

# High-Precision Measurement of Microbolometer Array Modulation Transfer Function (MTF)

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## ABSTRACT

Accurate knowledge of detector modulation transfer function (MTF) is required to evaluate the contrast performance of infrared imaging systems. However, the detector contribution cannot generally be isolated from a measured system MTF without accurate characterization of the measurement method and the detector free contributions of the test setup. We present a dedicated scanned-point-spread-function (PSF) platform for detector MTF extraction of microbolometer arrays. A characterized infrared PSF is translated across a selected detector location using six-axis positioning and autofocus-based focal-plane correction. The local response is Fourier transformed to obtain the system MTF. Configuration-specific detector free contributions, including the projected pinhole, relay optics, and detector window, are then removed to obtain the local pixel MTF. Integrated acquisition and analysis software provides configuration traceability, automated processing, and repeatability assessment. The platform was demonstrated in MWIR and LWIR configurations on a 14- $\mu\text{m}$ -pitch Jaumann microbolometer array. At the detector Nyquist frequency of 35.7 cy/mm, representative band-effective detector MTF values were 0.843 in MWIR and 0.794 in LWIR, compared with system-MTF values of 0.624 and 0.406, respectively. A frequency-dependent quantified contribution envelope was developed for representative MWIR and LWIR measurements, reaching 2.3% and 2.8% ( $1\sigma$ ) at Nyquist, respectively. These results demonstrate a traceable method for separating the local detector response from the measured system response across multiple infrared bands, providing a practical characterization tool for detector development and system MTF allocation.

**Keywords:** microbolometer arrays, modulation transfer function, scanned point-spread function, infrared imaging, detector characterization, MWIR, LWIR, focal-plane arrays

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## 1. INTRODUCTION

The spatial performance of an infrared imaging instrument is governed by the combined modulation transfer function (MTF) of its optical system, detector, and image-processing chain. Reliable knowledge of the detector contribution is therefore required to allocate contrast within an instrument-level MTF budget and to assess whether the targeted ground-sampling distance or spatial-resolution requirement can be achieved [1, 2].

This need is particularly important for spaceborne infrared imaging systems, for which detector performance must be characterized in the context of the complete instrument chain. Luqia, formerly INO, offers two uncooled microbolometer pixel architectures [3] that have been used in space missions and for which detector MTF characterizations are routinely required. The first architecture is sensitive over the 3-14  $\mu\text{m}$  spectral range and consists of a  $1024 \times 768$  pixels array with a 14  $\mu\text{m}$  pixel pitch. Its broad spectral response enables the simultaneous observation of relatively small thermal variations near ambient temperature and high-temperature events such as wildfires, making it particularly relevant to commercial Earth-observation constellations. The second architecture is based on the same readout integrated circuit (ROIC) and extends the spectral response from the ultraviolet to beyond 100  $\mu\text{m}$  through the deposition of a gold black coating on the pixel array [4]. Pixels can be trimmed to pitches corresponding to multiples of 28  $\mu\text{m}$ , depending on the targeted wavelength range. The combination of spatial resolution and ultra-wideband sensitivity makes this architecture suitable for broadband radiometry, as demonstrated by the Broadband Radiometer (BBR) on ESA's EarthCARE mission [5], as well as for planetary exploration instruments combining mineralogical characterization and temperature measurements, such as the Lunar Thermal Mapper (LTM) on Lunar Trailblazer [6]. Both detector architectures can also be integrated into a space-qualified package incorporating butler-block filters in close proximity to the focal plane for multispectral imaging.

For microbolometer arrays, the local spatial response cannot generally be inferred from the pixel pitch or from an idealized full-fill square-pixel aperture model alone. The active fill factor, absorber geometry, and inter-pixel thermal or electrical coupling can all modify the spatial response [7–9]. In the 3–14  $\mu\text{m}$  architecture, for example, the support arms of the suspended pixel platform are exposed, and their effective contribution to the pixel MTF is difficult to predict analytically. In the ultra-wideband architecture, thermal coupling may arise from pixel self-emission or from residual thermal bridges produced by the pixel-trimming process, potentially affecting the detector MTF. Additional spatial-response effects can occur at the detector-assembly level. When spectral filters are integrated in close proximity to the focal plane, for instance, transition regions between adjacent filters can partially vignette the incident beam for pixels near the filter boundaries. Although such effects are not intrinsic to the detector itself, their local impact on spatial response is relevant to the characterization of the assembled focal plane.

System-level MTF techniques, particularly the slanted-edge method, provide efficient and widely used measurements of the combined imaging response [10, 11]. Their principal advantages are experimental simplicity and the ability to obtain the information required to estimate the MTF at a given image location from a single frame. Extracting an accurate detector MTF from such measurements, however, presents several challenges. First, implementing the method over a spectral range extending from 3  $\mu\text{m}$  to beyond 100  $\mu\text{m}$  would require an all-reflective relay providing a sufficiently wide field of view to reimage the slanted edge while maintaining near-diffraction-limited image quality at a F-number near unity, representative of the targeted imaging systems. Second, measurements performed with our existing setups have shown that system-level MTF estimates obtained using the slanted-edge method can vary by several percent as a function of image noise and of the size and position of the analysis window along the edge. Such variations may be acceptable for many system-level measurements but become significant when the detector contribution must be isolated from the measured system response.

The sensitivity of the slanted-edge result arises in part from the processing required to recover the MTF. The edge angle must first be estimated and the edge-spread function (ESF) reconstructed. The ESF is then differentiated to obtain the line-spread function (LSF), a step that can amplify measurement noise [12, 13]. The MTF is subsequently obtained from the magnitude of the one-dimensional Fourier transform of the LSF. When the detector MTF is derived by separating the optical contribution from this system-level measurement, uncertainties introduced at each stage can propagate and lead to substantial uncertainty in the reported detector MTF.

For these reasons, a scanned point-spread-function (PSF) approach was selected for detector characterization. In this method, a well-characterized optical PSF is scanned across individual pixels. The resulting measurements directly provide a finely sampled one-dimensional spatial-response profile, equivalent to an LSF along the scan direction, thereby eliminating the ESF-differentiation step. The optical requirements are also substantially simplified: rather than reimaging an extended slanted-edge target over a wide field of view, the setup needs only to form a high-quality image of a point source over a small region of the detector, which can be achieved using commercially available off-axis parabolic mirrors. Finally, the scanned-PSF method provides a highly localized measurement of spatial response. This capability is particularly useful for investigating spatially varying effects such as residual thermal coupling between trimmed gold-black pixels or changes in MTF near integrated filters transition regions.

