ADVANCES IN IR ZOOM LENSES FOR SECURITY AND SURVEILLANCE APPLICATIONS

BACKGROUND

Infrared (IR) imaging technology is pivotal in modern security and surveillance systems, enabling the detection, recognition, and identification (DRI) of objects under various environmental conditions. These capabilities are essential across a broad range of applications, including intelligence, surveillance, reconnaissance (ISR), targeting, border security, and counter-drone operations.

While IR imaging dates back to many decades, its importance – and the challenges involved in deploying it – have continued to grow with advancements in sensor technology, as well as due to the increasing sophistication of threats and even new market trends. As a result, IR cameras equipped with high performance zoom lenses are more essential than ever for capturing clear imagery of people, vehicles, drones, and other targets at extreme distances.

This document explores some of the issues faced in designing and building high-performance IR zoom lenses for DRI applications. It provides an overview of the innovative solutions developed at MKS Ophir to meet these challenges and offers a snapshot of our long range product solutions in SWIR, MWIR, and LWIR, as a way to highlight the current state-of-the-art in this technology.

Products in these three spectral ranges coexist because each offers unique characteristics and benefits. While SWIR is the best spectral range for very long-range daytime observation, MWIR excels in very long-range day and night observation. Both MWIR and SWIR have excellent performances in harsh environmental conditions such as smoke, dust, heavy haze and high humidity. In addition, LWIR is the preferred spectral range for observing burning targets and against sun glints.

KEY REQUIREMENTS AND TRENDS IN DRI

DRI utilizes highly specialized imaging systems. These are necessary to meet the stringent requirements of the applications and to ensure optimal performance under an extremely broad range of often adverse conditions. But the performance demands of DRI are a moving target. They are continuously evolving due to several external factors. Some of the key drivers in this shifting landscape include:

Sensor Improvements

Ongoing technological advances continue to yield sensors with smaller pixels and larger pixel counts (meaning increased camera resolution). As a result, builders of IR imagers must strive to keep them from becoming “optics-limited.” This refers to a condition where the performance of the imaging system is primarily constrained by the performance of the optics, rather than by the sensor.

Today, sensors with a 10 µm pixel pitch are not uncommon, and they are trending towards even smaller sizes (8 µm, 7.5 µm or even 5 µm pixels). The SXGA sensor format (1280 x 1024 pixels) is relatively standard, with some systems utilizing even full HD format (1920 x 1080 pixels) sensors.

SWaP-C Optimization

Size, weight, power, and cost (SWaP-C) optimization is a key imperative in military system design today, guiding the development of advanced technologies across many platforms. For DRI systems, in particular, the increasing use of unmanned aerial vehicles (UAVs) and drones for surveillance introduces especially strict SWaP constraints. These platforms demand lightweight, compact, and energy-efficient optical systems that do not sacrifice performance.

Multi-Spectral Operation

Modern surveillance systems often benefit from multi-spectral imaging. By operating over multiple spectral bands simultaneously – including visible, SWIR, MWIR, and LWIR – they can perform more effective surveillance over a wider range of lighting and weather conditions. This enhances overall situational awareness and expands the capability for accurate detection, identification, and recognition of specific elements and threats within a scenery.

Environmental and Operational Challenges

Security and surveillance operations often occur in harsh environmental conditions, such as extreme temperatures, rain, fog, dust, and saltwater spray. Missions are carried out both day and night. Imagers may be subjected to shock and vibration. And their external surfaces may need to be cleaned periodically. Lenses must be designed to withstand these all these environmental and operating scenarios without compromising performance.

MKS OPHIR SOLUTIONS

Addressing each of these requirements requires deploying a specific technological arsenal in terms of both design and fabrication. Here, we'll review some of the methods employed at MKS Ophir to meet the rigorous demands of modern security and surveillance operations and consistently satisfy advanced DRI and SWaP-C requirements.

DRI Resolution Requirements

Ophir possesses a comprehensive suite of capabilities to address even the most demanding resolution and optical performance requirements for DRI lenses.

The foundation of these capabilities lies in our design process. Our engineers have a wealth of experience with DRI lenses and utilize the most advanced optical design software available. This enables us to create highly innovative solutions.

A critical factor in ensuring our designers' success is that our manufacturing capabilities provide them an expansive design space. That is, their design toolbox includes an extensive array of advanced materials, surface shapes, and surface types.

