SHRINKING PIXELS, MAINTAINING PERFORMANCE, IN INFRARED IMAGING SYSTEMS

NEXT-GEN OPTICS FOR SMALLER PIXEL PITCH MWIR & LWIR DETECTORS

New MWIR and LWIR detectors with smaller pixels offer the promise of more compact, cost-effective imaging systems. But they also require more sophisticated optics, precisely matched to their characteristics – otherwise, the end result is actually lower performance.

The infrared imaging market is undergoing a significant transformation driven by the miniaturization of pixel pitch in MWIR and LWIR detectors. Over the past decade, pixel sizes have shrunk from 17 μm to as small as 5 μm, enabling more compact, lightweight, and cost-effective imaging systems.

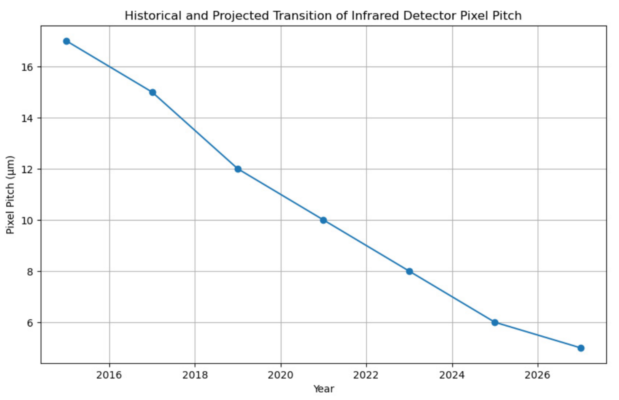

Figure 1: Trends in IR detector pixel pitch over the past decade.[1]

This trend is driven largely by growing demand for SWaP-C-optimized (Size, Weight, Power, and Cost) solutions across multiple markets. In defense, applications ranging from targeting systems to border surveillance increasingly require higher resolution and longer detection ranges – all while maintaining continuous zoom and line-of-sight (LOS) retention. In industrial applications, IR imaging is playing a critical role supporting new regulations in gas leak detection, homeland security, search and rescue, and smart infrastructure monitoring.

As a result, research projects that the global MWIR detector market will grow from $3.15 billion in 2025 to $7.07 billion by 2034, at a CAGR of 9.4%[2]. Similarly, the focal plane array (FPA) infrared detector market is expanding rapidly due to increased adoption in surveillance, environmental monitoring, and industrial automation.

However, incorporating this new generation of smaller pitch detectors poses significant challenges for the imaging system designer. In particular, they require lower fnumber optics with improved modulation transfer function (MTF) at higher spatial frequencies in order to maintain image quality.

This makes it impossible to use the same lenses designed for larger pitch detectors without paying a performance penalty. Instead, achieving high image quality with these small pitch sensors demands more complex optical systems. These must be designed specifically for the task, and then fabricated to tighter optical, mechanical, and assembly tolerances.

With its Ophir Infrared Optics product line, MKS addresses the challenges of building optics for smaller pixel pitch MWIR and LWIR detectors. This is achieved through a combination of advanced optical design, precision opto-mechanical engineering, and cutting-edge manufacturing, assembly and testing processes.

This whitepaper explores the optical issues involved in using small pixel pitch detectors. It then shows how Ophir IR lens solutions enable imaging system builders to take full advantage of these detectors, without sacrificing performance.

THE PROMISE OF SMALLER PIXELS

Infrared detector manufacturers have made significant progress in detector minimization over the past few years. MWIR detector array pixel sizes have gone from 15 μm to as little as 5 μm, and LWIR array pixels have shrunk from 17 μm to 8 μm.

These smaller pixel pitch detectors offer several potential benefits. One advantage is that reducing pixel size shrinks the physical size of a specific form factor detector (e.g. VGA or SXGA). This allows more devices to be fabricated on a single wafer which lowers the unit cost. This cost reduction is especially important for cooled MWIR detectors, where the focal plane array (FPA) is often the most expensive single component in the system.

Physically smaller MWIR FPAs are also easier to cool. Their reduced thermal mass allows for faster cooldown times, enabling more rapid system startup. These detectors also require lower steady-state cooling power, which reduces system size and energy consumption. In addition, smaller FPAs permit the use of shorter cold shield heights and shorter optical paths, which minimizes the amount of unwanted infrared radiation entering the system. This lowers parasitic thermal background noise and improves overall detector sensitivity.