This paper presents the developed scanned-PSF measurement platform, which combines a characterized infrared point source and reflective optical relay, six-axis detector positioning, autofocus-based focal-plane correction, and integrated acquisition and analysis software. The approach is demonstrated in mid-wave infrared (MWIR) and long-wave infrared (LWIR) configurations using a representative microbolometer array.

## **2. MTF MEASUREMENT GOALS**

### **2.1 Experimental Detector and Targeted Detector Classes**

The present work originates from an in-house detector-technology program in which both microbolometer pixel structures and complete detector assemblies are fabricated and characterized. The experimental demonstration uses a fabricated 14- $\mu\text{m}$ -pitch bolometric array incorporating a Jaumann-type absorber. This array has been reported separately with broad relative MWIR/LWIR spectral responsivity [4], shown in Figure 1. Its active pixel fill factor is below unity, making local spatial response characterization an informative complement to conventional bolometer measurements. The platform

developed here provides a traceable MTF tool for such studies, rather than relying only on pixel pitch or an ideal full-area square-pixel model.

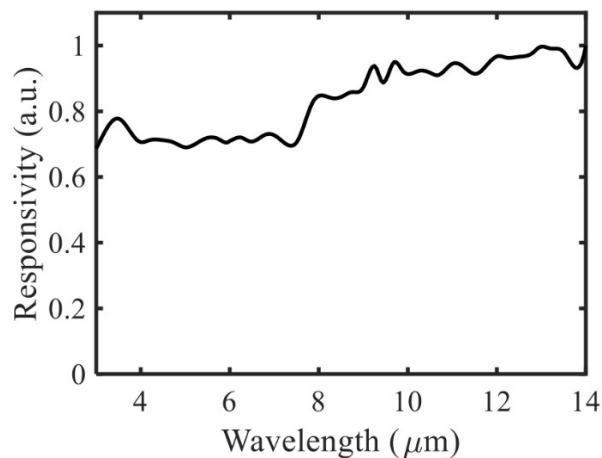


Figure 1: Relative spectral responsivity of the 14- $\mu\text{m}$ -pitch Jaumann microbolometer array. Adapted from Ref. [4].

The present paper extends the existing responsivity, NEP, linearity, and thermal-time-constant characterization with a localized spatial-transfer measurement capability. It therefore adds a traceable MTF tool to support bolometer development, characterization, and comparative studies.

## 2.2 Measurement Objectives and Design Allocation

The platform was designed to support detector MTF extraction with a target relative standard uncertainty below 5% at the detector Nyquist frequency. Because the local pixel MTF is derived from the measured system MTF after correction for the pinhole, relay-optics, and detector-window contributions, a tighter system-level measurement allocation of approximately 1% relative standard uncertainty at Nyquist was adopted during the test-bench design. This allocation was intended to preserve margin for the characterized setup contributions and guided the optical, motion-control, and analysis design.

These values are design targets and allocation criteria. The measured repeatability and quantified contribution envelope reported here are interpreted within that design allocation.

A further design objective was to use commercially available optical, optomechanical, motion-control, source, and metrology components where practical, while integrating them into a dedicated architecture and software workflow. This approach supports adaptable spectral configurations and maintainable test-bench implementation without relaxing the control required for local MTF extraction.

## 2.3 Platform Scope and Applicability

The present platform is designed for infrared MTF measurements above approximately 3  $\mu\text{m}$  and is demonstrated here in MWIR (3-5  $\mu\text{m}$ ) and LWIR (8-12  $\mu\text{m}$ ) configurations. Measurements at shorter wavelengths can be addressed by separate commercially available equipment. Longer-wavelength applications are discussed below.

Although the experimental results reported here were acquired on an in-house detector, the platform is intended to accommodate customer-supplied cameras and detector assemblies, subject to their mechanical, optical, electrical, and acquisition-interface constraints.

The same in-house technology detector portfolio includes a gold black configuration in which 14- $\mu\text{m}$  physical pixels are combined into effective 28- $\mu\text{m}$  units for longer-wavelength operation [4]. The gold black coating is trimmed to match the effective pixel format. The localized scanned-PSF methodology is well suited to investigating spatial-spreading effects associated with coating geometry, support structures, thermal bridges, or inter-pixel coupling. The MWIR/LWIR

configuration presented here provides the experimental foundation for applying the platform to these longer-wavelength detector classes.

Preliminary configuration analyses based on the expected responsivity and NEP of gold black bolometers support feasible platform configurations to wavelengths above 100  $\mu\text{m}$ . At increasing wavelength, wider spectral bands maintain signal level, while the physical pinhole diameter can be scaled with wavelength so that its spatial-filter contribution remains appropriate.

### 3. MEASUREMENT METHODOLOGY

#### 3.1 Scanned-PSF Measurement Principle

The selected MTF measurement method uses a characterized point-spread function (PSF) translated across the detector plane along one spatial axis. The platform can extract the response of a selected detector pixel or integrate a defined set of transverse neighboring pixels. For the results presented here, the corrected response was integrated across a three-pixel transverse strip centered on a selected detector location. This conservative choice captures a greater fraction of the diffracted PSF energy and improves the signal-to-noise ratio. The resulting sequence forms a one-dimensional local response profile as a function of the PSF position at the detector plane. Single-pixel extraction remains available when transverse integration is not applied. Figure 2 summarizes the sequence from localized PSF scan to local detector MTF extraction.

After applying the controlled processing and normalization procedure, the local response profile is Fourier transformed to obtain the system modulation transfer function,  $MTF_{system}$ . This quantity includes the spatial-frequency contributions of the projected pinhole, the relay optics, and the detector under test. The detector contribution is estimated by removing the characterized pinhole and optical transfer function contributions:

$$MTF_{detector} = \frac{MTF_{system}}{MTF_{optics} \times MTF_{pinhole}}$$

Figure 2 summarizes the transfer-function extraction up to the local detector MTF.

