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Design Of An Infrared Optical System For Gun Scope Application With An Uncooled Thermal Imaging Sensor In LWIR (8-12 µm) Region

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Abstract:
Thermal imaging systems play crucial roles in many fields. Long-infrared (LWIR) uncooled systems, operating in 8-12µm, offer significant advantages due to their cost-effectiveness, reliability, and compact design. These systems can provide a clear image in complete darkness through smoke, fog, dust, and severe weather conditions like rain and snow [1-4]. These systems are widely employed in handheld thermal cameras, automotive night vision, border security, firefighting, and industrial monitoring, providing real-time thermal imaging with minimal operational constraints. The design of an infrared optical system for a Gun scope (military and law-enforcement) application with an uncooled thermal imaging sensor in the LWIR region, has been presented in this paper. The uncooled thermal imager, a VOx microbolometer detector with a focal plane array (FPA) of 640x480 pixels, is used due to its high sensitivity and stability, which make it more suitable for military and law enforcement applications. The first-order parameters are determined using preliminary calculations. The design is optimized using SYNOPSYS™ optical design software. The final optical design is corrected for geometrical and chromatic aberrations. The results show that the modulation transfer function MTF is above 0.42 at Nyquist frequency, complying the design criteria [5] and is diffraction-limited over the full field of view. The RMS radius of the spot diagram is concentrated and is appreciably less than the detector pixel pitch of 17µm over the full field of view. Polychromatic modulation transfer plots, spot diagrams, distortion curve, and encircled energy plots are presented, showing exceptional performance. The final optical design consists of three lenses, weighing 210.0 grams, with one aspheric surface, and a shorter optical length (total length = 130mm) making the design light, simple, and compact for Gun scope application.

***Keywords**: Thermal imaging systems, Gun scope, Uncooled microbolometer sensor, SYNOPSYS™, Nyquist frequency, Polychromatic Modulation Transfer Function (MTF), Diffraction-limited, Geometrical aberration, Chromatic aberration, Aberration curves, Spot diagram, Aspheric surface.*

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I. Introduction

Thermal imaging systems are essential tools in numerous fields. They detect infrared radiation emitted by objects and convert it into visible images, allowing visualization of temperature differences. These systems are invaluable for conditions where conventional cameras fail, such as complete darkness, smoke, fog, dust, and inclement weather like rain and snow.

LWIR uncooled systems operate within the 8-12µm wavelength range and utilize microbolometer sensors that do not require cooling to cryogenic temperatures. This wavelength band is optimal for detecting thermal radiation emitted by objects at typical ambient temperatures. LWIR uncooled systems have many key advantages. They are cost-effective due to their lower manufacturing and maintenance costs compared to cooled systems. They are reliable as fewer optical components lead to a less complex system, increasing durability and lowering the failure rates. They have a compact design as they are smaller in size and lightweight, making these systems more portable and easier to integrate into various devices. These systems excel in providing clear images under challenging conditions, such as complete darkness, as they can form images without any visible light, in smoke, fog, and dust as they can penetrate obscurants to deliver clear thermal images, and in adverse weather conditions like rain and snow, where they effectively provide images. Their advantages and operational capabilities make them useful for Military, Law-Enforcement, and Commercial applications.

The Gun scope is an advanced LWIR uncooled system widely used by Military and Law-enforcement forces due to its enhanced situational awareness and operational effectiveness in challenging environments. The Gun Scope optical system integrates with an uncooled microbolometer to capture images using infrared (IR) radiations. The uncooled thermal sensor in this design is a Vanadium Oxide (VOx) microbolometer with a focal plane array FPA of 640X480 with a pixel pitch of 17µm. The VOx microbolometer is chosen for its Higher

Temperature Coefficient of Resistance TCR (enables it to detect minute temperature differences resulting in better performance [6]), Lower 1/f Noise (exhibits higher image quality and better sensitivity, especially in low-temperature environments [6]), Better Uniformity (translate into more consistent and reliable imaging performance [7]), Mature Technology (results in more reliable and higher-performing detectors[6]), Higher Sensitivity (achieve higher sensitivity levels, with noise equivalent temperature difference (NETD) as low as 20-30 mK [6]), and Thermal Stability (making them more suitable for applications where temperature variations are common [7]).

The optical system in a thermal Gun scope is a critical component, responsible for collecting infrared radiation from the environment and projecting a high-resolution image onto the detector array. The performance of the IR optical system directly impacts the scope's detection range, field of view, image clarity, and overall usability. Designing infrared optics for thermal Gun scopes presents both advantages and challenges. On the positive side, infrared materials have a higher refractive index, longer wavelengths, and lower relative dispersion, which helps in minimizing primary optical aberrations [8]. On the other hand, it must be ensured that the system resolution matches the detector pixel size for optimal image quality, infrared lenses are made from specialized materials such as germanium, chalcogenide glass, or zinc selenide, are expensive and have limited availability, optimizing optical design to prevent unwanted radiation from reaching the detector and designing optics to maintain performance across the full field of view make it challenging and complex.