Just as importantly, smaller pixel pitch opens new possibilities for system integration. Customers using older, larger pixel pitch detectors often face challenges such as bulky systems that are difficult to integrate into compact platforms, longer cooldown times with higher power consumption, and lower image fidelity at long ranges due to limited resolution. These issues reduce operational flexibility – especially in mobile, airborne, or handheld systems where SWaP-C constraints are paramount.

Smaller pixel pitch sensors address these limitations. For example, in UAV surveillance, they enable smaller, lighter payloads, supporting longer flight durations and faster startup. In handheld thermal imagers, they enhance portability and battery life, which is critical for field operatives. In border security, higher resolution improves long-range detection and identification even in harsh environments. These advantages – improved image clarity, higher thermal contrast, faster deployment, and better integration into multi-sensor platforms – are driving the shift toward smaller pitch detectors, particularly in SXGA (1280×1024) format.

THE CHALLENGE OF SMALLER PIXELS

However, not everything improves as pixels shrink. For example, smaller pixels collect fewer photons due to their reduced surface area. This lowers signal-to-noise ratio (SNR), which is particularly important in low-signal or long-range detection scenarios.

Smaller pixels also typically exhibit lower quantum efficiency, meaning a smaller percentage of incoming photons are converted into measurable signals. Plus, dynamic range tends to decrease with pixel size since a physically smaller pixel well holds less charge than a larger one.

Another issue is fixed-pattern noise. Manufacturing variation becomes more significant as pixel dimensions shrink, leading to greater non-uniformity in pixel response. This requires more aggressive calibration and correction in the signal processing chain, and even then, residual noise can degrade image quality.

Pixel-to-pixel crosstalk is also more problematic in small-pitch detectors. As pixel size approaches the diffusion length of the detector material, electrical and optical signal leakage between adjacent pixels becomes harder to control. This reduces spatial fidelity and further degrades MTF at the detector level, even before considering the optics.

OPTICS FOR SMALLER PIXELS: OPPORTUNITIES AND CHALLENGES

Security and surveillance operations often occur in Beyond just reducing cost and simplifying cooling, a smaller FPA also offers significant advantages in terms of optics, particularly the ability to improve SWaP-C optimization of imagers. A primary reason for this is because, as FPA size shrinks, the lens focal length needed to maintain the same field-of-view is also reduced.

This can lead to more compact, lighter optical systems, as shorter focal length lenses usually consist of smaller components. More compact lenses can simplify mechanical design, and offer greater flexibility for integration into compact gimbals, handheld enclosures, or multi-sensor payloads. They can also enable lighter, faster zoom and focus mechanisms with lower actuation power and quicker response times.

Shorter optical paths even simplify certain aspects of athermalization and stray light control. For fixed field-of-view systems in particular, these advantages can translate into measurable reductions in SWaP-C at the system level.

These are the promises of smaller pixel pitch sensors. But in reality, obtaining these optical benefits is far from straightforward. In some cases, it may even be impossible.

One key issue is that shrinking the pixel size for a given FPA form factor necessitates the use of lower f-number optics. To understand why this is so, consider three key optical relationships:

$$\text{imaging lens field-of-viev} = 2 \times \tan^{-1}\left(\frac{\text{sensor size}}{2 \times \text{lens focal lenght}}\right)$$

$$\text{f-number} = \frac{\text{lens focal lenght}}{\text{lens clear aperture}}$$

$$\text{spot size due to diffraction} = 2.44 \times \lambda \times f/\#$$

The first equation quantifies the statement made previously; namely, that as sensor size decreases, reducing the lens focal length by the same factor holds the field-of-view constant. The second equation shows that lens f-number remains constant if the lens clear aperture is also decreased by the same factor as the focal length (in other words, the optics are scaled proportionally).

The third equation, which governs diffraction-limited spot size, highlights a critical limitation. Spot size is determined solely by wavelength and f-number, independent of the absolute focal length or aperture diameter. This means that a lens with shorter focal length and smaller aperture will still produce the same diffraction spot size as a longer focal length lens with the same f-number.

However, if pixel size shrinks but diffraction spot size remains unchanged, light will spill into adjacent pixels. This degrades resolution and image quality. To avoid this and preserve performance, the lens diameter must remain constant even as the focal length is reduced. This results in a lower fnumber, which reduces the diffraction limited spot size accordingly.

For imaging lenses (as opposed to laser focusing lenses), the key performance metric is actually MTF rather than spot size. MTF measures how well the optical system preserves contrast at different spatial frequencies at the image plane. When both the sensor and the lens focal length are scaled down, the image projected onto the sensor also becomes proportionally smaller. This shifts the spatial frequencies (measured in line pairs/mm) contained within the image to higher values. Maintaining the same image quality (MTF) as was achieved on a larger pitch FPA therefore requires that the smaller lens delivers better MTF at higher spatial frequencies.