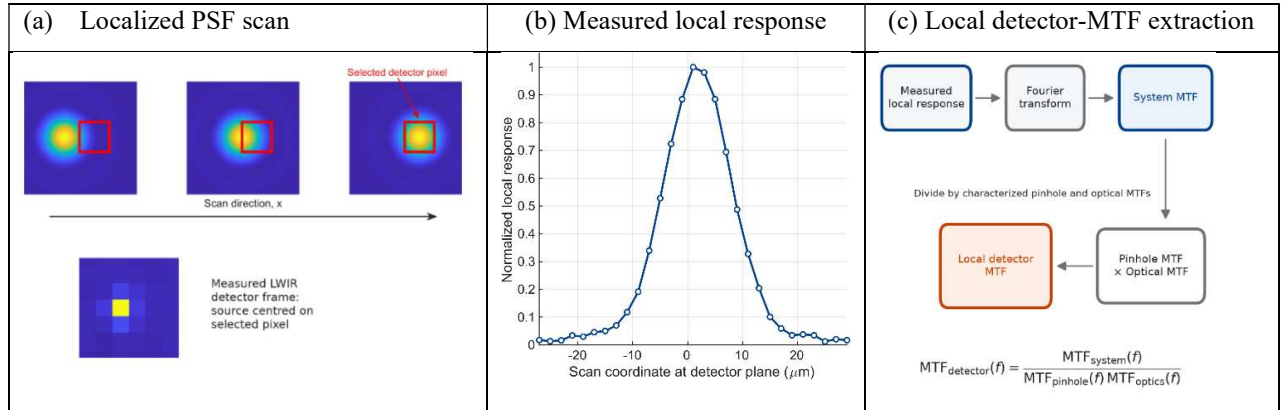


Figure 2: Principle of the scanned-PSF measurement method. (a) Localized PSF scan, (b) reconstructed local response profile, and (c) local detector-MTF extraction. The inset shows a measured LWIR detector frame with the source centered on the selected location.

Assuming that the included contributions are independent, the standard uncertainty of the extracted detector MTF is:

$$\sigma_{detector} = |MTF_{detector}| \sqrt{\left(\frac{\sigma_{system}}{MTF_{system}}\right)^2 + \left(\frac{\sigma_{optics}}{MTF_{optics}}\right)^2 + \left(\frac{\sigma_{pinhole}}{MT_{pinhole}}\right)^2},$$

where  $\sigma_{system}$ ,  $\sigma_{optics}$  and  $\sigma_{pinhole}$  are the errors made on the system MTF, the optical relay MTF and the pinhole image MTF, respectively. These are evaluated and reported in section 5.

### 3.2 Measurement Sequence and Processing

For each measurement configuration, the spectral condition, projected pinhole, optical configuration, scan settings, and processing parameters were recorded with the acquired data. The PSF was translated through a prescribed set of detector-plane coordinates while detector frames and corresponding position information were acquired.

At each scan coordinate, a source-on detector frame and an associated shutter-based offset frame were acquired. The corrected response was formed from these position-matched signal and offset measurements, reducing sensitivity to slow offset and thermal-background variations over the scan duration.

Before a measurement campaign, the autofocus routine characterized the focal-plane geometry. Image sets were acquired through focus sweeps at four spatially separated locations across the focal-plane array. The analysis determined the best-focus coordinate at each location and fitted a focal-plane equation. This model was then used by the acquisition software to correct the two angular degrees of freedom and axial focus along the scan trajectory. In addition to maintaining the local best-focus condition, this approach preserved the intended detector-row registration during scans extending over several hundred pixels.

The corrected responses across the three-pixel transverse strip centered on the selected detector location were integrated at each scan position to form the local response profile. The same controlled processing chain was applied to all results retained for the present study. This includes the correction and normalization operations required to calculate the system MTF and, where applicable, the transfer-function correction used to estimate local pixel MTF.

### 3.3 Comparison with the Slanted-Edge Method

The slanted-edge method is widely used for efficient system-level MTF measurements and naturally provides a spatially averaged response over multiple pixels. Its implementation requires edge localization and fitting, construction of an edge-spread function, numerical differentiation to obtain a line-spread function, and Fourier transformation. The resulting estimate can depend on the acquired region of interest, edge orientation, signal-to-noise ratio, and processing choices [14].

In contrast, the scanned-PSF approach controls the position of a characterized projected source at the detector plane and records the response within a controlled local transverse strip centered on a selected detector location as a function of that position. It therefore provides a spatially localized response profile from which a system MTF can be reconstructed. When the pinhole and optical transfer functions are characterized consistently, their contributions can be retained explicitly and removed to estimate the detector contribution. This approach requires controlled scan positioning, focus, signal level, and a documented processing and normalization chain.

Particular attention was given to the two conditions that most directly govern the credibility of a scanned-PSF measurement: controlled spatial sampling at the detector plane and independent characterization of the setup transfer function. The platform leverages in-house optical-metrology and motion-control capabilities to establish the projected-pinhole and relay-optics contributions and to execute the scan with controlled detector-plane coordinates. The scan step defines the spatial sampling and corresponding scan sampling Nyquist limit of the reconstructed response, while the scan extent defines the frequency resolution of the resulting MTF. These provisions enable detector-MTF extraction without treating the measurement optics or spatial sampling as negligible.

The scanned-PSF method was selected because the objective was localized detector-response characterization. The slanted-edge method remains well suited to efficient, spatially averaged system-level MTF measurements; the two methods address different measurement objectives.

### 3.4 PSF Selection and Sampling

For the MWIR and LWIR configurations reported here, a 50  $\mu\text{m}$  pinhole and a nominal magnification of 0.13333 were used, corresponding to a nominal geometric pinhole-image diameter of approximately 6.67  $\mu\text{m}$  at the detector plane. This geometric value does not by itself define the projected PSF, which also depends on the relay diffraction, geometric aberrations, and focus. The selected configuration balances projected-source size, throughput, diffraction, focus tolerance, and spatial sampling.

The pinhole and relay-optics transfer functions are characterized and included in the setup correction. Configuration values are summarized with the experimental setup in Section 4, and the related quantified contributions are addressed in Section 5.

## **4. TEST BENCH AND SOFTWARE DESIGN**

### **4.1 Test-Bench Architecture**

The platform is organized into source, optical-relay, and detector-scanning-and-acquisition modules, as illustrated in Figure 3. This modular architecture separates spectral selection, formation and characterization of the projected source, and detector-plane scanning and acquisition. The nominal optical path is indicated to clarify the folded all-reflective relay geometry.

The source module combines a stabilized thermal source, spectral filtering, a motorized shutter, and a calibrated pinhole. This arrangement provides the localized infrared source used for the step-scan measurement while allowing the spectral condition to be adapted to the measurement band. The pinhole is mounted in the Luqia QuickPOZ positioning mechanism [15]. During initial installation, the pinhole assembly is manually aligned to the nominal optical axis. Subsequent removal and reinstallation of the pinhole mount yielded a repositioning standard deviation of  $2.6\text{ }\mu\text{m}$  ( $1\sigma$ ,  $n = 10$ ) along the relevant transverse axis. This capability supports repeatable pinhole exchange when the projected source must be adapted to detector pitch, signal-to-noise ratio, throughput, or diffraction constraints. The resulting end-to-end variability associated with complete setup reconfiguration is evaluated separately in Section 5.