The optical system of the Gun scope is designed to achieve maximum system performance and high resolving power, gather the maximum amount of image flux, and minimize the system's complexity, cost, and weight. Achieving maximum system performance requires that the optical components provide the highest possible image quality and resolution by reducing optical aberrations and maximizing the efficiency of infrared light collection to guarantee clear and precise target acquisition. High resolving power allows the Gun scope to distinguish between closely spaced objects. Optimizing the Gun scope to gather the maximum amount of infrared radiation from the target scene and direct it to the detector array results in an efficient light collection that enhances the scope's sensitivity, enabling it to detect low-intensity heat signatures, which is particularly important in low-visibility conditions such as complete darkness, smoke, or fog. Focusing on reducing the Gun scope's complexity, cost, and weight ensures that it is more practical and accessible for field use. This involves selecting cost-effective materials, simplifying the design for manufacturability, and minimizing the number of optical elements without compromising performance. A lightweight, cost-effective optical design enhances portability and ease of use, especially during extended operations.

II. Design And Experimental Work

Technical Design Parameters (Design Specifications):

A Vanadium Oxide VOx microbolometer FPA with a resolution of 640X480 pixels is selected for the Gun Scope optical system design due to its better performance. The FPA features a unit cell of 17µm x 17µm, a square pixel with image plane dimensions of 10.88 mm by 8.16 mm and array aspect ratio of 1.33. The detector has a window (filter) made of germanium having a thickness of 1mm and spectral range of 8-12 µm. Based on FPA specifications, the first-order optical parameters are calculated as shown in Table-1.

Table-1: First-order Parameters

Entrance Pupil Diameter (mm)	70
System Focal Length (mm)	105
HFOV×VFOV (deg)	5.94×4.45
Full diagonal FOV (deg)	7.42
System Length (mm)	< 140
F/number	1.5
Detector window thickness (mm)	1
Distance from window to FPA (mm)	0.95

Design Performance Criteria:

The optical design of the Gun scope system must satisfy some criteria to make it a best performance design. From an optical perspective, the system is required to achieve a diffraction blur (spot size) that matches the detector unit cell and for good performance should be smaller than the detector unit cell (17µm). The optical cut-off frequency is 65.3 cycles/mm on the image plane. The system Nyquist frequency is 29.4 cycles/mm in image plane or 3.088 cycles/mrad in the object space. The other design criteria require the polychromatic modulation transfer function (MTF) to be greater than or equal to 0.424 for the Nyquist frequency [5] and be near diffraction-limited for the full field of view. The distortion should be less than 2% for the full field of view. From a mechanical and financial perspective, the design must have a compact form factor with reduced weight, small dimensions, and a short optical path, while maintaining a simple structural configuration and making it cost-effective from a manufacturability aspect.

Design Procedure:
Gun Scope Optical Design Steps:

To meet the technical design specifications outlined in Table-1 and the performance criteria mentioned earlier, specific design steps must be followed [9]. The procedure has been adapted for this Gun scope optical design based on the work performed during the design and optimization phases, as illustrated in Fig. (1).

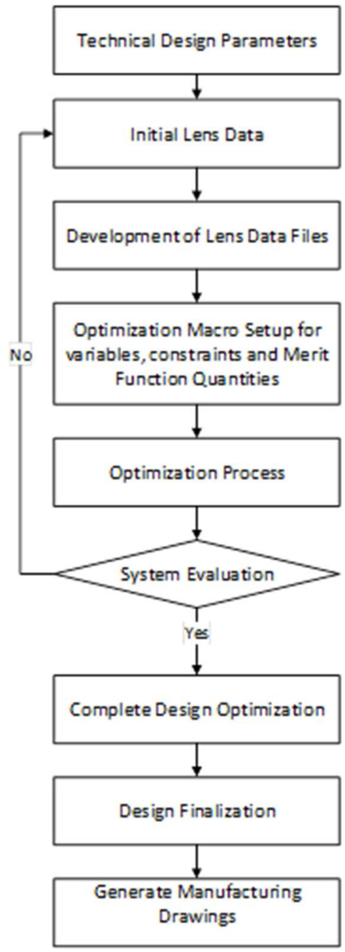

Figure-1: Gun Scope Optical Design Steps

Gun Scope Optical System Modeling and Optimization in SYNOPSYS™:

This study extensively utilizes the optical design software SYNOPSYS™ [10] for system analysis and optimization. The final design is achieved by following a systematic approach, as outlined in Figure-1. The key design steps are summarized below:

1. Initial Parameter Calculation

- The first-order optical parameters are determined based on the system requirements.
- Using paraxial formulas (paraxial y-u ray tracing), the basic lens powers and spacings are calculated to achieve the desired total optical power [11].