While reducing f-number can help to improve MTF, it also makes the system more sensitive to manufacturing and assembly tolerances. One reason for this is that lower f-number means a smaller depth-of-focus. Additionally, it increases the angle-of-incidence of marginal rays, which complicates the optical design

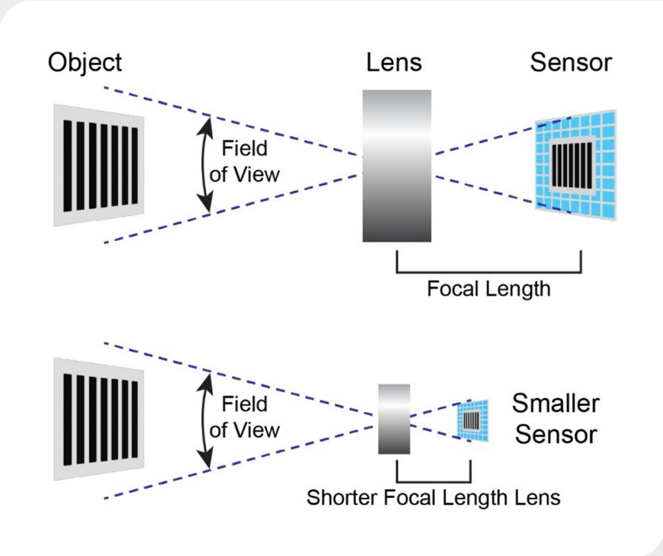

Figure 2: A shorter focal length lens is required to keep field of view constant as detector size shrinks.

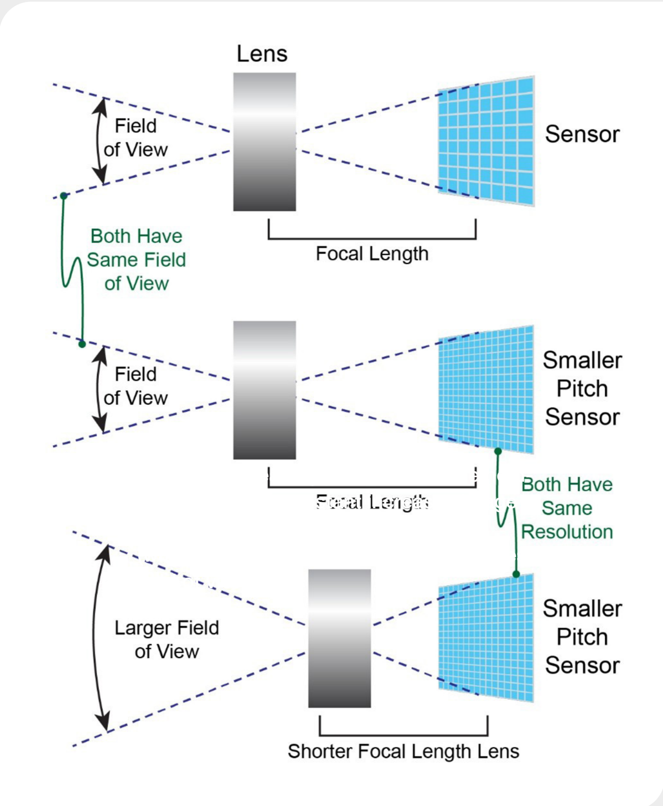

Figure 3: Increasing pixel count while holding sensor size constant increases image resolution. Reducing lens focal length (without changing detector size) increases field of view.

and may require larger entrance pupils than sensor size alone would suggest. It can also make the design and application of optical coatings more difficult.

In continuous zoom systems, in particular, where multiple moving groups of optics must maintain image quality across a wide range of focal lengths, the difficulty of compensating for the effects of low fnumber becomes pronounced. The result can be a lens that is longer, heavier, and more expensive than its larger-pixel predecessor, despite the detector being physically smaller.

OPHIR OPTICS SOLUTIONS

Effectively utilizing small pitch FPAs requires a new, ground-up optical and optomechanical design approach. Simply scaling down an existing lens or relaxing design goals is not enough. Unless deliberate measures are taken to overcome the optical penalties imposed by imaging on small pitch FPAs, the potential SWaP-C gains can be easily lost.

The Ophir Optics product line offers unique advantages through our vertically integrated design and manufacturing process, which is essential for meeting the extreme precision demands of small pixel pitch optics. As pixel sizes shrink and f-numbers decrease, the depth of focus becomes extremely shallow, making the exact positioning of optical elements relative to the detector absolutely critical. Even micron-level misalignments can lead to significant image degradation due to distortion or defocus.