The optical-relay module uses gold-coated off-axis parabolic mirrors to provide an all-reflective F/1.15 relay suitable for the targeted infrared wavelength range. Avoiding refractive relay elements limits chromatic effects in the measurement path and also permits the use of visible alignment tools, including a 635-nm source and a visible camera. The relay wavefront was characterized with a visible Phasics wavefront sensor. The measured optical-path-difference map was then propagated to the longer measurement wavelengths and incorporated into the polychromatic optical-relay MTF model. For both configurations, the polychromatic relay model uses the blackbody spectral radiance weighted by the measured transmission of the corresponding spectral filter. The numerical integrations span 2.5–5.5  $\mu\text{m}$  for the MWIR configuration and 7–13  $\mu\text{m}$  for the LWIR configuration.

The detector-scanning-and-acquisition module mounts the detector under test on a six-axis hexapod. This positioning capability provides the mechanical degrees of freedom required for detector alignment, scan execution, and application of the autofocus-derived focal-plane corrections. Thermal panels isolate selected portions of the setup to reduce sensitivity to environmental thermal variations, while optical stops and baffles at multiple locations constrain the field of view and suppress unwanted stray radiation. A two-sided shutter provides a reflective reference on one side and a high-emissivity surface on the other, supporting the position-matched offset acquisition described in Section 3.

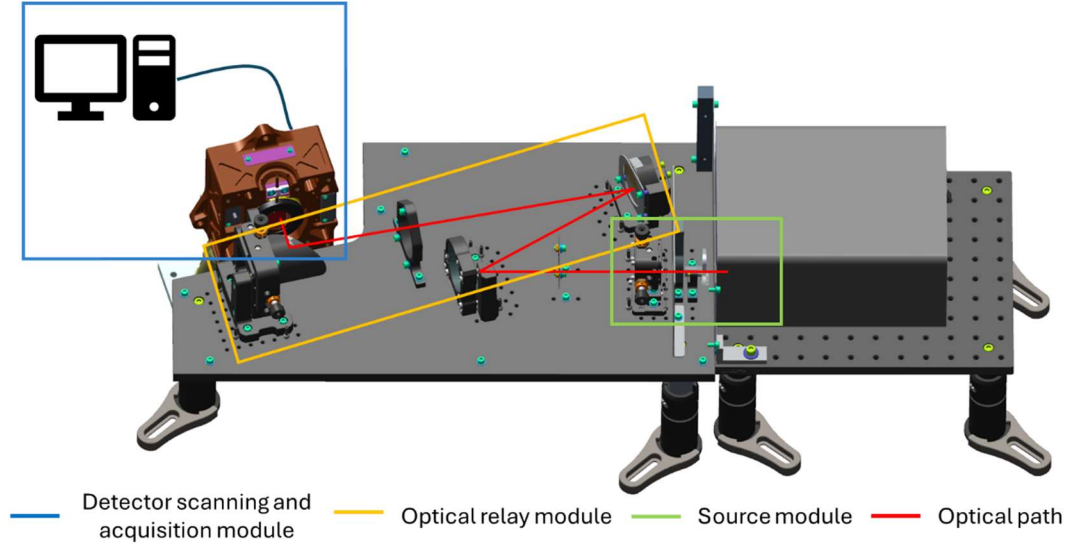


Figure 3: Modular architecture of the scanned-PSF test bench. The source module generates the spectrally conditioned projected pinhole source, the optical-relay module forms and relays the localized source to the detector plane, and the detector-scanning-and-acquisition module positions the detector under test and records the scan data. The red line indicates the nominal optical path.

The main parameters used for the representative MWIR and LWIR measurements are summarized in Table 1. Mechanical, optical, and scan parameters common to both configurations were maintained unchanged, while the spectral filter, spectral weighting, and blackbody temperature were adapted to each measurement band.

Table 1: Principal experimental parameters for the representative MWIR and LWIR measurements.

| Parameter                                              | MWIR                                                                                | LWIR                                                                             |
|--------------------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| Spectral filter band                                   | 3–5 $\mu\text{m}$                                                                   | 8–12 $\mu\text{m}$                                                               |
| Spectral weighting                                     | Planck $\times$ measured filter transmission, integrated over 2.5–5.5 $\mu\text{m}$ | Planck $\times$ measured filter transmission, integrated over 7–13 $\mu\text{m}$ |
| Blackbody temperature                                  | 350 $^{\circ}\text{C}$                                                              | 450 $^{\circ}\text{C}$                                                           |
| Pinhole diameter                                       | 49.7 $\mu\text{m}$                                                                  |                                                                                  |
| Relay magnification                                    | 0.1333                                                                              |                                                                                  |
| Relay F-number                                         | 1.15                                                                                |                                                                                  |
| Nominal pinhole image diameter                         | 6.63 $\mu\text{m}$                                                                  |                                                                                  |
| Scan step                                              | 2.0 $\mu\text{m}$                                                                   |                                                                                  |
| Number of scan positions                               | 29                                                                                  |                                                                                  |
| Scan direction                                         | Horizontal                                                                          |                                                                                  |
| Detector pixel pitch                                   | 14 $\mu\text{m}$                                                                    |                                                                                  |
| Detector Nyquist frequency                             | 35.714 cy/mm                                                                        |                                                                                  |
| Spectral integration nodes                             | 81                                                                                  |                                                                                  |
| Transfer functions removed for detector MTF extraction | Pinhole, relay, and detector-window MTFs                                            |                                                                                  |

## 4.2 Acquisition and Analysis Software

Custom software orchestrates source control, shutter operation, hexapod positioning, autofocus, detector acquisition, and data management. It applies the focal-plane model determined by the autofocus routine to generate the commanded scan coordinates and retains the measurement configuration and processing metadata with the acquired data. These include the spectral condition, projected pinhole, optical configuration, scan coordinates, and processing settings, preserving traceability between the measurement configuration and the analysis result.

The analysis workflow extracts the corrected response across a defined transverse analysis strip centered on the selected detector location at each scan coordinate, reconstructs the local response profile, and calculates the system MTF. It first removes the characterized pinhole and relay-optics transfer functions to obtain the local detector MTF and then applies the detector-window correction to obtain the local pixel MTF reported in this work. The workflow also incorporates an externally calculated detector-window MTF, including thickness-dependent propagation effects. For the results reported here, this contribution was removed after detector-MTF extraction to obtain the window-corrected local pixel MTF.

