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Image Quality Metric Analysis- A Core Design Perspective- For The Gun Scope Optical System With An Uncooled LWIR Thermal Imaging Sensor

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Abstract:
Gun scopes equipped with uncooled thermal imaging sensors operating in the LWIR (Long-Wave Infrared) range of 8–12 µm offer significant advantages due to their affordability, reliability, and compact design. These systems provide clear imaging even in complete darkness and can penetrate through smoke, fog, dust, and adverse weather conditions such as rain and snow [1-4]. Gun scopes play a crucial role in military and law enforcement applications, including enhanced target acquisition [5], surveillance and reconnaissance [6], and search and rescue operations [6]. The Gun scope optical system is designed around an uncooled LWIR thermal imaging sensor, a microbolometer, featuring a focal plane array (FPA) with a resolution of 640×480 pixels and a 17 µm pixel pitch. The optical system is designed using SYNOPSYS™ optical design software. The system has an F-number of 1.5, a focal length of 105 mm, and a full field of view of 7.42°. The optical design consists of three lenses, including one aspheric surface, with a total weight of 210 grams and an optical length of 130 mm. This configuration ensures a simple, compact, and lightweight system [7]. Performance analysis is conducted using both geometrical and diffraction-based image quality metrics, including polychromatic modulation transfer function (MTF), spot diagrams, encircled energy, and distortion [7]. These metrics directly impact the image quality produced by the optical system [8]. The design criteria include polychromatic MTF to be greater than 0.42 at Nyquist frequency and diffraction limited over the full field of view, the RMS spot size to be less than the detector pixel pitch 17µm, encircled energy to be more than 80%, and distortion to be less than 2%. The optical system design accomplished these design requirements successfully [7]. This paper focuses on key image quality metrics relevant to the core of the design process but not typically specified in the end-product specifications. These include optical path difference (OPD), transverse ray curves, astigmatic field curves, Strehl ratio, and image analysis using extended sources. Understanding these parameters aids in optimizing optical performance during the design phase.

Key Word: *Gun scope, Uncooled microbolometer sensor, SYNOPSYS™, Nyquist frequency, Polychromatic Modulation Transfer Function (MTF), Diffraction-limited, Geometrical, Spot diagram, Optical Path Difference OPD, Transverse Aberration Curves, Astigmatic Field Curve, Aspheric surface.*

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I. Introduction

Thermal imaging gun scopes are advanced optical devices that detect infrared radiation emitted by objects and convert it into visible images. Operating in the Long-Wave Infrared (LWIR) range of 8–12 µm, these scopes use microbolometer sensors to capture thermal radiation without requiring cryogenic cooling.

Thermal imaging gun scopes offer several key advantages. They detect heat signatures, allowing users to see in complete darkness and through visual obstructions such as smoke, fog, and dust. Unlike traditional optics, these scopes provide clear imaging regardless of lighting conditions, making them highly effective for nighttime operations and adverse weather, including rain and snow. Uncooled LWIR systems are more affordable and reliable due to their simplified design, which reduces maintenance requirements and enhances durability. Their lightweight and compact construction improves portability and ease of integration into various devices, increasing their versatility.

These capabilities are essential for military and law enforcement operations, where situational awareness and target acquisition are critical. Thermal imaging gun scopes enhance surveillance, reconnaissance, and search-and-rescue missions by detecting distant heat signatures and identifying concealed or camouflaged threats. In security applications, they strengthen perimeter monitoring and intrusion detection, ensuring better protection of sensitive areas and assets.

The Gun Scope optical system integrates with an uncooled microbolometer to capture images using infrared (IR) radiation. The uncooled thermal sensor in this design is a Vanadium Oxide (VOx) microbolometer with a focal plane array (FPA) of 640×480 and a pixel pitch of 17 µm. The optical system in a thermal gun scope is a crucial component, responsible for gathering infrared radiation from the environment and projecting a high-resolution image onto the detector array. The performance of the IR optical system directly affects the scope's detection range, field of view, image clarity, and overall usability.

Designing infrared optics for thermal gun scopes presents both benefits and challenges. On the positive side, infrared materials have a higher refractive index, longer wavelengths, and lower relative dispersion, which helps reduce primary optical aberrations [8]. However, ensuring that the system resolution aligns with the detector pixel size is essential for optimal image quality. Infrared lenses, typically made from specialized materials such as germanium, chalcogenide glass, or zinc selenide, are costly and not widely available. Additionally, optimizing the optical design to block unwanted radiation from reaching the detector and ensuring consistent performance across the full field of view makes the design process complex and demanding.

The optical system of the gun scope is engineered to maximize system performance and resolving power, collect the highest possible image flux, and minimize complexity, cost, and weight. Achieving peak performance requires that the optical components deliver superior image quality and resolution by minimizing optical aberrations and enhancing the efficiency of infrared light collection, ensuring clear and precise target acquisition. High resolving power enables the gun scope to differentiate between closely spaced objects. Optimizing the scope to capture the maximum amount of infrared radiation from the target scene and direct it to the detector array improves light collection efficiency, enhancing the scope's sensitivity to detect low-intensity heat signatures—especially critical in low-visibility conditions such as complete darkness, smoke, or fog.