The ability to use virtually any desired surface shape or type – including traditional spheres, aspheric elements, freeforms, and even diffractive or holographic elements – enables us to achieve high MTF targets, minimize chromatic aberrations, and maintain superior performance throughout the entire zoom range of the lens.

Of course, the full performance potential of our designs can only be realized if they are faithfully reproduced in production. Our extensive range of high-precision fabrication techniques are essential in achieving this goal. This includes the ability to accurately produce optical surfaces and maintain tight mechanical tolerances on components. It also involves the ability to deposit high-quality coatings. Finally, we employ a variety of techniques to ensure that optical elements are perfectly aligned within an assembly.

It's also worth noting that Ophir can fabricate large diameter optics. These can be crucial for achieving very high magnifications in DRI zoom lenses.

Another essential advantage at Ophir is that we bring design and manufacturing together – our entire process from design through final assembly is all performed in a single facility. One example of where this helps us is in producing complex assemblies. Here, it's possible for us to use an interferometer to measure an assembly during production and then feed the actual test data back to the designer. They can then recalculate any changes in component spacing or alignment needed to improve performance, and these can be directly implemented by the assembly personnel. This allows us to maximize performance of every single production unit.

Having vertically integrated approach within a single facility also enables us to fully implement design for manufacturing (DFM) principles and derive the greatest benefits of that practice. Because our designers participate in the fabrication process, they can see which design approaches are most practical and successful. This is essential to the process of continuous improvement that enables us to successfully keep pace with the ever-increasing demands of the market.

SWaP-C Optimization

Leveraging a variety of advanced IR materials also allows us to minimize the total element count in a lens system, thereby decreasing package size and weight and even reducing manufacturing costs. The use of aspheres and diffractive capabilities, in particular, offers another powerful tool for minimizing lens aberrations and reducing component count.

Together, these are critical to our ability to produce continuous zoom lens designs. Being able to use a single lens instead of multiple, single focal length lenses (or even multiple zoom lenses with smaller focal length ranges) is a very powerful way to reduce system size and weight while still maintaining high performance. It also provides greater flexibility for the user by allowing rapid changes in magnification during operation.

Our capabilities for SWaP-C optimization are further extended through the use of folded-optics configurations, as well as multi-spectral designs.

Environmental Stability and Durability

Much of the technology used to enhance the environmental characteristics of long range DRI lenses relates to materials – both optical and mechanical. For example, materials such as titanium and magnesium alloys are often used in the construction of our lenses. These materials are specifically chosen for their combination of mechanical strength, low density (meaning light weight), and resistance to corrosion.

Athermalization techniques are employed by our engineers to ensure that the lenses maintain focus and performance across a wide range of temperatures. Combining materials having different thermal expansion coefficients enables us to create assemblies that inherently compensate for thermal changes. Lenses that remain stable and accurate in varying environmental conditions reduce the need for frequent recalibration, enhancing the operational efficiency of surveillance systems.

In terms of optics, our lenses are equipped with hard carbon (HC / DLC) and high durability (HD) coatings. These enhance resistance to scratching, abrasion, and environmental degradation. This ensures that the lenses maintain high performance even under adverse conditions and extends their operational lifetime.

Ophir lens assemblies are optimized for weight and rigidity, and to withstand shock and vibration. Our engineers design and test any moving parts (like zoom mechanisms) to guarantee long life without maintenance in extreme environmental conditions. Ophir lenses meet or exceed IP67 environmental standards, providing reliable performance in rain, dust, and other harsh environments.

PRODUCTION CAPABILITIES

Ophir manufactures a wide range of optics for security and surveillance applications, including:

- SWIR lenses
- MWIR lenses for cooled cameras
- LWIR lenses for uncooled cameras
- Lightweight IR zoom lenses
- Long-range IR zoom lenses

We offer lenses for different spectral ranges because there is no single spectral region that can provide the “best” results for every operational parameter in every application. The chart summarizes where each type of long-range DRI lenses excels, as well as its drawbacks.

	VIS	SWIR	MWIR	LWIR
Very long-range observation (day)	••	•••	NA	NA
Very long-range observation (night)	NA	•	•••	••
Fog conditions (day)	•	••	•	•
Smoke and dust conditions (day)	•	•••	••	•
Heavy haze condition (day)	•	•••	••	•
High humidity – maritime (day)	••	•••	••	•
Burning targets – blooming	•	••	•	•••
Sun glints	•	•	••	•••
Pulsed laser spot detection	NA	•••	•• Special Optics Only	NA
Materials classification	••	•••	••	•

Performance levels: High ••• Med •• Low •

Table 1: Performance Comparison: SWIR vs MWIR vs LWIR

This is why multi-spectral operation is so valuable – it can simultaneously capitalize on the advantages of each spectral region while avoiding its limitations.