The final results reported in this work were regenerated using a frozen corrected processing configuration. This ensures that the representative measurements, repeatability series, and quantified contribution calculations use a consistent analysis definition.

For a prepared configuration, the combination of repeatable pinhole mounting, autofocus, automated acquisition, and integrated analysis requires limited manual alignment, enabling a measurement sequence, including data processing, to be completed within a few hours under the established procedure.

OpenAI ChatGPT was used to assist with the development and refinement of selected data-processing and figure-generation scripts. All generated code, calculations, and resulting outputs were reviewed and validated by the authors.

## 5. TEST BENCH VALIDATION AND QUANTIFIED CONTRIBUTIONS

This section characterizes the optical-relay, pinhole, and system-level variability contributions and propagates the included terms through the local detector MTF extraction procedure to form the quantified contribution envelope.

### 5.1 Optical Relay MTF

The optical-relay contribution to the MTF is computed over the waveband of interest from a wavefront map measured using a Phasics SID4 GE wavefront sensor. The wavefront is measured in single pass at 635 nm, with the Zernike terms corresponding to tip, tilt, and focus removed. Because the optical relay is entirely reflective, the measured optical path difference can be scaled to the wavelength of interest and used to compute the corresponding monochromatic PSF. The measured wavefront error has an RMS value of 95.8 nm, corresponding to 0.1508 waves at 635 nm and 0.0319 waves at 3  $\mu\text{m}$ . The uncertainty associated with the measured wavefront map was derived from the Phasics calibration certificate, which specifies a  $\pm 15$  nm bound on the measured optical path difference. Treating this bound as a rectangular distribution gives a relative phase-scale standard uncertainty of 0.0904 with respect to the measured 95.8 nm RMS wavefront error.

Another key parameter governing the dimensions of the PSF in the output focal plane is the relay output F-number. The F-number is determined from the focal length of the output off-axis parabola and the diameter of the aperture stop. A visible source is used to verify that the aperture stop is fully illuminated. The uncertainty in the F-number is calculated from the specified tolerances on the aperture-stop diameter and parabola focal length, yielding an output F-number of  $F/\# = 1.15 \pm 0.012$ . For the representative LWIR local-pixel MTF, propagation of the relay  $F/\#$  uncertainty through the optical model results in an MTF uncertainty of 0.00396 ( $1\sigma$ ), or 0.499% at Nyquist.

The polychromatic PSF is obtained by computing monochromatic PSFs at a discrete set of wavelengths spanning the waveband of interest and combining them using spectrally dependent weighting factors. At each wavelength, the PSF is weighted by the blackbody spectral radiance and the transmission of the spectral filter. This spectral weighting is applied only to the optical-relay model and includes the source radiance and spectral-filter transmission. Detector responsivity and detector-window transmission are not included in this weighting. The wavelength dependence of the gold-coated OAP reflectivity was neglected because its effect over the considered bands was found to be negligible. The source spectrum is modeled using Planck's law at the user-defined blackbody temperature. The effect of uncertainty in the actual blackbody

temperature relative to the value used in the spectral weighting was evaluated using the manufacturer's temperature specification and was found to have a negligible impact on the calculated MTF.

The relay PSF reconstructed from the measured phase map was compared qualitatively at 635 nm with an independently acquired visible-camera profile. Both profiles were normalized to unit peak and transversely integrated for the comparison. The agreement of the main-lobe and secondary-feature structure provides a consistency check for the phase-map-based relay-PSF reconstruction.

It is noted that the detector under test typically has an optical window and that it can have integrated filters which will also affect the optical MTF. The thickness of these elements is known and their impact on the measurement is evaluated analytically and removed to isolate the contribution from the pixels alone.

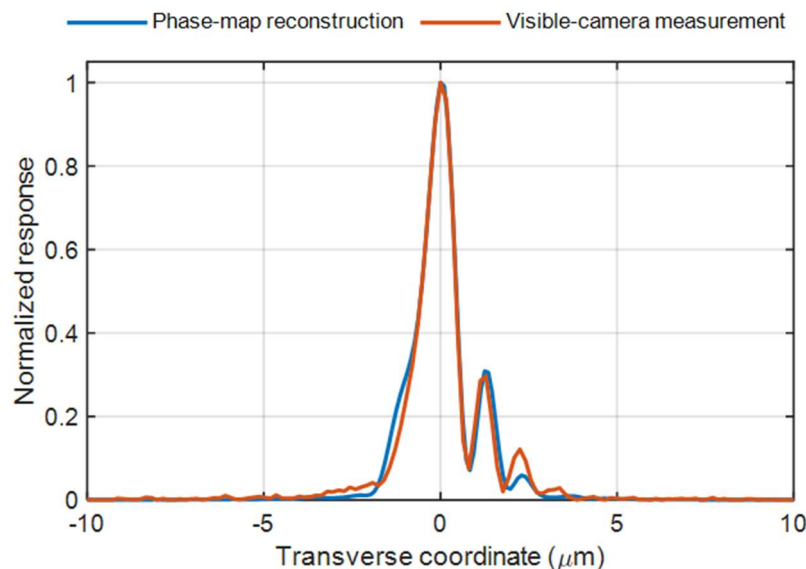


Figure 4: Qualitative consistency check at 635 nm between the transverse-integrated profile reconstructed from the measured relay phase map and an independently measured visible-camera profile. Both profiles are normalized to unit peak.

## 5.2 Pinhole MTF

The pinhole MTF contribution is computed from the pinhole diameter and the optical relay magnification. The pinhole, procured from National Aperture, has a diameter of  $49.7 \pm 0.5 \mu\text{m}$ . The relay magnification, calculated from the focal lengths of the two parabolic mirrors and their associated tolerances, is  $0.13333 \pm 0.0011$ . For the representative LWIR local-pixel MTF, the pinhole-diameter uncertainty contributes 0.00065 ( $1\sigma$ ), corresponding to 0.082% at Nyquist. The sensitivity to relay magnification was quantified separately as 0.00092 (0.12% at Nyquist).

The sensitivity to relay magnification was quantified separately as 0.00092 (0.12% at Nyquist). Because the corresponding focal-length tolerance is already represented in the retained relay F/# uncertainty contribution, the magnification sensitivity was not separately root-sum-square (RSS)-combined.

## 5.3 System-Level MTF

The 1-D system MTF is obtained by scanning the detector at the optical-relay output along one spatial axis. Three tests were performed to characterize distinct operational variability contributions: complete setup reconfiguration, fixed-configuration scan repeatability, and autofocus sensitivity.