2. Lens Data File Configuration

- Initial lens design data is entered into the Lens Data file (.RLE), following the structured data file format.
- This file includes essential system definitions such as aperture size, system units, wavelength region, object parameters, and surface definitions.
- Each lens is specified with its surface type, radius of curvature, thickness, material, and glass type.
- The first lens is assigned as an aperture stop and is designated as a real stop by setting a negative value. This ensures that the pupil shape and position are determined by using real-ray tracing instead of paraxial rays.

- To model the entering beam accurately at all field points, the software's real pupil feature with the wide-angle option is utilized.
- The full-diagonal field of view (FOV) is defined using the detector array's diagonal dimensions in combination with the software's FFIELD option.
- The lens description file also incorporates the front window of the detector package. The parallel plate introduces minimal aberrations, since the system operates at a relatively slow f-number.

3. Optimization Setup
- A custom optimization macro is generated by declaring variables in the PANT section.
- Mechanical constraints, aperture limits, and optical ray aberrations are incorporated into the AANT section, defining the merit function for optimization.

4. Optimization Process
- Initially, a real-ray-based merit function is applied to minimize optical aberrations.
- Optimization targets rays at three key field positions: on-axis, 0.75 field, and full field, with gradually reduced weighting.
- The optimization considers three wavelengths: 8 µm, 10.2 µm, and 12 µm, with corresponding weights of 0.8, 1.0, and 0.8, respectively.
- Axial and lateral chromatic aberrations are controlled by adjusting ray intercept differences.
- Following the initial optimization, an optical path difference (OPD)-based merit function is implemented to achieve diffraction-limited performance, using the same targeted rays but in OPD terms.

5. Performance Evaluation
- The system performance is assessed using the Image Analysis Dialog (MIM) to verify compliance with design criteria and performance requirements.

6. Complete Optimization.
- The optimization and evaluation steps are iterated multiple times to refine the design and ensure it meets the required technical specifications and performance benchmarks.

7. Design Finalization:
- Design is finalized, technical design specifications are achieved, and the performance criteria are met successfully.

8. Manufacturing Drawings:
- Manufacturing drawings are generated after the design is finalized.

Final Technical Design Specifications (Achieved):

Following the above design steps, the Gun scope optical design technical specifications are finalized, and the achieved parameters are shown in the Table-2.

Table-2: Final Technical Design Specifications

	Required Technical specifications	Final Technical Specifications
Entrance Pupil Diameter (mm)	70	70
System Focal Length (mm)	105	105
HFOV×VFOV (deg)1	5.94×4.45	5.94×4.45
Full diagonal FOV (deg)	7.42	7.42
System Length (mm)2	< 140	130
F/number	1.5	1.5

Figures (2), (3), and (4) show the Gun scope optical design's 2D layout, wired layout, and 3D shaded model.