This sensitivity means that optical design and mechanical assembly must be executed at an exceptionally high level. The entire optical path—from lens design to final assembly—must be optimized to maintain image quality and ensure consistent focus across the field. Our in-house control over every stage of the process allows for:

- Tight tolerances in lens alignment and centration, ensuring optimal focus on the detector plane.
- Advanced calibration and compensation techniques during assembly to correct for any residual errors.

- Robust mechanical architectures that maintain alignment under thermal and mechanical stress.
- Precision fabrication of spherical, aspheric, diffractive, flat, and free-form components from virtually all IR materials, including chalcogenide glasses.
- Deposition of a variety of high-performance optical coatings, including those intended specifically for use on low f-number optics with steep surfaces.

Because we control the full lifecycle—from design to fabrication to testing—we can deliver optics that consistently meet the demanding requirements of next-generation infrared systems. This capability is especially critical for continuous zoom lenses and high-resolution applications, where performance and reliability cannot be compromised.

Here we explore in more detail our capabilities in optical design, fabrication, and assembly:

Optical Design

Building this class of advanced IR lenses requires deep expertise in optical design. The Ophir Infrared Optics design team has many decades of experience in creating imaging systems for the most demanding applications.

However, our group understands more than just design theory. They work side-by-side with our fabrication and assembly teams in a single, fully integrated facility. This close collaboration ensures that every optical and optomechanical design performs well and will also be practical to manufacture and robust under real-world use conditions. This is why we are able to consistently deliver optics that meet the highest standards for performance and reliability, even in the most demanding applications.

Our team is equipped with the most advanced and sophisticated optical design software available. Moreover, MKS's fabrication capabilities extend well beyond traditional spherical surfaces to include aspheric, freeform, and even diffractive or holographic surfaces. Additionally, we can fabricate these optics from a wide range of both traditional and advanced optical materials.

Together, this provides our designers with an expansive potential design space, allowing them to explore a variety of highly innovative solutions. These capabilities are all essential contributors to our ability to create low f-number, continuous zoom lenses with exceptional MTF specifications, while still minimizing element count, size, and weight, and optimizing other important characteristics, such as athermalization.

Mechanical Engineering

The mechanical design of optical systems for small-pixel detectors is equally demanding. A reduced depth-of-focus and tighter image tolerances mean even minor mechanical shifts can degrade resolution. Lens assemblies with large continuous zoom ratios (especially those that hold focus over that entire range) must maintain micron-level mechanical precision. In addition, these systems must be ruggedized for use in harsh environments, withstanding shock, vibration, and wear, particularly in UAV and mobile surveillance platforms.

Thermal behavior presents another major challenge. Optical materials refractive index varies with temperature (dn/dT). In addition, all materials expand and contract with temperature, potentially defocusing the system or shifting boresight. Effective athermalization requires careful material selection and precise modeling of system response across broad temperature ranges (often as much as –32 °C to +71 °C).

MKS addresses these challenges with robust, thermally stable mechanical architectures and backlash-free actuators. Our focus and zoom systems are engineered for environmental durability and high repeatability. These stringent standards are even maintained for folded optical designs, which are sometimes used to achieve more compact system packaging. Athermalized designs are optimized to maintain boresight and focus without active compensation, ensuring consistent performance under field conditions.

Fabrication, Assembly, and Testing

Lens systems with tight optical and mechanical tolerances require precise assembly. Micron-level misalignments in lens centration, tilt, or spacing can noticeably reduce system MTF, particularly at high spatial frequencies.

We take several measures during system assembly to ensure wavefront precision, mechanical alignment, and exact detector positioning. For example, during lens assembly, we use interferometric testing to measure wavefront errors. If performance doesn't meet specifications at any point, these measurements are used to calculate the value for spacers or compensators which are put into the assembly to restore it to full performance. Using this process, we can adjust each and every lens we make to minimize residual errors and align them to meet stringent boresight and line-of-sight stability requirements. This is especially important in optics for multi-sensor payloads and long-range targeting systems.

We employ a range of precision fabrication processes, including CNC polishing, diamond turning and magnetorheological finishing (MRF), to consistently produce optics with low wavefront distortion and minimal scatter. Advanced anti-reflection and hard carbon coatings are then applied to maximize transmission and durability.

Finally, each lens undergoes environmental stress testing, including thermal cycling, vibration, and shock. This ensures it delivers its design performance under real-world operating conditions.