Reducing the gun scope's complexity, cost, and weight makes it more practical and accessible for field operations. This involves selecting cost-effective materials, simplifying the design for easier manufacturing, and minimizing the number of optical elements without compromising performance. A lightweight, cost-efficient optical design enhances portability and usability, particularly for prolonged missions.

II. Design And Experimental Work

Technical Design Parameters (Design Specifications):

In the design of the Gun Scope optical system, a Vanadium Oxide (VOx) microbolometer FPA with a resolution of 640×480 pixels is chosen [7]. The FPA has a unit cell size of 17 µm × 17 µm, image plane dimensions of 10.88 mm × 8.16 mm, and an array aspect ratio of 1.33. The detector includes a 1 mm thick germanium window (filter) with a spectral range of 8–12 µm. Based on the FPA specifications, the first-order optical parameters are calculated, as summarized 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 Gun Scope system's optical design must meet specific criteria to ensure optimal performance. From an optical standpoint, the system should achieve a diffraction blur (spot size) that matches the detector unit cell and, for enhanced performance, should be smaller than the detector unit cell (17 µm). The optical cut-off frequency is 65.3 cycles/mm at the image plane, while the system's Nyquist frequency is 29.4 cycles/mm in the image plane or 3.088 cycles/mrad in object space. Additionally, the design must ensure that the polychromatic modulation transfer function (MTF) is at least 0.424 at the Nyquist frequency and remains near diffraction-limited across the entire field of view. Distortion should be kept below 2% for the full field of view.

From a mechanical and financial perspective, the design should be compact and lightweight, with a short optical path while maintaining a simple structural configuration. Cost-effectiveness is also a key factor, requiring a design optimized for efficient manufacturability without compromising performance.

Design Procedure:

Gun Scope Optical Design Process; System Modeling and Optimization in SYNOPSYS^{TM}:

This study employs the optical design software **SYNOPSYS™** [9] for comprehensive system analysis and optimization. The final design is developed using a structured methodology [7]. The key design steps are given below:

1. Initial Parameter Calculation

- The first-order optical parameters are derived based on system requirements.

- Paraxial formulas (paraxial y-u ray tracing) are used to compute basic lens powers and spacings to achieve the required total optical power.

2. Lens Data File Configuration
- The initial lens design data is input into the Lens Data file (.RLE), following the standard data file structure.
- This file defines essential system parameters such as aperture size, system units, wavelength range, object parameters, and surface properties.
- Each lens is specified with its surface type, radius of curvature, thickness, material, and glass type.
- The first lens is designated as an aperture stop and defined as a real stop by assigning a negative value, ensuring the pupil shape and position are determined through real-ray tracing rather than paraxial rays.
- The software's real pupil feature with the wide-angle option is utilized to accurately model the incoming beam at all field points.
- The full-diagonal field of view (FOV) is set based on the detector array's diagonal dimensions, using the software's FFIELD option.
- The lens data file also includes 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 created by defining variables in the PANT section.
- The AANT section incorporates mechanical constraints, aperture limits, and optical ray aberrations, establishing the merit function for optimization.

4. Optimization Process
- Initially, a real-ray-based merit function is applied to minimize optical aberrations.
- The optimization targets rays at three critical field positions: on-axis, 0.75 field, and full field, with progressively reduced weighting.
- Three wavelengths—8 µm, 10.2 µm, and 12 µm—are considered, with weights assigned as 0.8, 1.0, and 0.8, respectively.
- Axial and lateral chromatic aberrations are controlled by adjusting ray intercept differences.
- After the initial optimization, an optical path difference (OPD)-based merit function is employed to achieve diffraction-limited performance, applying the same targeted rays but in OPD terms.

5. Performance Evaluation
- The system performance is analyzed using the Image Analysis Dialog (MIM) to confirm compliance with design specifications and performance requirements.

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

7. Design Finalization
- The design is finalized once all technical specifications are achieved, and performance criteria successfully met.

8. Manufacturing Drawings
- Upon finalizing the design, manufacturing drawings are generated for production.

Final Technical Design Specifications (Achieved):

By following the outlined design steps, the technical specifications for the Gun Scope optical system are finalized, and the achieved parameters are presented in Table-2 [7].

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 (1), (2), and (3) show the 2D layout, wired layout, and 3D shaded model for the optical design of Gun scope.