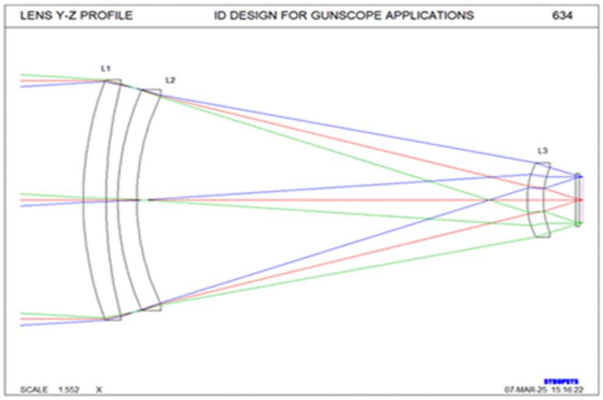

Figure 2: 2D Layout

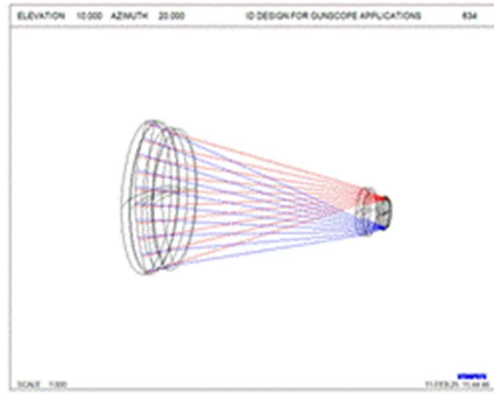

Figure 3: Wired Layout

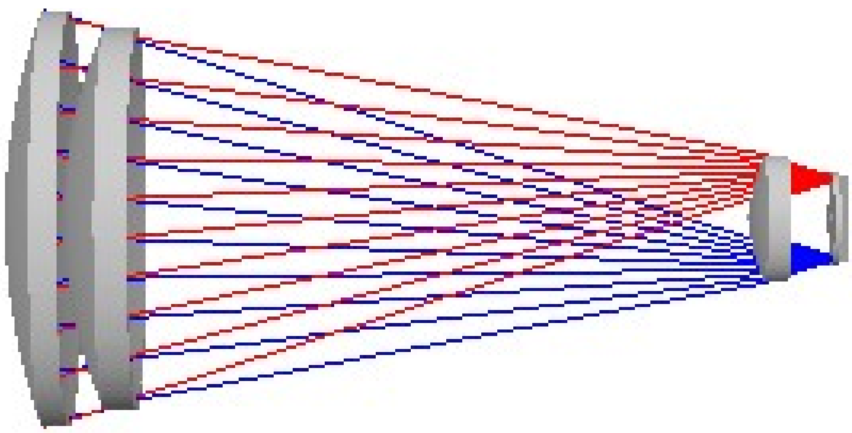

Figure 4: Shaded Model

III. Results And Discussion

Optical Design Details:

The optical system designed for the Gun scope application consists of three lenses, as illustrated in Fig.2. The first element (L1) is an aspheric lens fabricated from germanium, the second element (L2) is a spherical lens made of zinc selenide, and the third element (L3) is a spherical germanium lens.

In the long-wave infrared (LWIR) spectral region, germanium is selected due to its high refractive index (~4), which results in low dispersion. In achromatic doublet configurations, germanium typically serves as the crown (positive) element. Zinc selenide, with a refractive index 2.4, exhibits higher dispersion than germanium. Due to their contrasting dispersion characteristics, L1 and L2 function as an achromatic doublet, effectively mitigating chromatic aberrations. Furthermore, germanium's high refractive index allows for optical elements with longer radii of curvature, thereby facilitating aberration control.

The third optical element (L3) focuses incident radiation onto the image plane. The system features a back focal length of 8.5 mm, allowing for the integration of a shutter between the optical assembly and the detector. This configuration enables nonuniformity correction, a critical requirement for LWIR detector calibration.

The aspheric surface of L1 is optimized to correct third-order spherical and low-order aberrations. As the system's aperture stop, L1 plays a key role in minimizing spherical aberration across the field of view. Third-order aberration data, presented in Table-3 and Figure-5, indicate effective correction.

Incorporating an aspheric surface, reduces the total number of optical elements to three, leading to a more compact and lightweight design. Additionally, the fabrication of aspheric germanium optics for LWIR applications is both cost-effective and manufacturable using single-point diamond turning, making it a practical choice for precision optical components.

Table-3: Final Technical Design Specifications

Third Order Aberration Analysis	
3rd Order Aberrations	Values
SPH ABER (SA3)	0.00306
COMA (CO3)	0.01133
TAN ASTIG (TI3)	-0.00547
SAG ASTIG (SI3)	-0.00435
PETZVAL (PETZ)	-0.00379
DISTORTION (DI3(FR))	0.00199
AX COLOR (PAC)	0.00013
LAT COLOR (PLC)	0.00053
SECDRY AX) (SAC)	-0.00724
SECDRY LAT) (SLC)	0.00012