The impact of controlled setup reconfiguration was first evaluated in both the MWIR and LWIR and was used to represent the measurement-sequence variability in the uncertainty analysis. Each trial comprised re-seating the spectral filter and pinhole holder, manually pre-aligning the detector under test to position the source near the target pixel, applying autofocus for focal-plane coordinate corrections, and acquiring an MTF scan. The resulting LSF profiles and associated MTFs are shown in Figure 5. At Nyquist, the mean system MTF was  $0.613 \pm 0.014$  in the MWIR ( $n = 5$ ) and  $0.398 \pm 0.011$  in the LWIR ( $n = 3$ ), corresponding to relative standard deviations of 2.28% and 2.76%, respectively.

To further characterize the measurement variability, scan repeatability under a fixed setup configuration was evaluated separately in the LWIR. The setup was left unchanged, and six consecutive scans ( $n = 6$ ) were acquired. At Nyquist, the mean system MTF was  $0.388 \pm 0.003$ . The corresponding relative standard deviation of approximately 0.8% is consistent with the 1% system-level design allocation introduced in Section 2.2. Because scan-to-scan variability is inherently included in the controlled setup-reconfiguration measurements described above, this contribution was not treated as an independent uncertainty term and was not separately combined in the overall uncertainty envelope.

In a third test, the autofocus routine was evaluated separately to quantify its contribution to the local detector MTF uncertainty. Although autofocus is part of the controlled reconfiguration procedure described above, its focal-position sensitivity was assessed independently to distinguish this local contribution from the variability of the complete measurement sequence. For the representative LWIR local-pixel MTF, the autofocus contribution was 0.000359 ( $1\sigma$ ), corresponding to 0.045% at Nyquist. This contribution is negligible compared with the other sources of variability investigated and was therefore reported separately rather than RSS-combined.

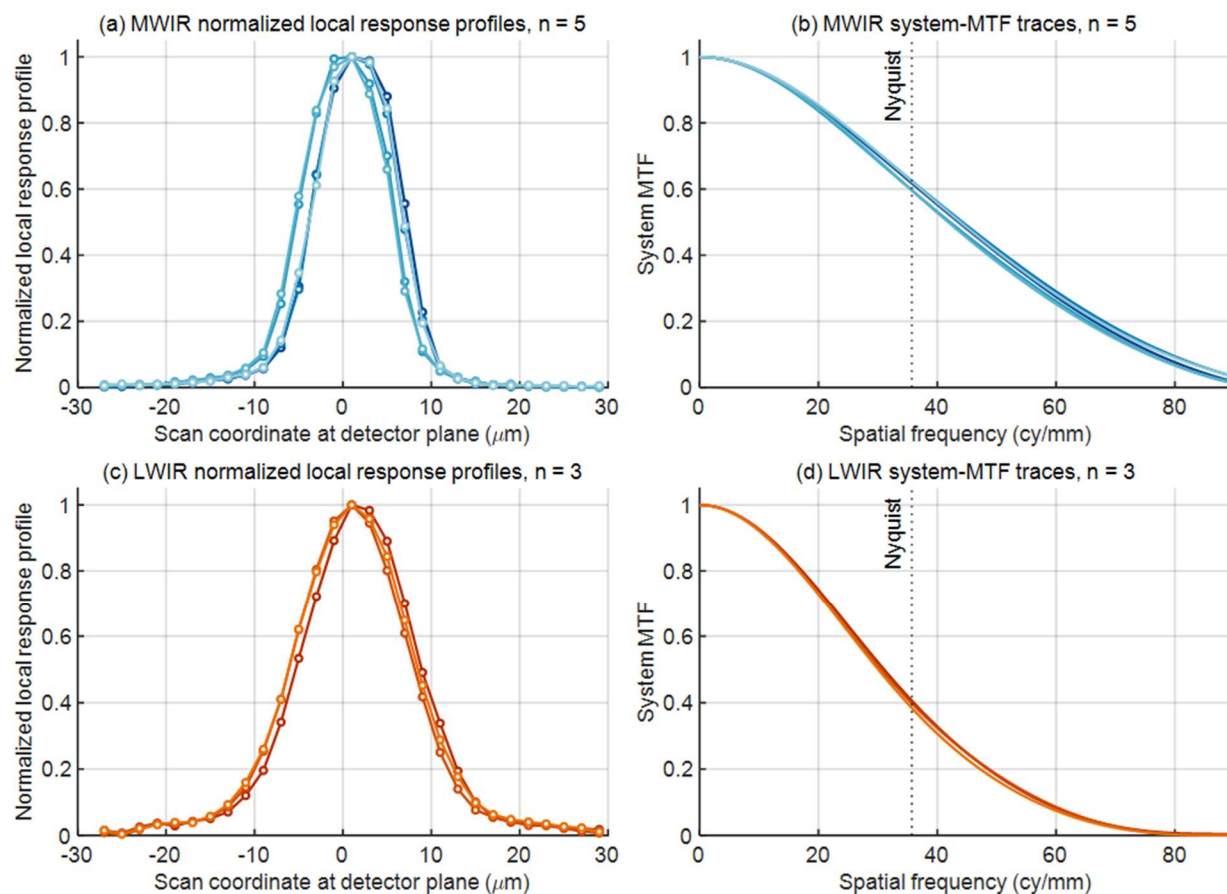


Figure 5: Operational repeatability following controlled setup reconfiguration and autofocus. (a,c) Peak-normalized local response profiles for MWIR ( $n = 5$ ) and LWIR ( $n = 3$ ), respectively, at the selected center-field location. Corresponding system-MTF traces (b,d); dashed-lines indicate the band-specific Nyquist frequency. Each trace represents one complete measurement following filter/pinhole re-seat, device under test (DUT) pre-alignment, autofocus for focal-plane coordinate correction, and MTF scanning.

## 5.4 Quantified Contribution Study for Local Pixel MTF

The quantified uncertainty contributions to the local pixel MTF were evaluated by propagating the identified measurement and setup uncertainties through the MTF correction procedure. The representative LWIR case is summarized in Table 2 and illustrated as a function of spatial frequency in Figure 6. The setup-reconfiguration contribution corresponds to the variability of the complete operational measurement sequence, including filter and pinhole re-seating, device under test (DUT) pre-alignment, autofocus, and MTF acquisition. Because scan-to-scan repeatability and autofocus-positioning sensitivity are inherently represented within this complete sequence, they were characterized separately but were not independently combined in the RSS uncertainty envelope. The relay-magnification sensitivity was reported separately, as discussed in Section 5.2.