Additionally, what constitutes "best" performance is application specific. The diverse tasks served by these optics each have their own specific performance goals and imperatives. But there are certain key requirements that tend to be shared by all applications. As a result, all Ophir optics are designed and built to:

- Maintain boresight through the full zoom range
- Maintain a fixed f-number through the full zoom range
- Maintain focus through the full zoom range
- Operate over a wide range of temperatures and harsh environmental conditions
- Deliver high image quality
- Provide a fast field-of-view change with continuous optical zoom adjustability
- Provide compatibility with popular cooled MWIR and uncooled LWIR detectors

PRODUCT SNAPSHOT

Ophir manufactures well over one hundred different IR zoom lenses, and more than a dozen specifically for DRI applications. So, it's not possible to review them all in this document.

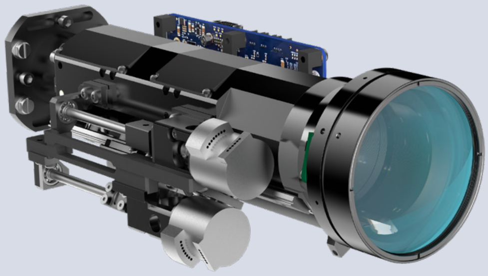
To provide just a snapshot of the overall capabilities at Ophir, three of our long focal length, continuous zoom lenses for SWIR, MWIR, and LWIR detectors are detailed here. Each delivers state-of-the-art capabilities for DRI applications in its particular spectral range.

SWIR & NIR 25-250mm f/5.5 (NFOV) f/4.0 (WFOV)

Operation in these spectral bands delivers long detection range, plus a good balance between day and nighttime operation and the ability to penetrate haze, smoke, and maritime fog. This groundbreaking long-range SWIR zoom lens is the first highly SWaP optimized, continuous zoom lens compatible with the latest 5 µm SXGA SWIR detectors (as well as 10 µm SXGA, and 15 µm VGA sensors). It employs a unique mechanical and optical design to achieve a weight of just 0.86 kg and a length of 214 mm. This makes

Ophir SWIR & NIR 25-250mm Key Benefits

- Extended wavelength coverage 0.7 - 1.7 µm
- 26 km detection range
- Compatible with 5 µm pixel SXGA detectors
- Coated to withstand harsh environments



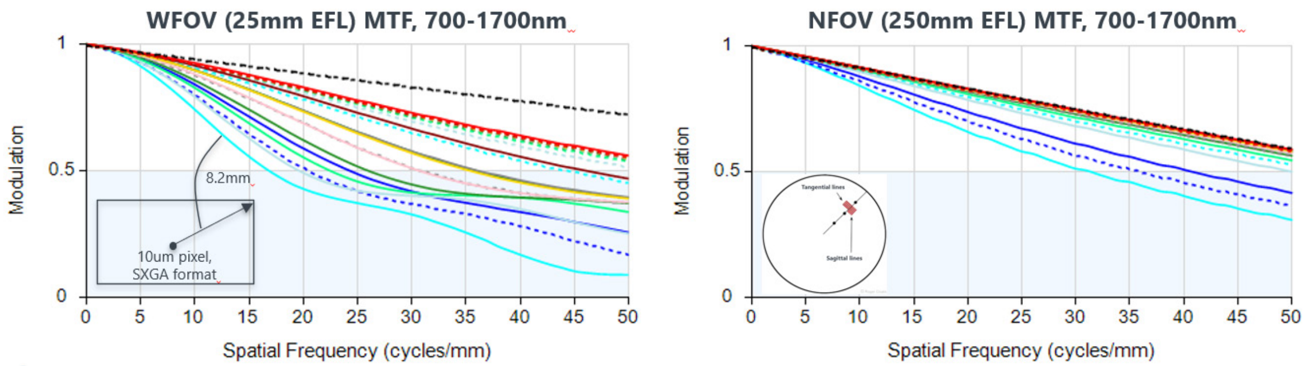


Fig. 1. (a) describes the MTF performances at the WFOV zoom position (25mm), while Fig. 1. (b) presents the performances at the NFOV position (250mm EFL). These charts plot the Sagittal (S) and Tangential (T) components of the MTF as a function of the spatial frequency at different field positions across the focal plane for both WFOV and NFOV in combination with SXGA,10µm detectors.