Real-World Application: Ophir SupIR® 10–135mm f/1.8 Lens for Next-Gen SXGA MWIR Detectors

Smaller pitch infrared FPAs offer the promise of lower system cost and improved SWaP for imaging platforms – an appealing combination is likely to drive strong demand for them in DRI and related applications.

However, many system developers underestimate the complexity involved in fully realizing the potential of these new detectors. Unless the optics are specifically designed and fabricated to meet the tighter tolerances and higher MTF demands of smaller pixel pitch detectors, the anticipated performance gains can quickly be lost.

MKS is one of the few companies worldwide with both the design expertise and vertically integrated fabrication capabilities needed to build lenses that fully capitalize on the performance potential of today's small pitch FPAs.

Image 1: Ophir SupIR 10-135mm f/1.8 designed for 5 µm SXGA MWIR detectors

Our Ophir SupIR 10-135mm f/1.8 motorized continuous zoom MWIR imaging lenses exemplifies our leadership in this technology. It is the first lens from MKS designed specifically for next generation, cooled, SXGA (1280×1024) MWIR detectors with a 5 µm pixel pitch. This highly SWaP-C optimized lens weights only 780g with a 90mm front diameter and 129mm length, offers a 14x continuous zoom ratio (10 – 135 mm focal length), together with high MTF to maximize image quality for long-range target detection and thermal contrast enhancement.

Figure 4 graphs describe the MTF values as a function of spatial frequency at various field positions for both the NFOV (135mm EFL) and WFOV (10mm EFL) zoom positions. As can be seen, the performance is close to the diffraction limit (upper curve) at all frequencies and fields.

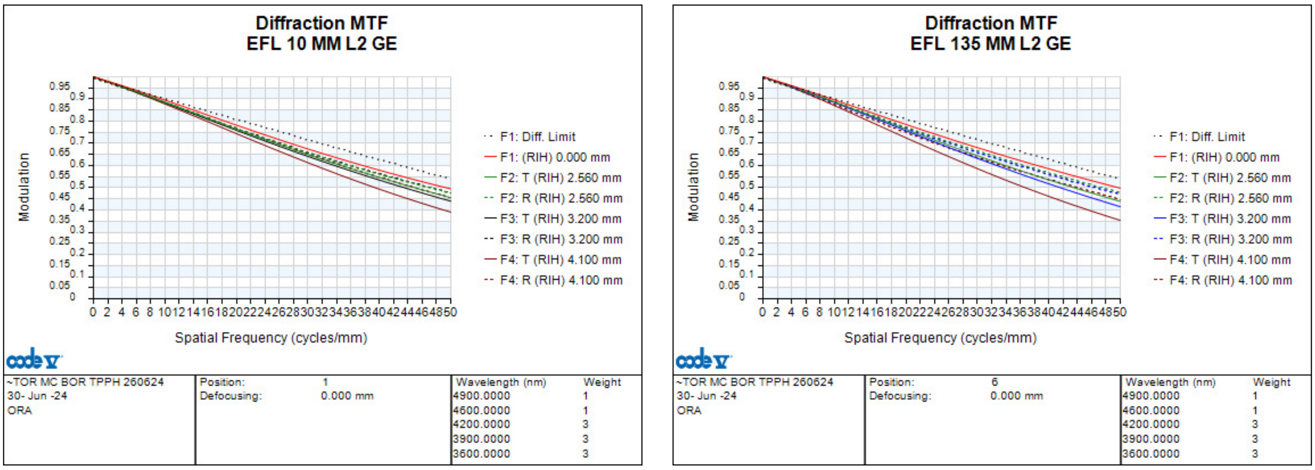

Figure 4: MTF graphs. Left: WFOV 10mm; Right: 135mm NFOV

This lens demonstrates a NATO vehicle detection range of over 17 km. Specifically, it produced a 49mK NETD at f/1.8, with a 30Hz frame rate, 0.2km-1 atmospheric attenuation coefficient, and 50% detection probability. The Johnson Criteria [3] for detection was 1 spatial cycle on target with a 2°C vehicle size and ΔT.

CONCLUSION

Smaller pitch infrared FPAs offer the promise of lower system cost and improved SWaP for imaging platforms – an appealing combination which is likely to drive strong demand for them in DRI and other demanding applications.

However, many system developers underestimate the complexity involved in fully realizing the potential of these new detectors. Unless the optics are specifically designed and fabricated to meet the tighter tolerances and higher MTF demands of smaller pixel pitch detectors, the anticipated performance gains can quickly be lost.

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