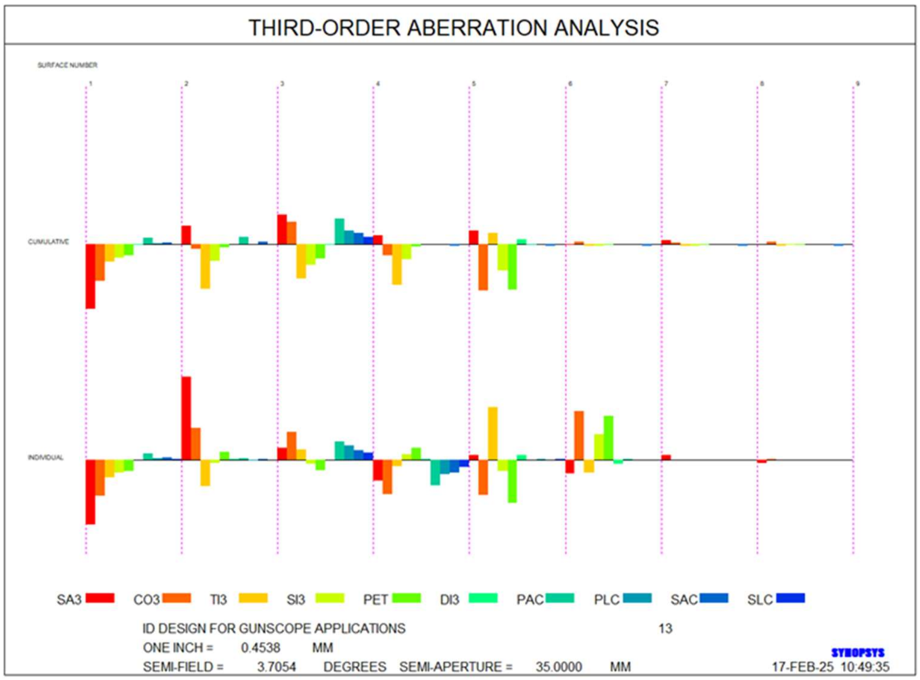

Figure-5: Third Order Aberration Analysis Graphical Representation

In this design, an optical system with an F-number (F#) of 1.5 is employed to minimize aberrations such as spherical aberration and coma, as detailed in Table-3, thereby enhancing image quality. The selection of F# 1.5 also improves system robustness by reducing sensitivity to decentering, tilt, and focal shifts—critical factors in ensuring reliable performance under operational field conditions, as required in Gun scope applications.

Furthermore, an F# of 1.5 provides an increased depth of field, enabling the system to maintain focus over a broader range of distances. This design achieves a depth of field extending from infinity down to 450 meters, ensuring target clarity across varying engagement ranges. The system also features a field of view of 7.42°, facilitating long-range target detection while preserving fine details—an essential requirement for precision aiming and situational awareness in Gun scope applications.

The three-lens design with an optical length of 130mm ensures a compact and lightweight configuration. Calculations of individual element weights, Table-4, indicate that the total mass of the optical system is 210 grams, making it well-suited for applications requiring portability and minimal weight.

Table-4: Element Weight Calculations

	Volume (mm3)	Sp. Gravity (g/ cm3)	Mass (gram)
Element surf 1 2	20406.25	5.33	108.76
Element surf 3 4	17629.84	5.27	92.90
Element surf 5 6	1562.79	5.33	8.33
Total Mass			209.99

Performance Analysis:

In this Gun scope optical design, various analytical metrics are utilized to assess and quantify system performance. Image quality is a key factor in determining overall optical efficiency, and each metric provides valuable insights into different aspects of aberration control and optical performance. The following sections present a detailed analysis of these metrics, explaining their significance in evaluating the design's performance.

Modulation Transfer Function MTF: The Modulation Transfer Function (MTF) is a crucial metric for assessing the spatial resolution and overall image quality of thermal imaging systems. It quantifies the system's ability to preserve contrast at varying spatial frequencies, offering insight into how effectively fine details are transferred from the object to the image while accounting for diffraction and aberrations. Mathematically, MTF is defined as the ratio of image modulation (contrast) to object modulation as a function of spatial frequency [9].

A system exhibiting a diffraction-limited MTF curve indicates that its performance is solely constrained by the fundamental limits of diffraction, confirming that the optical design is free from significant aberrations and is operating at its highest theoretical efficiency [8,9].

The design requirements specify that the polychromatic MTF must be ≥ 0.424 at the Nyquist frequency [5] and should be near diffraction-limited across the full field of view. Figure-6 presents the MTF across all wavelengths at various field points (on-axis, 0.5 FOV, 0.75 FOV, and full FOV) at a cutoff frequency of 65.3 lp/mm. Similarly, Figure-7 illustrates the MTF for the same field points at the Nyquist frequency of 29.4 lp/mm. The results confirm that the design meets all specified criteria, with an MTF of 0.446 on-axis and 0.441 at full field at the Nyquist frequency, while maintaining diffraction-limited performance across the full field of view.