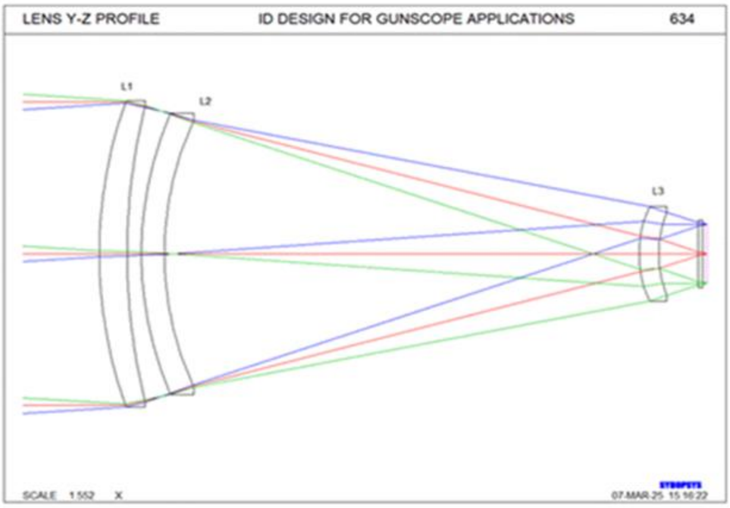

Figure 1: 2D Layout

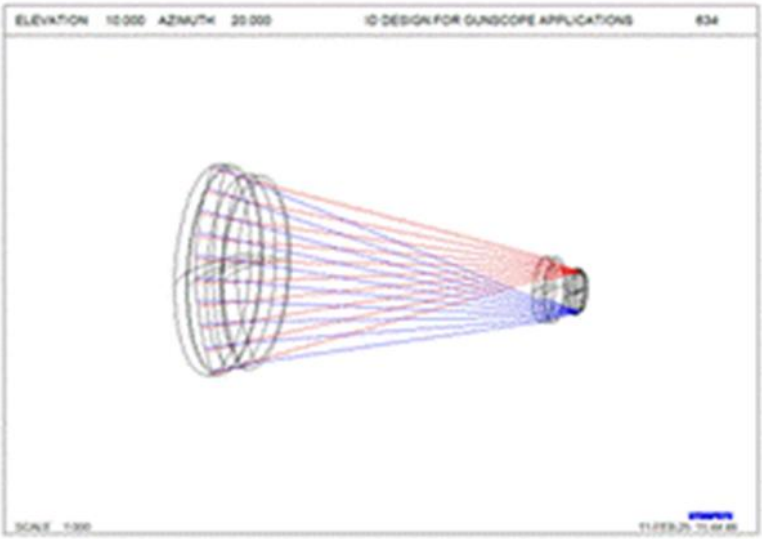

Figure 2: Wired Layout

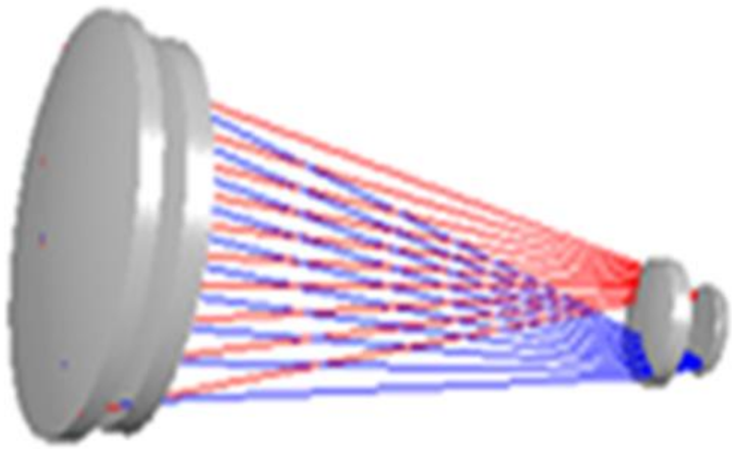

Figure 3: 3D Shaded Model

III. Results And Discussion

Gun Scope Optical Design Details:

The optical system designed for the Gun Scope application comprises three lenses, as shown in Fig.1. The first element (L1) is an aspheric germanium lens, the second element (L2) is a spherical zinc selenide lens, and the third element (L3) is a spherical germanium lens.

In the long-wave infrared (LWIR) spectral region, germanium is used for its high refractive index (~4), which minimizes dispersion. Zinc selenide, with a refractive index of 2.4, has a higher dispersion than germanium. Due to their contrasting dispersion properties, L1 and L2 form an achromatic doublet, effectively reducing chromatic aberrations. The third optical element (L3) is responsible for focusing the incoming radiation onto the image plane.

The aspheric surface of L1 is optimized to correct third-order spherical and low-order aberrations. As the aperture stop of the system, L1 plays a significant role in reducing spherical aberration across the field of view. Third-order aberrations are effectively corrected [7].

Integrating an aspheric surface reduces the total number of optical elements to three, resulting in a more compact and lightweight design. Furthermore, the fabrication of aspheric germanium optics for LWIR applications is cost-effective and feasible using single-point diamond turning.

This design employs an optical system with an F-number (F#) of 1.5 to minimize spherical aberrations and coma, thereby enhancing image quality. An F# of 1.5 increases the 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 to 450 meters, ensuring clear target visibility across varying engagement ranges.

With a field of view of 7.42°, the system supports long-range target detection while preserving fine details—an essential feature for precision aiming and situational awareness in Gun Scope applications.

The three-lens configuration, with an optical length of 130mm, ensures a compact and lightweight design. The total weight of the optical system is 210 grams [7], making it well-suited for applications requiring high portability and minimal weight.

Performance Analysis:

The optical performance of the Gun Scope system is evaluated and quantified using various image quality metrics, which include both geometrical and diffraction-based parameters. Defining these metrics is essential for assessing the effectiveness of any optical design. The identified image quality metrics for the Gun Scope are crucial in describing how users perceive image clarity and performance. These include Modulation Transfer Function (MTF), spot diagram, encircled energy, and distortion. The Gun Scope optical design meets all these criteria, demonstrating high image quality [7].

