3. The schematic results of our IR objective design

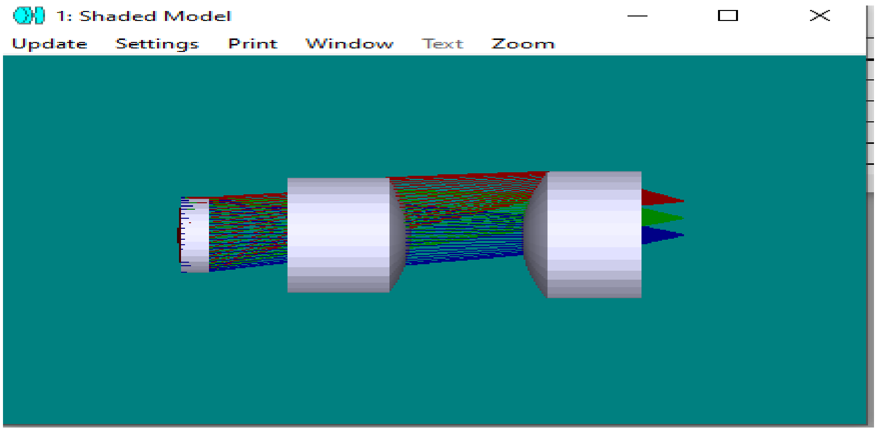


Fig.4. Shaded model layout with used materials for each lens

## V. Results and Performance

### 1. Spot diagram:

Our simulation shows the RMS spot diagram which is clearly concentrated at the airy diameter which equals to approximately the pixel pitch of the used detector.

Fig.4. show the spot diagram for (on axis FOV , .5 FOV ,total FOV) concentrated on Airy diameter which also lies within the dimension of detector pixel.

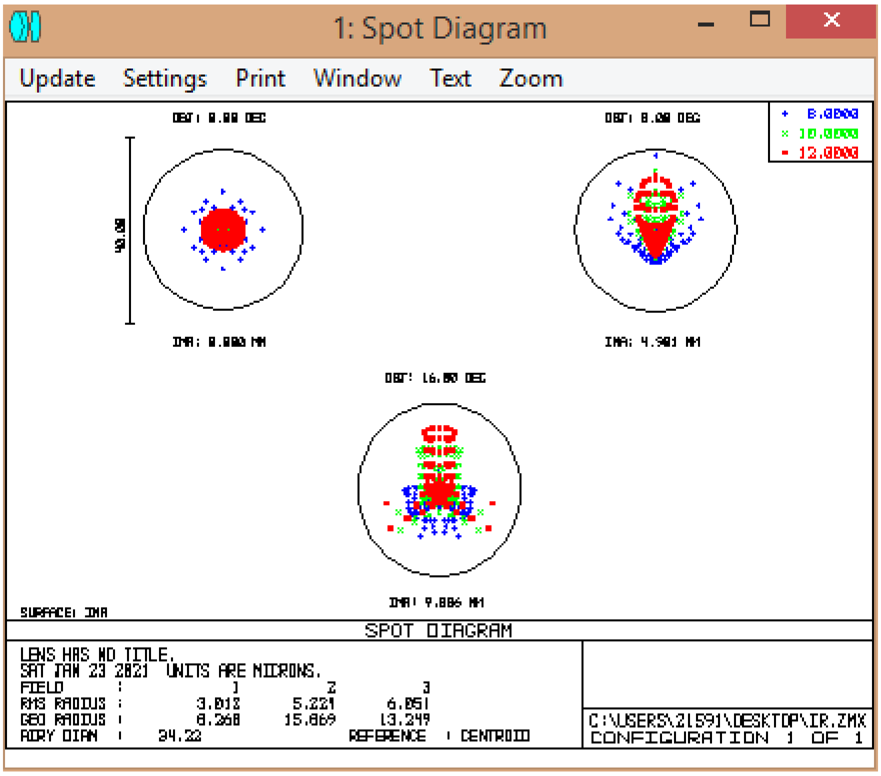


Fig.4. spot diagram for our IR objective design at focal length of 35mm and pixel size 25µm

## 2. Modulation transfer function (MTF):

We estimated the MTFA whichis about .63 at the spatial frequency resolution boundary (20 cycle/ millimeter) which is higher than .5 leading to high resolution image and also clearly affects the performance of the system to higher value. Fig.5. shows the MTF for on-axis FOV , .5 FOV , and bordering FOV at frequency 20 cycle/ millimeter.