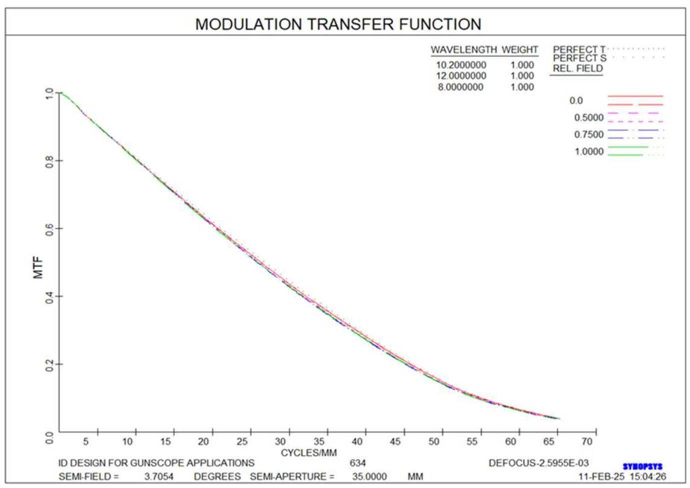

Figure-6: Polychromatic Diffraction Limited MTF at Cut off Frequency 65.3 lp/mm

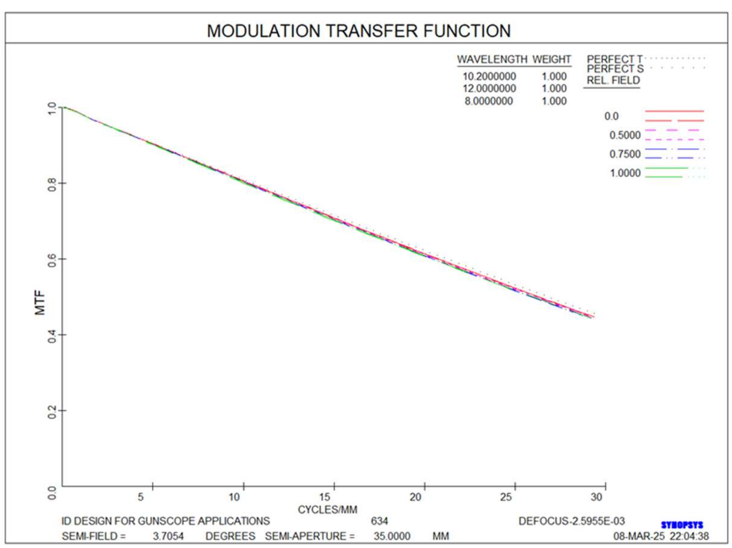

Figure-7: Polychromatic Diffraction Limited MTF at Nyquist Frequency 29.4 lp/mm

Spot Diagram: The spot diagram is a highly effective metric, particularly when evaluating optical systems designed for pixelated sensors. As a graphical representation, it provides a quick and intuitive assessment of optical quality by visualizing the distribution of rays at the image plane. By analyzing spot distribution, aberrations such as astigmatism, coma, spherical aberration, and chromatic aberration can be readily identified.

Spot diagrams typically include the RMS spot radius or diameter, quantifying how light is concentrated. The RMS spot diameter represents the size of a circle that contains approximately 68% of the total light energy. A key design criterion is that the RMS spot diameter should be smaller than the sensor pixel size, ensuring that the image of a point source remains within a single pixel for optimal resolution and contrast [9].