In optical system design, these metrics are typically aligned with product specifications. However, additional image quality metrics are used during the design process to optimize the system using an optimization process. These include Optical Path Difference (OPD), Transverse ray curves, Astigmatic curves, Strehl ratio, and image analysis with extended sources. These parameters play a fundamental role in the core design process, helping to identify and correct optical aberrations.

As previously discussed, the optimization process initially applies a real-ray-based merit function to minimize aberrations. Subsequently, an OPD-based merit function is implemented to achieve diffraction-limited performance. The following section provides a comprehensive analysis of these image quality metrics related to the core design process, detailing their importance in evaluating the system's overall optical performance.

Optical Path Difference OPD:

Optical Path Difference (OPD) is a key parameter in optical system analysis that quantifies the phase variations introduced by an optical system. It plays a crucial role in enhancing image quality during the optimization process and is also instrumental in refining the design during athermalization analysis. Additionally, OPD is used to adjust the near-focus performance of the system by repositioning a lens or a group of lenses to compensate for optical deviations.

It represents the difference in optical path length between an ideal reference wavefront and the actual wavefront emerging from the system. OPD is instrumental in assessing wavefront aberrations and overall image quality.

The Rayleigh criterion, which defines the minimum resolvable angular separation between two-point sources, is directly influenced by OPD. A system is considered diffraction-limited when OPD remains within $\lambda/4$, indicating that its performance is constrained only by diffraction and operates at peak theoretical efficiency for its aperture size. Keeping OPD below this threshold minimizes phase errors, ensuring optimal contrast transfer and image quality.

Figure 4 presents OPD plots for the design wavelengths at various field positions, including on-axis, 0.5 FOV, 0.75 FOV, and full FOV. The results indicate that the system's OPD values remain well within $\lambda/4$, confirming diffraction-limited performance across all field angles. This demonstrates effective aberration control and high image quality.

Transverse Ray Curves:

Transverse ray curves serve as a crucial graphical tool for evaluating an optical system's performance. These curves illustrate the positions of rays at various points within the system, providing valuable insight into optical aberrations such as spherical aberration, coma, astigmatism, and chromatic aberrations across the field of view and spectral bandwidth. By analyzing these curves, designers can assess how well the system maintains focus and controls aberrations.

Ray trace curves also play a key role in determining whether the optical resolution aligns with the detector's pixel size. If the rays remain within the pixel boundaries, the system can fully utilize the detector's resolution, ensuring optimal imaging performance [10].

Figure 5 presents the transverse ray curves for this design, revealing that secondary color aberration and coma at full field are minimal. Additionally, the curves remain well within the 17µm scale on the vertical axis, confirming that the system achieves diffraction-limited performance.

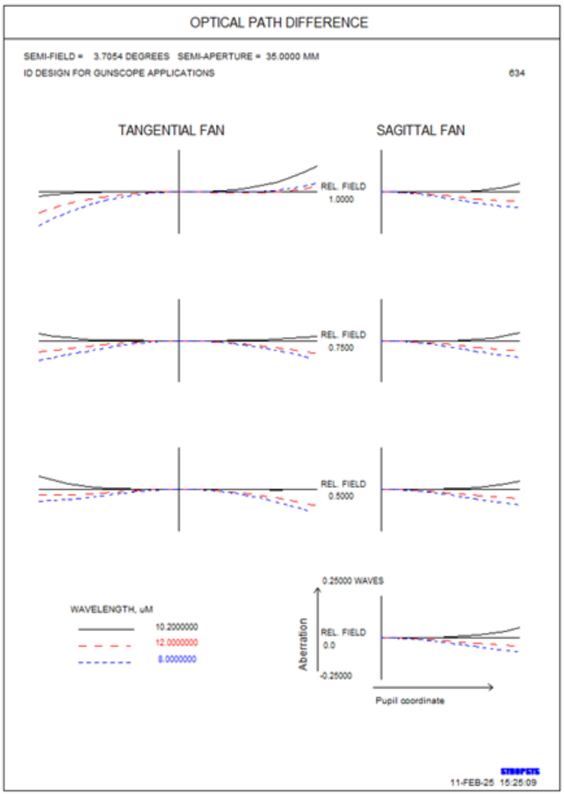

Figure 4: Optical Path Difference Plot

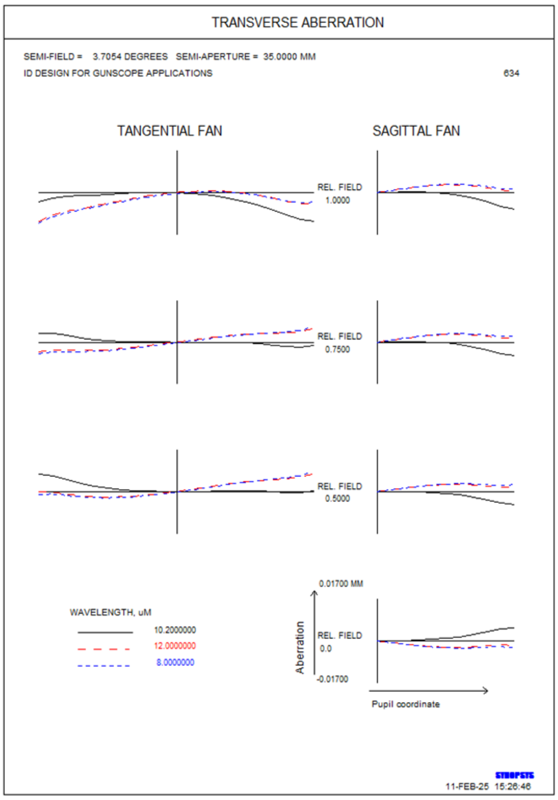

Figure 5: Transverse Aberration Curves

Astigmatic Field Curve:

In an astigmatic optical system, the sagittal and tangential planes do not converge at the same point along the optical axis, resulting in two distinct line foci at different distances. This separation causes image blur and degrades optical performance. The astigmatic field curve visually represents the variation in focal points for the sagittal and tangential planes across the field of view. For an astigmatism-corrected system, the departure of the sagittal and tangential focal planes from the ideal image plane should be minimal across all wavelengths, ensuring improved image sharpness and uniformity.

Figure 6 presents the astigmatic field curves for the Gun Scope optical design, demonstrating that the total field curvature departure for all design wavelengths is less than 0.03mm. Additionally, up to 0.6 FOV, the sagittal and tangential focal curves overlap across all wavelengths, confirming that the system is well-corrected for astigmatism and maintains high optical accuracy.

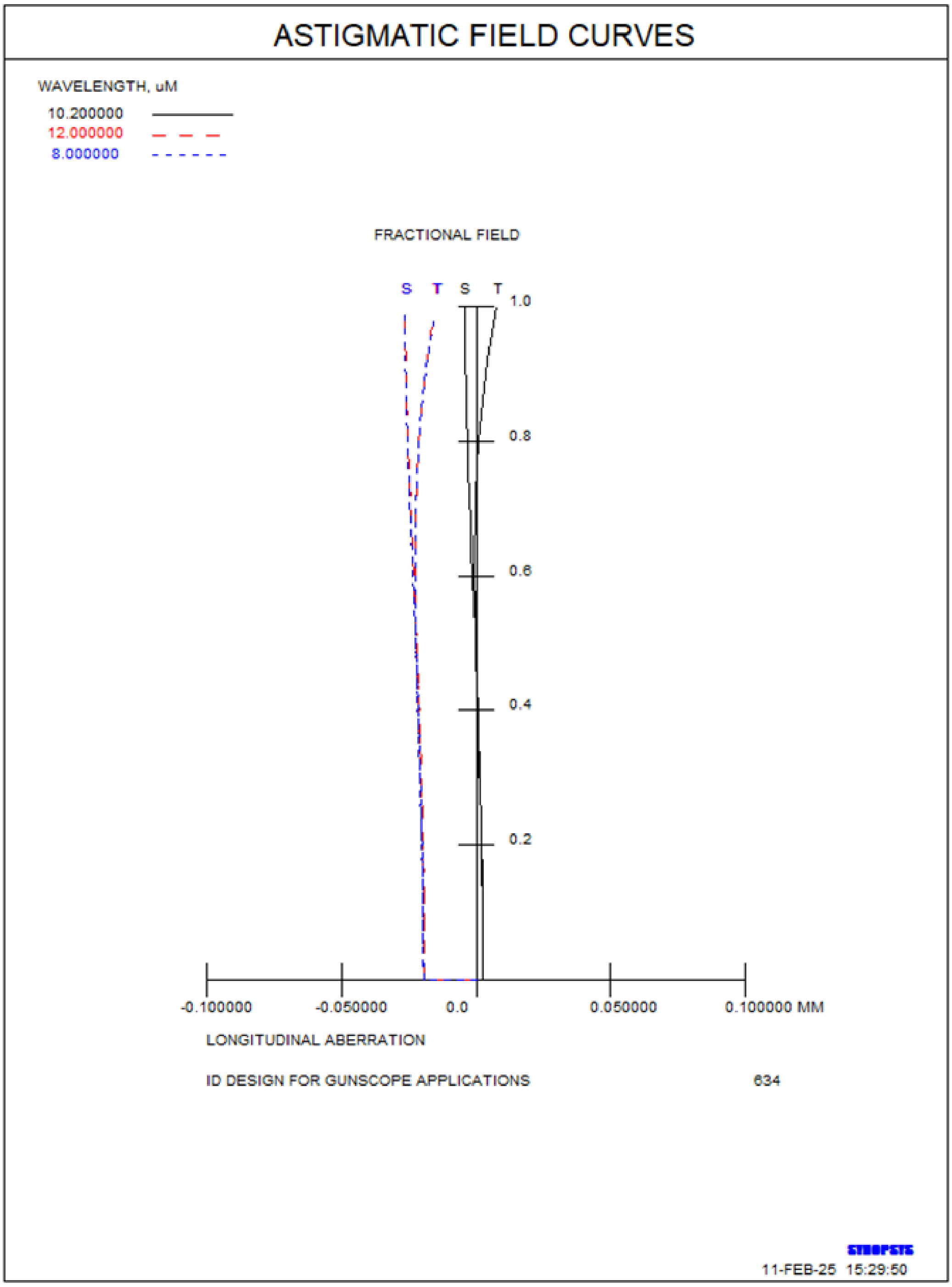

Figure 6: Astigmatic Field Curve

Strehl Ratio:

The Strehl ratio is a key metric for assessing the optical image formation quality in a system. It is defined as the ratio of the peak intensity of an aberrated image to that of an ideal, diffraction-limited image. This ratio ranges from 0 to 1, where a value of 1 represents a perfect optical system with no aberrations. A higher Strehl ratio indicates better optical performance, ensuring that the captured images are sharp and highly accurate. For acceptable image quality, the Strehl ratio should be at least 0.8, while a value of 0.95 or higher is required for high-quality imaging.