For the representative LWIR measurement, the setup-reconfiguration variability measured at the system-MTF level was 0.011 at Nyquist, as reported in Figure 5. Propagation through the setup correction used to recover the local pixel MTF results in a corresponding detector MTF contribution of 0.0217 ( $1\sigma$ ), as reported in Table 2. This distinction explains the difference between the system-level variability reported in Figure 5 and the larger contribution appearing in the detector MTF uncertainty budget.

The reconfiguration series shown in Figure 5 was used to estimate the operational standard deviation, whereas the envelope in Figure 6 was centered on the representative measurement retained for the final detector MTF extraction.

Table 2 summarizes the individual contributions at Nyquist and identifies those retained in the RSS combination. For the representative LWIR local pixel MTF of 0.794 at Nyquist, the combined quantified contribution is approximately 0.022 ( $1\sigma$ ), corresponding to a relative uncertainty of approximately 2.8%. As shown in Figure 6(a), this combined uncertainty is propagated over spatial frequency to form the quantified contribution envelope around the representative local pixel MTF. Figure 6(b) shows the corresponding frequency-dependent contributions, with setup reconfiguration dominating the overall envelope and the optical-relay and pinhole terms remaining substantially smaller.

The same uncertainty-propagation procedure was applied to the representative MWIR measurement. The individual contributions were of comparable order of magnitude and led to a combined relative uncertainty of 2.32% ( $1\sigma$ ) at Nyquist. Thus, for both spectral bands, the quantified local detector MTF uncertainty remains below the initial target of 5%.

Table 2: Quantified contribution summary for the representative LWIR detector MTF measurement. **Bold entries** are included in the RSS uncertainty envelope; non-bold entries are quantified separately and are not RSS-combined.

|               | Uncertainty contribution                  | Absolute detector MTF SD uncertainty contribution @Ny | Pixel MTF Value @ Ny | RSS relative SD uncertainty ( $1\sigma$ /MTF) |
|---------------|-------------------------------------------|-------------------------------------------------------|----------------------|-----------------------------------------------|
| Optical Relay | <b>Wavefront-map phase error</b>          | <b>0.00123</b>                                        | 0.7938               | <b>0.52%</b>                                  |
|               | Magnification                             | 0.00092                                               |                      |                                               |
|               | <b>F/#</b>                                | <b>0.00396</b>                                        |                      |                                               |
|               | <b>Blackbody temperature</b>              | <b>0.00003</b>                                        |                      |                                               |
| Pinhole       | <b>Diameter</b>                           | <b>0.00065</b>                                        |                      | <b>0.08%</b>                                  |
| System        | Scan repeatability                        | 0.00585                                               |                      | <b>2.73%</b>                                  |
|               | <b>Setup re-configuration variability</b> | <b>0.0217</b>                                         |                      |                                               |
|               | Autofocus positioning                     | 0.000359                                              |                      |                                               |
| <b>Pixel</b>  | <b>Combined quantified envelope</b>       | <b>0.0221</b>                                         | <b>0.7938</b>        | <b>2.78%</b>                                  |

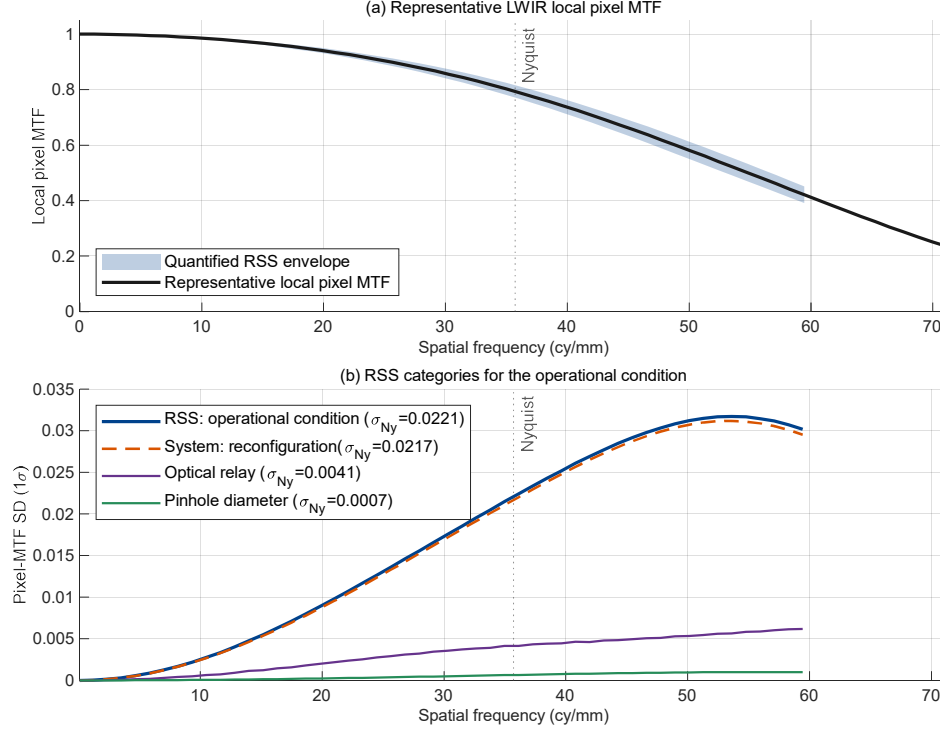


Figure 6: Representative LWIR local pixel MTF, corrected for the detector-window contribution, with a quantified contribution envelope. (a) Local pixel MTF obtained under the operational setup-reconfiguration condition. The shaded region denotes the absolute detector MTF standard deviation at  $1\sigma$ . (b) Frequency-dependent contributions retained in the RSS combination, grouped as system, optical-relay, and pinhole terms. The included terms are combined in quadrature over their common 0–60 cy/mm support.

## 6. EXPERIMENTAL RESULTS & DISCUSSION

### 6.1 Multi-Band Local Detector MTF Results

Representative local detector MTF results obtained with the scanned-PSF platform are presented in Figure 7 for the MWIR and LWIR configurations. The reported quantity is a band-effective local pixel MTF under the configuration-specific source and spectral-filter weighting defined in Section 5.1. The two measurements therefore demonstrate the same transfer-function extraction procedure under distinct spectral and optical conditions.

In each panel of Figure 7, the measured system MTF is shown together with the characterized setup MTF and the resulting local pixel MTF. At the detector Nyquist frequency of 35.7 cy/mm, the MWIR system and setup MTFs were 0.624 and 0.740, respectively, yielding a local pixel MTF of 0.843. The corresponding LWIR values were 0.406, 0.511, and 0.794. These results illustrate the importance of accounting for the setup response when extracting the local pixel MTF, particularly in the LWIR configuration, where the setup MTF is lower at Nyquist.