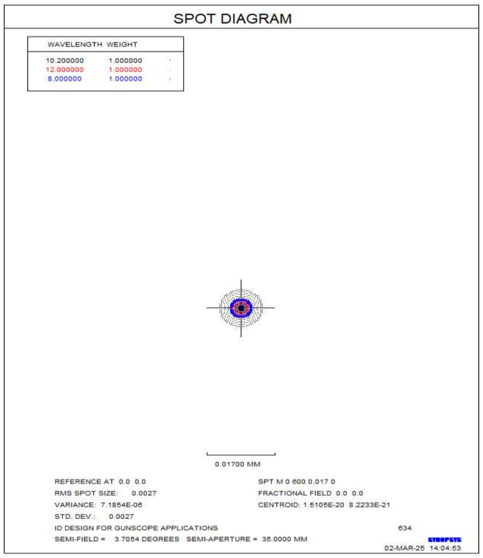

Figure 8: Spot Diagram for on axis on 17µm

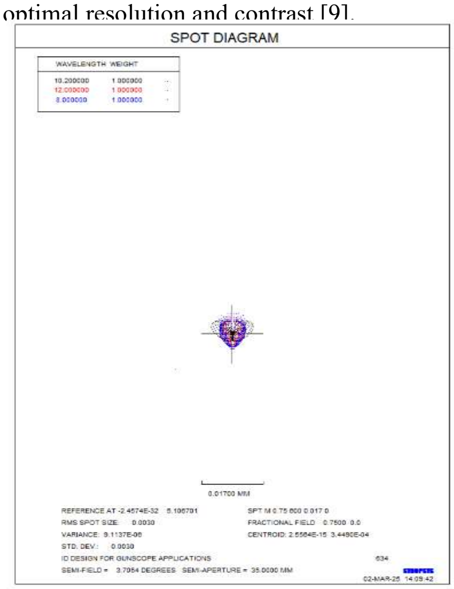

Figure 9: Spot Diagram for 0.75 FOV on 17µm

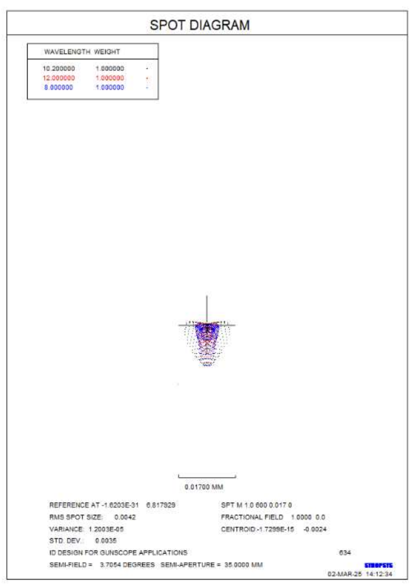

Figure-10: Spot diagram for Full FOV on 17µm

Figures (8), (9), and (10) illustrate spot diagrams at different field positions, including on-axis, 0.75 FOV, and full FOV, respectively. The diagrams confirm that all spots remain within the 17µm pixel size, meaning the system effectively captures all rays within each pixel. Additionally, the RMS spot diameter is 8.4µm at full field, significantly smaller than the sensor pixel size, ensuring that more than 68% of the light energy is concentrated within a single pixel.

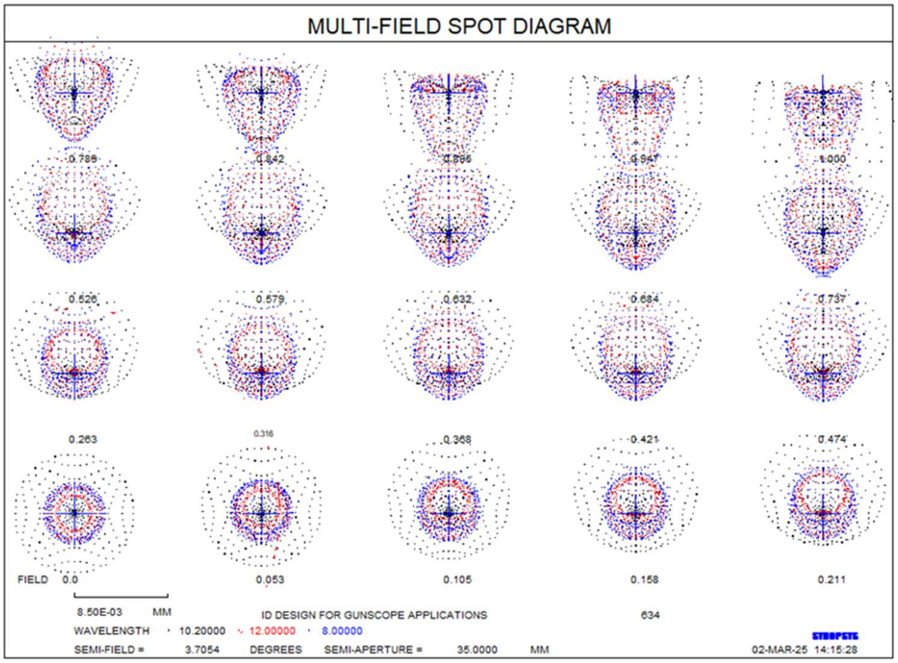

Figure 11:Multi-Field Spot Diagram on 17µm pixel

Figure-11 provides a multi-field spot diagram representation on a 17µm pixel, offering a comprehensive view of spot distribution across the field. The results confirm that the optical design meets the required performance criteria, ensuring high image sharpness and minimal aberration effects.

Distortion: Distortion is a critical parameter for assessing the performance of an optical system, as it quantifies the deviation of the image from its actual geometric shape. This aberration results in straight lines in the object appearing curved or bent in the image, affecting image accuracy. Distortion is classified into two types: Barrel distortion, where the image appears to bulge outward, and Pincushion distortion, where the image appears to pinch inward.

For the Gun Scope optical design, a key requirement is to maintain distortion below 2% to ensure accurate image representation. Figure-12 presents the normalized distortion curve, demonstrating that distortion remains below 1% at full field, fully meeting the design specifications.