Image 1: SWIR vs. Visible imagery taken simultaneously.

it approximately 60% lighter than competitive SWIR lenses. The SWIR lens is also chromatically corrected to support operation all the way down to 0.7 µm with minimal distortion.

It can be clearly seen (Fig. 1) that the lens maintains high MTF values at the above zoom positions (and actually also for the intermediate zoom positions, which are not shown here). Top performance levels are targeted for the narrow FOV, as subtle details are more of a necessity for this FOV.

The MTF performance for the 5 µm sensor, especially in the narrow and medium FOV positions, is close to the diffraction limit, and is substantially better than the performance for the 10 µm sensor. This is because the maximum off-axis field for the 5 µm sensor is half of that of the 10 µm sensor, but the cy/mm are doubled from 50 to 100.

The Sagittal MTF at both the WFOV and NFOV is close to the diffraction limit over the whole focal plane, while the Tangential component is lower, especially at the WFOV.

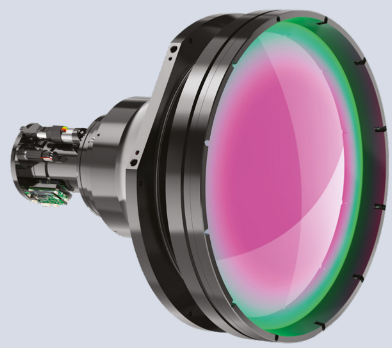
SupIR® (MWIR) 60-1200 mm f/4.0

MWIR imaging offers the longest possible nighttime detection range, combined with excellent performance even in harsh environmental conditions including smoke, haze, and high humidity. This lens provides superior DRI ranges (exceeding 28 km) for vehicle detection and long-range surveillance and is very well-suited to counter-unmanned aerial systems (C-UAS) applications. It is compatible with 10 µm pixel sized 1280x1024 SXGA format cooled MWIR cameras. In terms of performance, it maintains accurate line-of-sight and focus throughout the entire zoom range.

As can be seen in Fig.2, both Sagittal and Tangential MTF are quite close to the diffraction limit for this lens over the whole focal plane, especially at the WFOV. This implies sharp, high-performance image quality capabilities.

SupIR® (MWIR) 60-1200 mm f/4.0
Key Benefits

- Compatible with 10 µm SXGA/HD detectors
- Continuous zoom with extended range
- Withstands severe shock and vibration
- Automatic focus compensation throughout temperature and zoom ranges



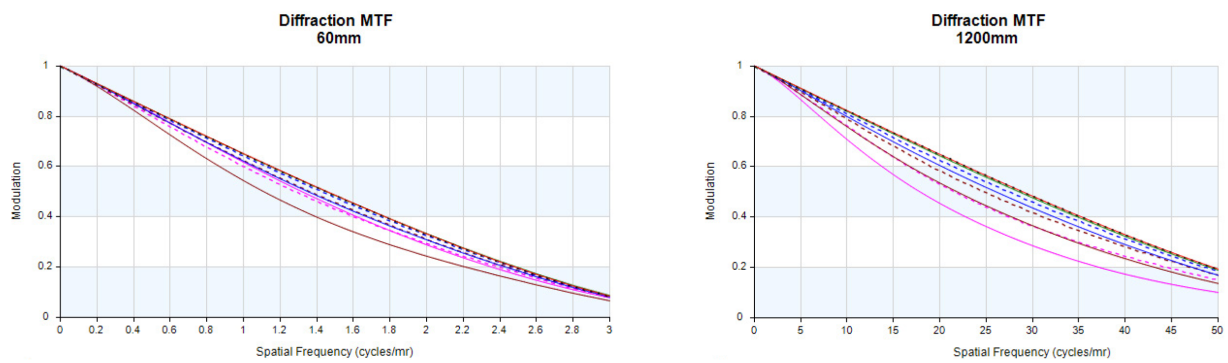


Fig. 2 shows the MTF charts of the 60-1200mm f/4 lens at both NFOV and WFOV.

Image 2: Thermal imaging captured by 60-1200 mm f/4 zoom lens, of objects at a distance of 16.3 km.