For reference, a common first-order estimate of pixel MTF assumes an ideal square aperture with a width equal to the 14- $\mu$ m pixel pitch, yielding an MTF of  $2/\pi$ , or approximately 0.637, at Nyquist. Such a geometric sinc model, however, does not fully represent the spatial response of a real detector pixel. Even when the physical dimensions of the active region are known, the resulting MTF can be further modified by the detector architecture, absorber structure, support structures, and inter-pixel coupling or spreading mechanisms [7-9]. Consequently, neither pixel pitch nor geometric fill factor alone is sufficient to predict the effective local pixel MTF. The measured values of 0.843 in the MWIR and 0.794 in the LWIR therefore highlight the importance of directly characterizing the local pixel response rather than inferring it solely from pixel geometry.

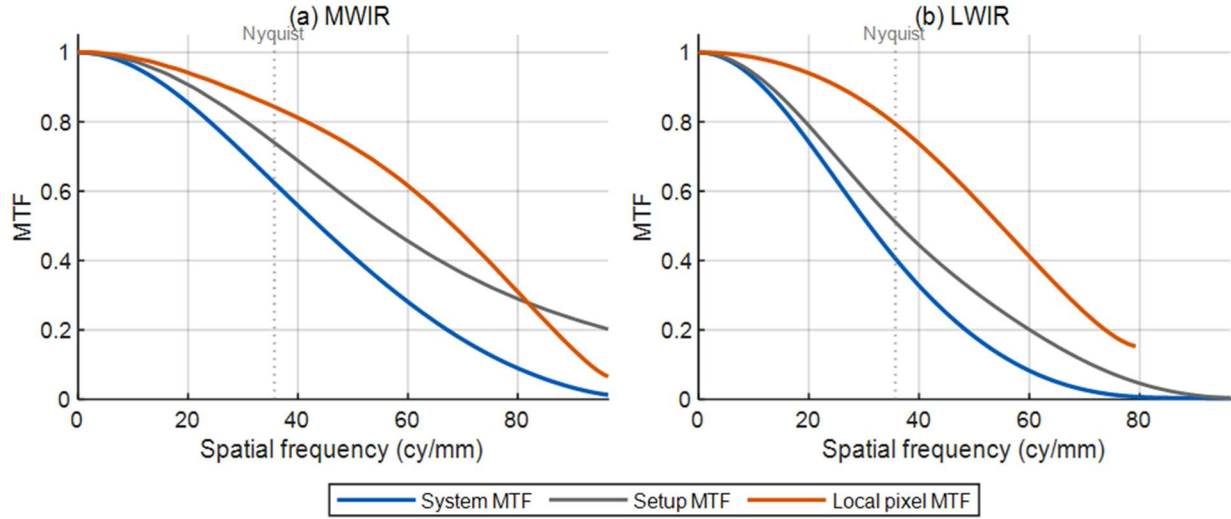


Figure 7: Representative multi-band transfer-function results obtained with the scanned-PSF platform. (a) MWIR and (b) LWIR measurements. The measured system MTF, characterized setup MTF, and local pixel MTF are shown for the same transfer-function extraction chain. The vertical dotted line indicates the detector Nyquist frequency.

The transverse scan provides a local measurement centered on a selected detector region rather than an array-averaged system response. The results in Figure 7 therefore represent the spatial response measured locally at the selected detector location and illustrate the ability of the method to separate the local pixel response from the measured system response.

The transfer-function branches in Figure 7 are shown beyond the detector Nyquist frequency to illustrate the behaviour of the extraction procedure. At higher spatial frequencies, the decreasing setup MTF makes the division increasingly sensitive to residual measurement variations; these portions of the curves are therefore shown primarily as a diagnostic of the transfer-function extraction rather than as an independent detector-performance metric.

The quantified  $1\sigma$  uncertainty envelopes associated with the extracted local pixel MTFs are 2.32% in the MWIR and 2.8% in the LWIR at Nyquist, as established in Section 5.4.

## 6.2 Next Steps

The present results establish the measurement capability and quantified performance of the scanned-PSF platform, while also identifying several areas for further maturation. First, the controlled setup-reconfiguration campaign will be extended to a larger number of repetitions in both MWIR and LWIR, using the same selected detector location and a consistent reconfiguration procedure. This will strengthen the statistical basis of the operational variability currently estimated from a limited number of trials.

An independent system-level MTF reference, for example using a calibrated transmission slit or another characterized reference detector, will also be investigated to provide an external validation of the complete measurement chain. These activities are intended to increase confidence in the quantified measurement performance and extend the applicability of the platform without changing the underlying scanned-PSF measurement principle.

## 7. CONCLUSION

This work established a scanned-PSF platform for localized MTF characterization of infrared detector arrays. The platform combines a reconfigurable infrared source, an all-reflective optical relay, detector-plane scanning, and a transfer-function-based analysis workflow to separate the local pixel response from the measured system response. The modular architecture was developed to support configuration changes in source size, spectral band, and detector geometry while maintaining a common measurement and analysis approach.

The platform was demonstrated experimentally in both MWIR and LWIR configurations on a 14- $\mu\text{m}$ -pitch Jaumann microbolometer array. At the detector Nyquist frequency, representative band-effective local pixel MTF values of 0.843 in the MWIR and 0.794 in the LWIR were extracted from measured system MTF values of 0.624 and 0.406, respectively. These measurements illustrate the importance of characterizing and removing the setup transfer function rather than inferring the local pixel response from the measured system MTF or from pixel geometry alone.

The measurement performance of the platform was assessed through controlled repeatability and uncertainty studies. A quantified contribution analysis propagated the identified setup and measurement uncertainties through the detector MTF extraction procedure, resulting in relative  $1\sigma$  uncertainty envelopes of 2.32% in the MWIR and approximately 2.8% in the LWIR at Nyquist. Controlled setup reconfiguration was the dominant operational contribution, while scan repeatability and autofocus sensitivity were characterized separately to assess their individual effects without double counting contributions already contained in the complete reconfiguration sequence.

The same architecture and analysis workflow can support controlled pixel-to-pixel comparisons, investigation of local detector structures and spatial nonuniformities, adaptation to different detector pitches and source conditions, and measurements in additional infrared spectral bands. In particular, the reconfigurable all-reflective relay and source architecture were designed to facilitate extension toward FIR configurations. The demonstrated MWIR/LWIR performance thus provides a validated baseline for broader localized detector-response characterization across infrared detector technologies and spectral regimes.

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