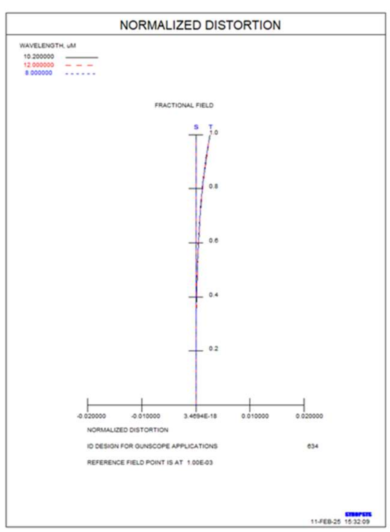

Figure 12: Normalized Distortion

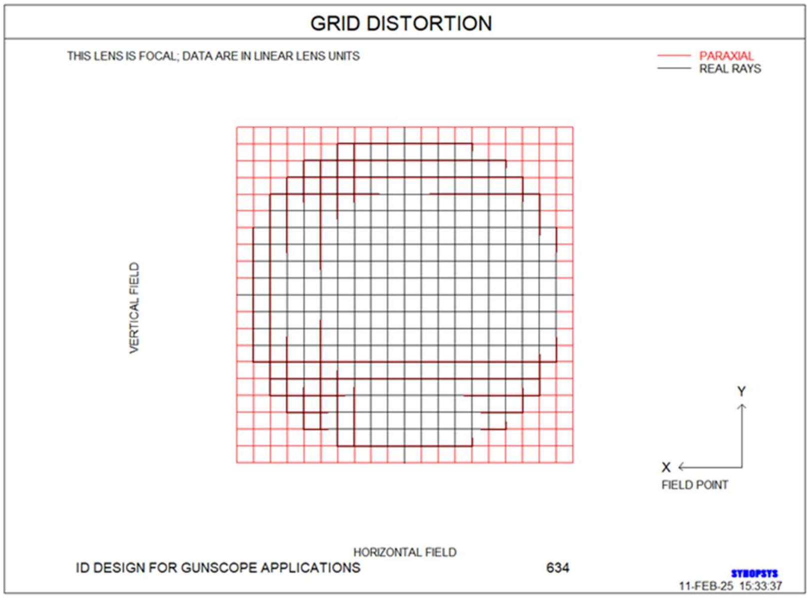

Figure 13: Grid Distortion

Additionally, Figure-13 provides a grid distortion plot, comparing the paraxial image positions with actual image points, confirming that distortion is minimal and well within acceptable limits.

Encircled Energy: Encircled energy is a key metric for assessing an optical system's performance, as it quantifies the energy concentration from a point source within a specified radius around the image center. This measurement is crucial in ensuring that the detector captures sufficient energy for optimal image quality. For a well-designed system, at least 80% of the total energy from a point source should be contained within the detector's pixel pitch [9].

Figure-14 illustrates the energy distribution for a 0.1mm radius, displaying three encircled energy curves for on-axis (red), 0.7 FOV (green), and full field (blue). The plot indicates that a 14.8µm radius contains 80% of the total encircled energy, while a 17µm radius captures 84%, ensuring that more than 80% of the energy falls within the detector's 17µm pixel pitch. This confirms that the design meets a critical performance criterion, ensuring efficient energy capture by the detector.

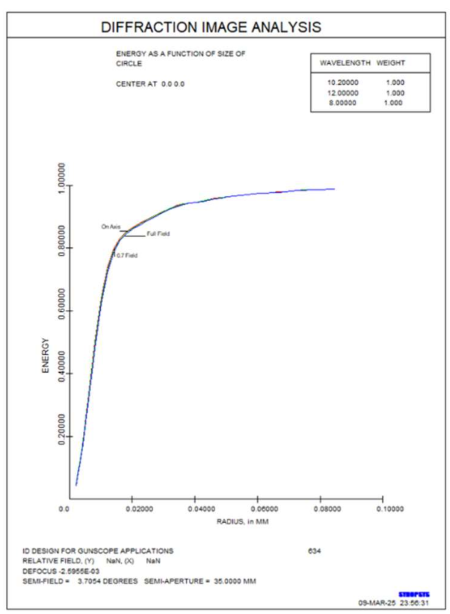

Figure 14: Encircled Energy Plot

The comprehensive results and analysis presented for the Gun Scope optical system demonstrate that the design successfully meets all technical specifications and performance requirements. Additionally, the system is optimized for simplicity and compactness, utilizing only three lenses, which contributes to a lightweight design. The inclusion of a single aspheric surface further enhances performance while maintaining cost-effectiveness.

In conclusion, this optical design not only fulfills all design criteria and technical specifications but also offers a practical, efficient, and economical solution. The final lens data is provided in Table-5.

Table-5: Final Lens Data

Material	R1 (mm)	R2 (mm)	Thickness	Conic value
Germanium	111.19	153.94	6.00	-2.27, 8.78E-08 (R4)
Zinc Selenide	86.66	78.36	5.0	
Germanium	28.24	27.63	4.0	

IV. Conclusion

An optical system has been designed and analyzed for a Gun scope application utilizing an uncooled microbolometer FPA-based sensor operating in the 8–12µm wavelength range. The system exhibits well-corrected optical performance, achieving an MTF value of 0.441 at full field for the Nyquist frequency, while maintaining a diffraction-limited performance across the entire field of view. The geometrical image blur (RMS spot size) measures 8.4µm at full field, significantly smaller than the 17µm pixel size, ensuring high-resolution imaging. Additionally, distortion remains below 1%, and the encircled energy is more than 80%, indicating that optical design fully meets the design criteria.

The design consists of three lenses, including one aspheric surface, with a total system mass of 210 grams and an optical length of 130mm. These attributes contribute to a compact, lightweight, and cost-effective configuration, making the design highly suitable for Gun scope applications.

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