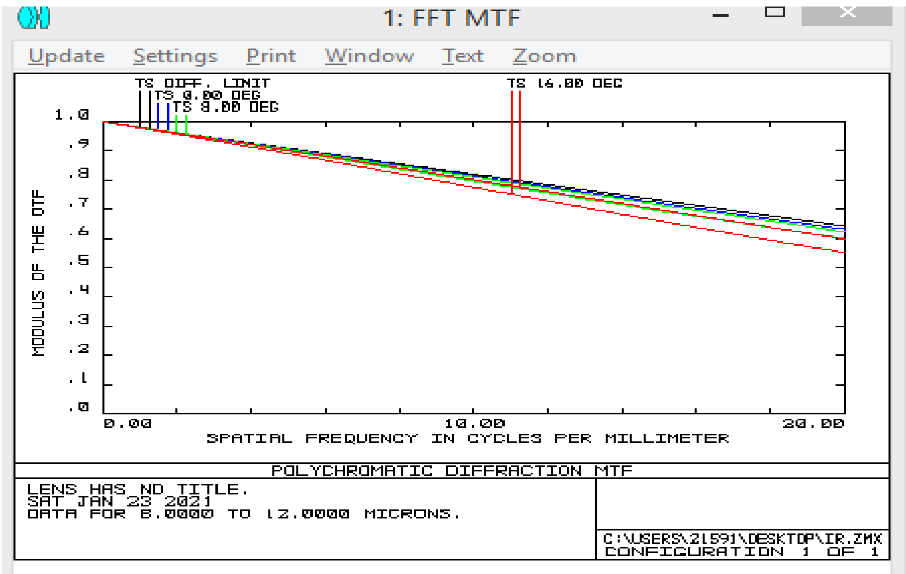


Fig.5. MTF of our IR objective design for different analyzed FOV

3.Depth of FocusCurve:

The depth of focus which corresponds to an OPD of ± $^{1}/_{4}\,\lambda\ wavelength$ δ= ±2λ $(f/\#)^2$is

Wave front depth δ is equal to 39.2 µm.

The max shift in focal length is about 20.7396µm which is less than 25% wave focus depth as shown in Fig.6.

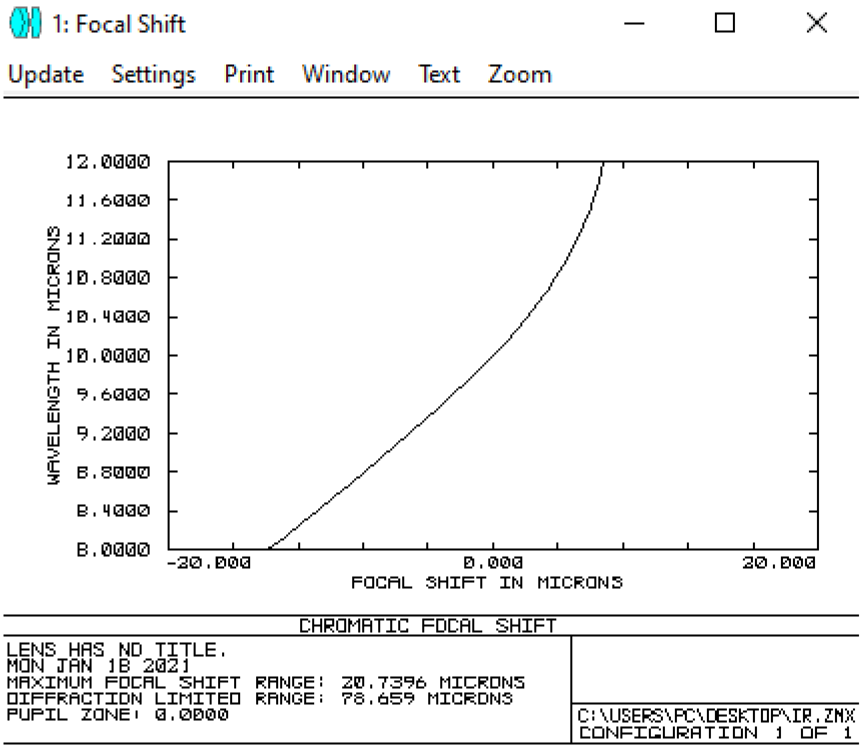


Fig.6. Chromatic focal shift for our IR designed objective

4. Field curvature and distortion:

The simulated results for the field curvature and distortion at off-axis FOV ($\pm 16^{\circ}$) are displayed in Fig.7. The results show that field curvature has nearly uniform flat object across the frame and for distortion which is less than 2%