Figure 7 presents the Strehl ratio curve for all designed wavelengths across the entire field of view. The results indicate that the Strehl ratio exceeds 0.985 at the on-axis field point and remains above 0.978 at the full field. These values are significantly higher than the 0.95 threshold, confirming that the system operates near the diffraction limit, ensuring exceptional image quality.

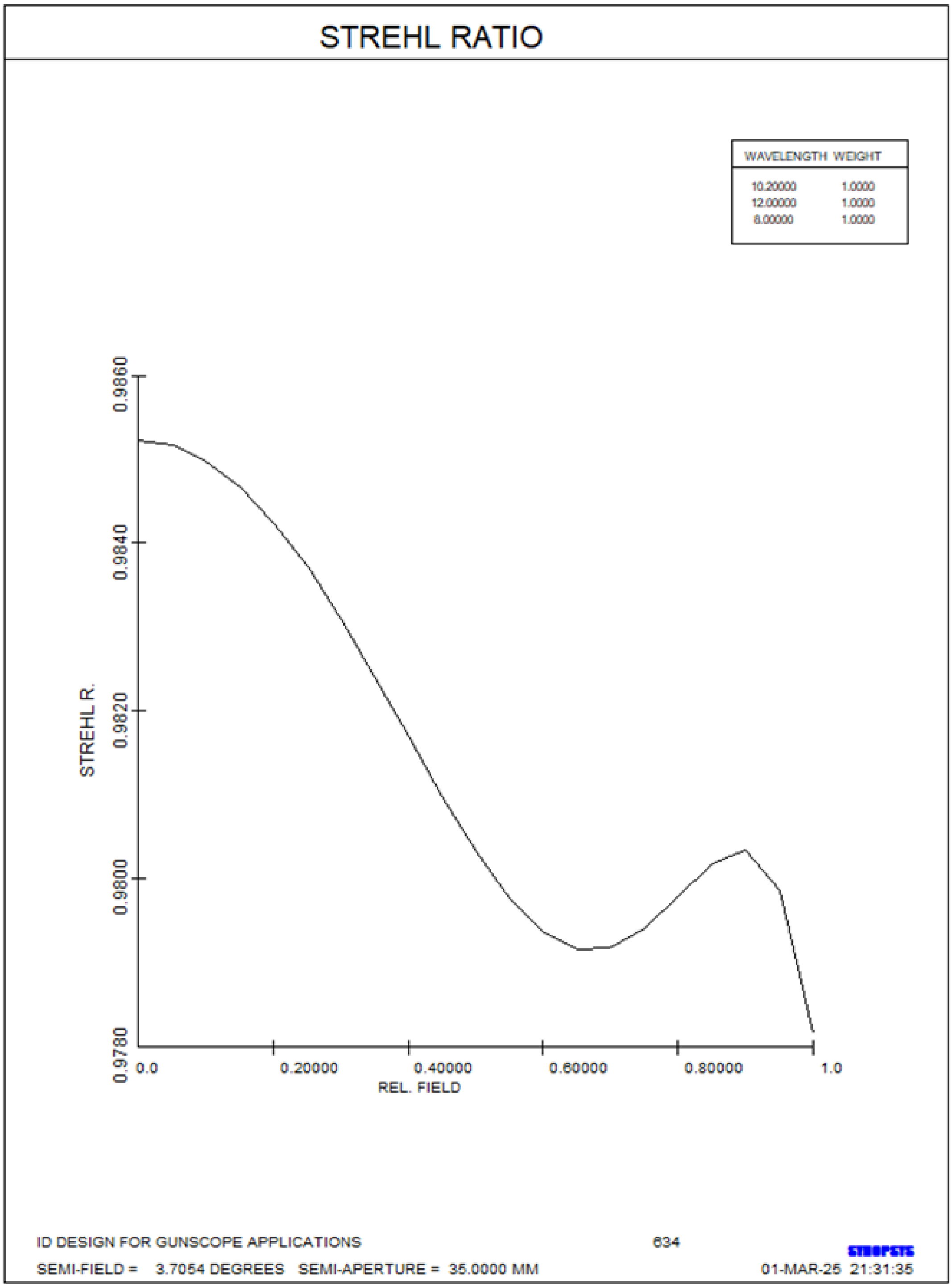

Figure 7: Strehl Ratio for all field points

Image Analysis Using Extended Sources:

SYNOPSYS^{TM} offers a specialized Image Analysis Tool designed to simulate the impact of lens aberrations and diffraction on image quality using various test targets. These targets include sine wave, square wave, double star target, circle, square, 3 bar, and AF target.

The AF target consists of three-bar patterns with varying spatial frequencies, derived from the Air Force resolution targets, making it a valuable tool for evaluating an optical system's resolving power. This analysis visually represents how these targets appear when viewed through the designed optical system at a specified spatial frequency, measured in line pairs per millimeter (lp/mm).