SupIR (LWIR) 40-300 mm f/1.5

The most outstanding feature of LWIR sensing is that detects thermal radiation emitted naturally by objects. This allows LWIR sensors to function without any external light source – even in complete darkness. And, even in daylight conditions, LWIR is less affected by sunlight reflections (glint) than shorter wavelengths. Plus, LWIR imaging is less affected by adverse weather or other environmental conditions that other wavelengths.

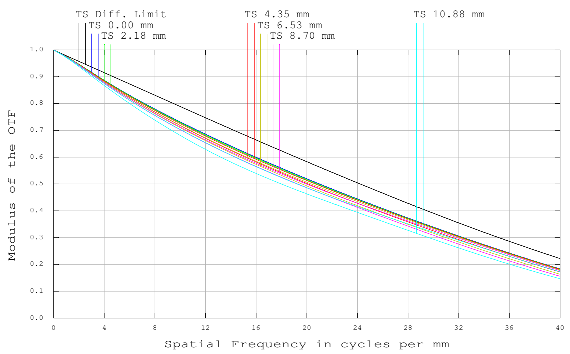
This LWIR zoom lens offers an unmatched combination of detection range, durability, athermalization, and detector compatibility. In particular, the 7.5X zoom ratio provides a broad field-of-view (FOV) that makes it easier to locate and zoom in on targets without losing orientation. This capability is aided by the fact that the lens maintains continuous sharp focus over its entire zoom range. It offers a vehicle detection range exceeding 12.5 km.

This lens supports both 12 µm and 17 µm pixel pitch 1280x1024 SXGA format uncooled LWIR cameras. This makes it versatile and easy to integrate into different camera systems.

SupIR (LWIR) 40-300 mm f/1.5 Key Benefits

- Compatible with 12 µm pixel 1280x1024 SXGA uncooled LWIR cameras
- Passive athermalization for consistent operation under any conditions
- Vehicle detection range exceeding 12.5 km
- High-durability, low reflection hard-carbon AR coatings

WFOV MTF (40mm EFL) MTF 40-300mm



NFOV (300mm EFL) S&T MTF 40-300mm

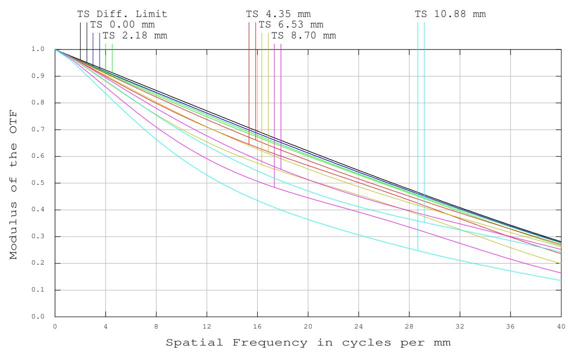


Fig. 3. (a) describes the MTF performances at the WFOV zoom position (40mm), while Fig. 3. (b) presents the performances at the NFOV position (300mm EFL).

In general, the lens maintains high MTF values at the above zoom positions, across the entire focal plane. This especially true at the WFOV position where the off-axis MTF, even at the detector corners, is close to the on-axis MTF values.

DRI Lenses Performance Comparison

Note. Calculated values real world performance may vary depending on the weather conditions.

Assumptions: 23mK NETD (f/4) for MWIR cooled detector | 50mK NETD (f/1.0) for LWIR uncooled detectors | 30Hz frame rate | 50% detection probability | 0.2km^{-1} atmospheric attenuation coefficient | Human ΔT = 5°C | vehicle ΔT = 2°C. SWIR assumptions: 1280 detector | TRM4 model | Day mode | 0.7µm to 1.7µm spectral range | 25Hz frame rate | Overcast daylight irradiance | 0.2 path radiance factor | 0.2km^{-1} atmospheric attenuation coefficient | 50% detection probability | Human and vehicle target 50% reflectivity | 15% background reflectivity

Detection, recognition, identification ranges for each of the three example lenses.

CONCLUSION

Ophir's high-performance SWIR, MWIR, and LWIR zoom lenses provide advanced, long-range DRI, low-SWaP capabilities with state-of-the-art small-pixel, large-format, IR detectors. These lenses meet the evolving demands of modern security and surveillance operations by combining cutting-edge optical design, advanced materials, and comprehensive manufacturing solutions to deliver unmatched performance, durability, and operational flexibility

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