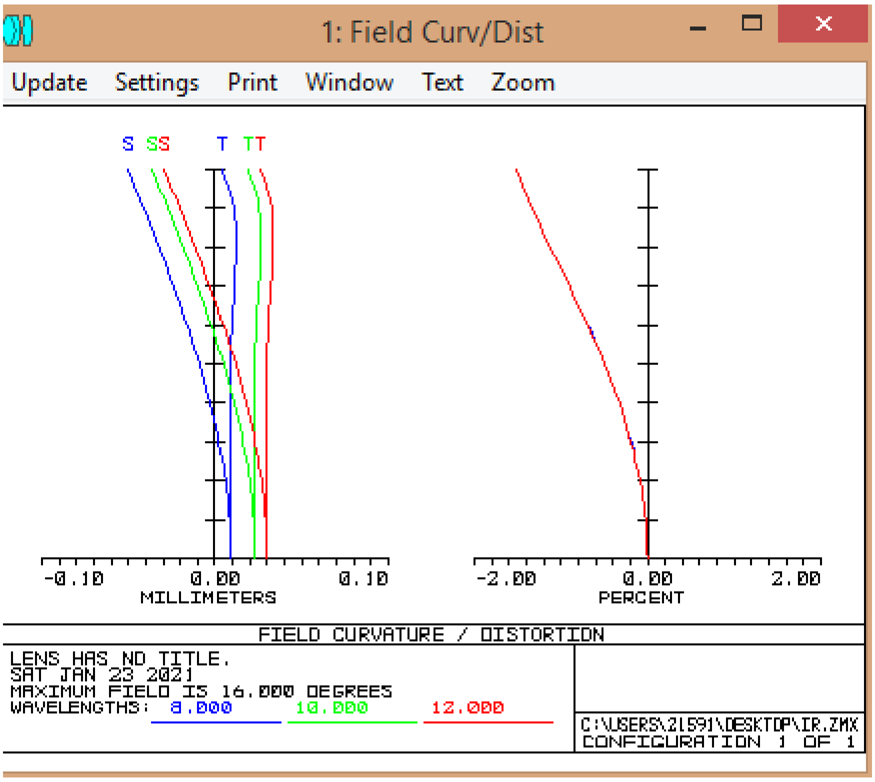


Fig.7. The schematic figure of field curvature and distortion of our IR objective design

The previous results show that our objective design achieves all needed requirements and then the design is good from optical, mechanical and price point of view. So this design can be used for different observation camera in military for patrols or observations points, and in civilian applications such safety companies.

TABLE III show the prescription data of our objective design.

1: Prescription Data

Update Settings Print Window

```
System/Prescription Data

File : C:\Users\21591\Desktop\IR.ZMX
Title: Lens has no title.
Date : SAT JAN 23 2021


LENS NOTES:

       Notes...



GENERAL LENS DATA:

Surfaces                 :               7
Stop                     :               1
System Aperture          : Entrance Pupil Diameter = 25
Glass Catalogs           : infrared
Ray Aiming               : Paraxial Reference, Cache On
 X Pupil shift           :              0
 Y Pupil shift           :              0
 Z Pupil shift           :              0
Apodization              : Uniform, factor =   0.00000E+000
Effective Focal Length   :             35 (in air at system temperature and pressure)
Effective Focal Length   :             35 (in image space)
Back Focal Length        :       9.987027
Total Track              :       92.47057
Image Space F/#          :            1.4
Paraxial Working F/#     :            1.4
Working F/#              :       1.402309
Image Space NA           :      0.3363364
Object Space NA          :      1.25e-009
Stop Radius              :           12.5
Paraxial Image Height    :       10.03609
Paraxial Magnification   :              0
Entrance Pupil Diameter  :             25
Entrance Pupil Position  :              0
Exit Pupil Diameter      :       111.7759
Exit Pupil Position      :       156.5091
Field Type               : Angle in degrees
Maximum Field            :             16
Primary Wave             :             10
Lens Units               :   Millimeters
Angular Magnification    :     -0.2236619

Fields          : 3
Field Type: Angle in degrees
#        X-Value         Y-Value          Weight
 1       0.000000        0.000000        1.000000
 2       0.000000        8.000000        1.000000
 3       0.000000       16.000000        1.000000

Vignetting Factors
#      VDX        VDY        VCX        VCY        VAN
1   0.000000   0.000000   0.000000   0.000000   0.000000
2   0.000000   0.000000   0.000000   0.000000   0.000000
3   0.000000   0.000000   0.000000   0.000000   0.000000

Wavelengths      : 3
Units: Microns
#          Value           Weight
 1       8.000000        1.000000
 2      10.000000        1.000000
 3      12.000000        1.000000
```

```
ELEMENT VOLUME DATA:

Values are only accurate for plane and spherical surfaces.
Element volumes are computed by assuming edges are squared up
to the larger of the front and back radial aperture.
Single elements that are duplicated in the Lens Data Editor
for ray tracing purposes may be listed more than once yielding
incorrect total mass estimates.

                            Volume cc   Density g/cc        Mass g
Element surf   1 to   2      2.570479       5.327000     13.692942
Element surf   3 to   4     20.800545       7.372000    153.341620
Element surf   5 to   6     22.659774       5.327000    120.708617
Total Mass:                                             287.743179
```

## VI. Conclusion

A compact high resolution IR  objective operation in (8-12μm )spectral band show its high performance in optical and compactness point of view has been successfully modeled and designed. Our results achieved the design constraints since its MTFA is higher than .5 and near diffraction limit at spatial frequency (20 cycle/ millimeter) which means no aberration in our designed IR objective. Also the spot diagram of the objective shows the image to apoint source formed by objective is focused in the pixel pitch with value for RMS radius less than pixel dimension. These achieved limitations show that high quality of formed image. This objective can work with high resolution uncooled detector model  (U6010), to construct thermal imaging camera with high resolution performance. The required wide FOV with design limitation is achieved since our objective design has complete FOV. In addition to that the design has simple construction that leads to relatively low cost in manufacturing. So both good qualities for imaging and relatively low cost device are well achieved. Compact construction of the proposed thermal camera also makes it suitable for different civilian applications.

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