Figures 8-14 present images of selected test targets captured through the Gun Scope optical design at the Nyquist frequency of 29.4 lp/mm, demonstrating the system's imaging performance.

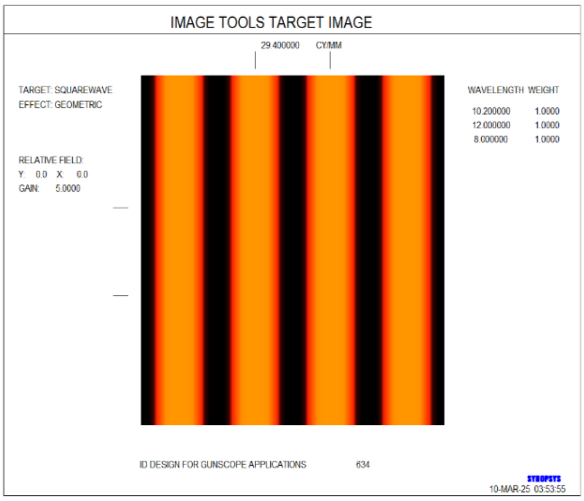

Figure 8: Image Analysis using Square Wave Source

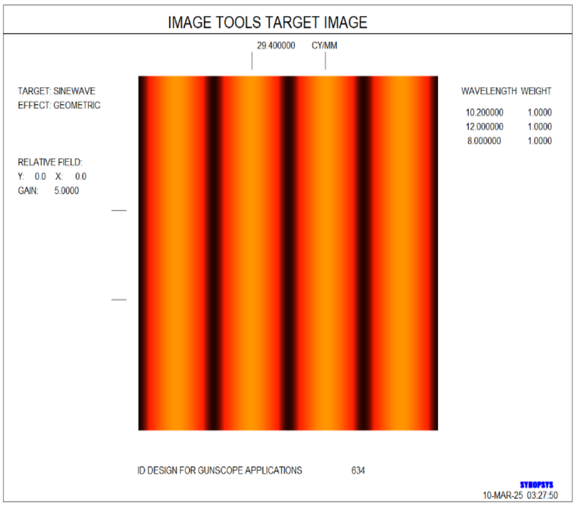

Figure 9: Image Analysis using Sine Wave Source

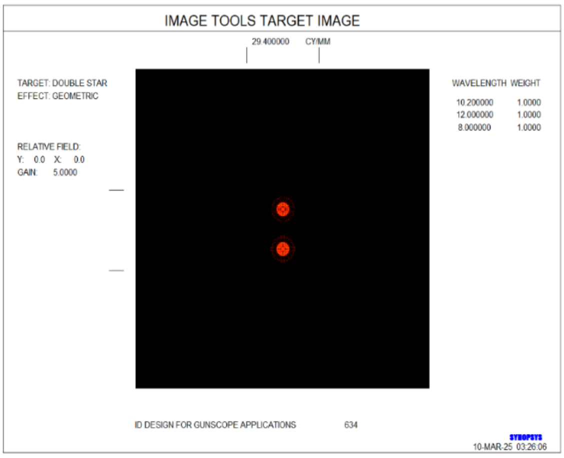

Figure 10: Image Analysis using Double Star Source

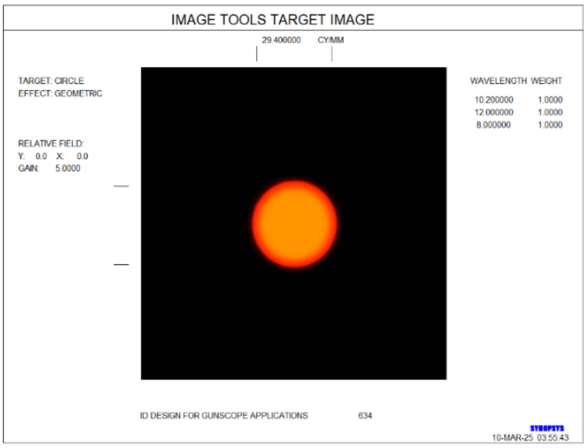

Figure 11: Image Analysis using Circle Source

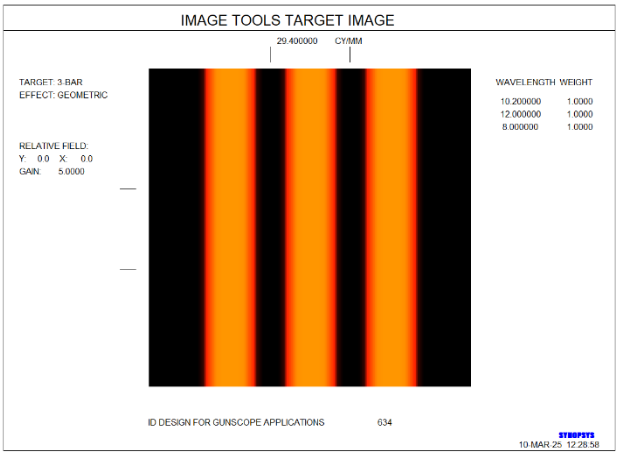

Figure 12: Image Analysis using 3 Bar Source

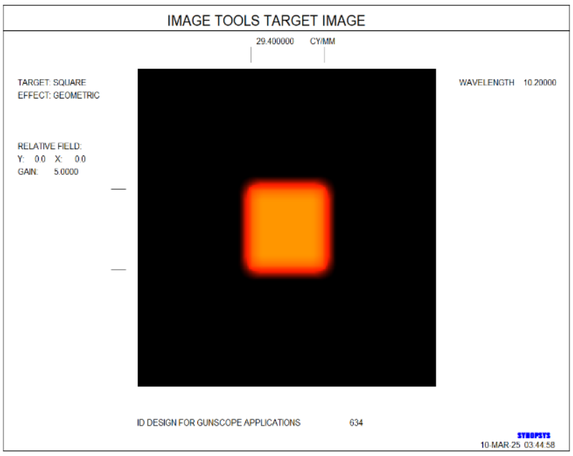

Figure 13: Image Analysis using Square Source

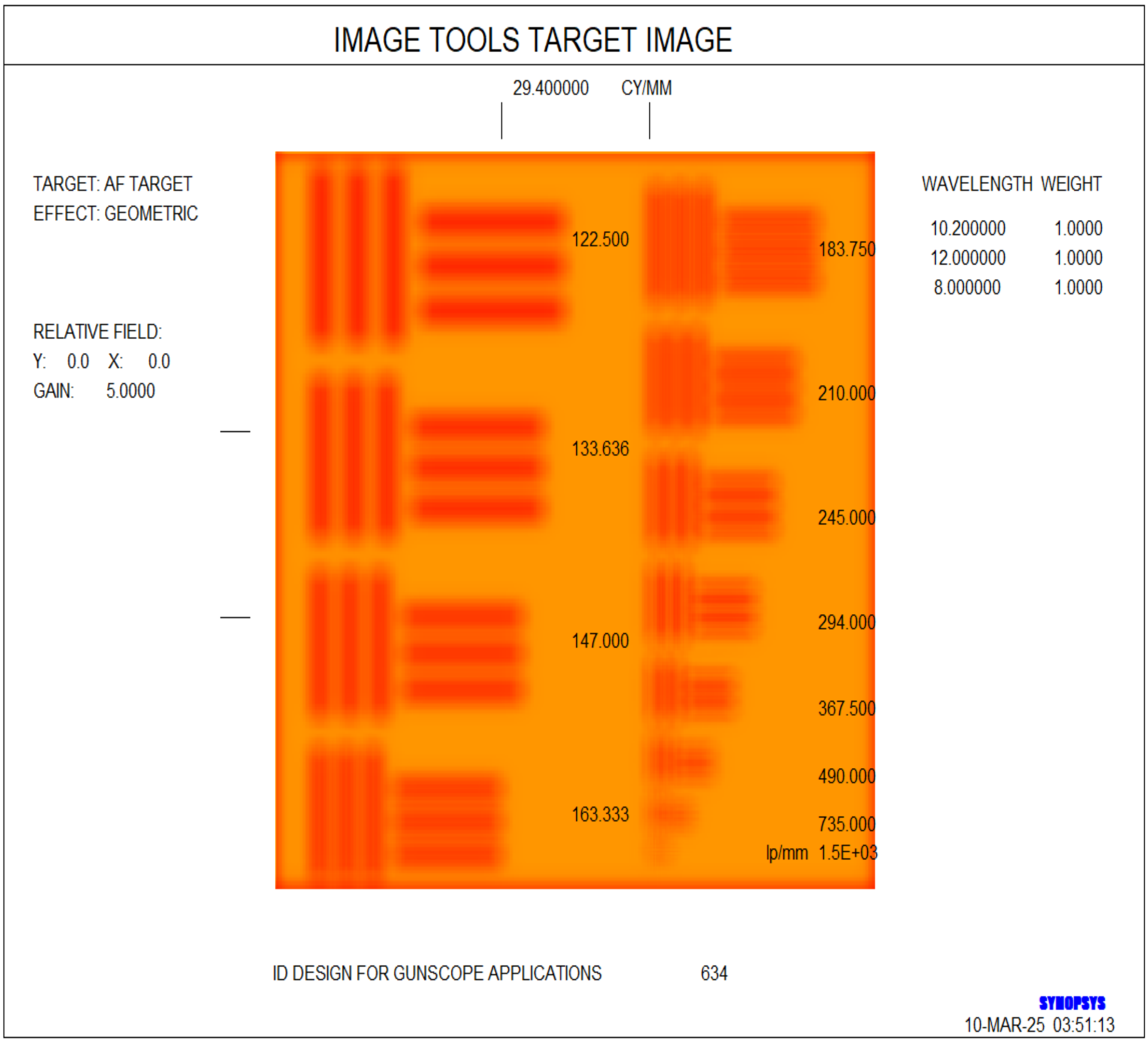

Figure 14: Image Analysis using AF Target Source

IV. Conclusion

A detailed analysis of the Gun Scope optical system's performance is presented using image quality metrics that are integral to the core design process. The design successfully meets all specified image quality criteria, confirming that it achieves diffraction-limited performance while also satisfying product-related metric requirements. In conclusion, by utilizing these core design metrics, the optical system not only meets technical specifications but also fulfills key performance criteria, including MTF, spot diagram, encircled energy, and distortion. This ensures a practical, efficient, and cost-effective solution.

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