Ultraviolet through Infrared Imager Performance Testing

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ABSTRACT

The objective of any imaging system is to optimize the amount of pertinent information collected from a scene. Whether it is used for artistic reproduction, scientific research, or camouflage detection, a camera has the same ultimate requirement. In the era of broadband, multi-spectral, hyperspectral, and fused sensor systems, both spectral and spatial data continue to play battling roles in determining which is dominant in how well an imaging system meets its definitive objective. Typically sensor testing requires hardware and software exclusively designed for the spectral region of interest. Thus an imaging system with ultraviolet through infrared imaging capabilities could require three or more separate test benches for sensor characterization. Obviously this not only increases the complexity, and subsequently the cost of testing, but also more importantly tends to produce discontinuous results. This paper will outline the hardware and software developed by the authors that employ identical test methods and shared optics to complete infrared, visible, and ultraviolet sensor performance analysis. Challenges encompassing multiple emitting source switching, splitting, and combining will be addressed along with new single fused type source designs. Decisions related to specifying optics and targets of sufficient quality and construction to provide coverage of the full spectral region will be discussed along with sample performance specifications and data. Test methodology controlled by a single automated software suite will be summarized including modulation transfer function, signal to noise ratio, uniformity, focus, distortion, intrascene dynamic range, and sensitivity. Selected examples of results obtained by this test set will be presented.

Keywords: Infrared, Visible, Ultraviolet, Multi-Spectral, Test, MTF, SNR, Blackbody, Integrating Sphere, Optics

1. INTRODUCTION

Sensor testing is imperative to all imaging systems. The results of which typically serve to either validate operational specifications or to verify image quality. The confirming of operational parameters is usually a relatively straightforward task as these parameters delineate how they are to be verified. Image quality on the other hand is a much more prejudiced specification. The term "quality" is defined as: a degree or grade of excellence or worth[1]. Image quality is no exception and is traditionally a subjective specification that often requires an array of objective tests to confirm agreed on performance.

The task of image analysis becomes even more complex when facing broadband camera systems. Multi-spectral imaging systems are becoming more prevalent as optical surveillance continues to grow as one of the most important aspects of threat detection and prevention. From night vision goggles to unmanned vehicles, broadband imaging technology and fusion systems are proving to be of fundamental importance. Although the basic imager evaluation methodology remains the same, the supporting test bench grows increasingly multifaceted when coupled to a system that can acquire data across multiple spectral regions.

A typical test set up required for camera testing would include a calibrated radiation source, a set of precision targets, and suitable projection optics. Following the traditional approach one could possibly conceive of three separate systems all specified for individual spectral regions of interest, such as ultraviolet, visible, and infrared. When testing a multi-spectral imager each region would be tested individually and the results would subsequently be combined in reporting. Unfortunately this method not only becomes expensive and complex but also is vulnerable to discontinuity caused by differences in methodology introduced by separate testing hardware. It is instead better to use a single optical system and set of targets capable of being utilized across the entire spectrum of interest. Various radiation sources can be optically combined, simply switched into position, or even fused themselves. Add to this a set of control/analysis software and the comprehensive test system is complete.

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2. RADIATION SOURCES

In order to project a test image a uniform source of energy is required to fully backlight the imaging plane. This radiation source is specified based on the particular spectral response of the sensor or sensors under test. The source must not only uniformly illuminate the target and be diffuse but must also be calibrated so that its energy output is known over the wavelengths of interest. It is best to perform a direct radiometric calibration although it is also acceptable to derive energy output from known emissivity values.

2.1 Ultraviolet

The source chosen to provide ultraviolet energy is a Xenon arc lamp. Depending on the wattage required this lamp can be mounted in a standard natural convection or forced liquid cooled chassis. The radiant output of the arc lamp enters a Polytetrafluoroethylene (PTFE) coated integrating sphere as directed by an aluminized ellipsoidal reflector through a variable attenuator. A calibrated photodiode within the sphere maintains closed loop control of the output by feeding back to the attenuator drive. The final uniform stable output of the sphere is then used to backlight the imaging plane. See Figure 1 for typical relative spectral output of a Xenon arc lamp coupled to a PTFE coated integrating sphere.

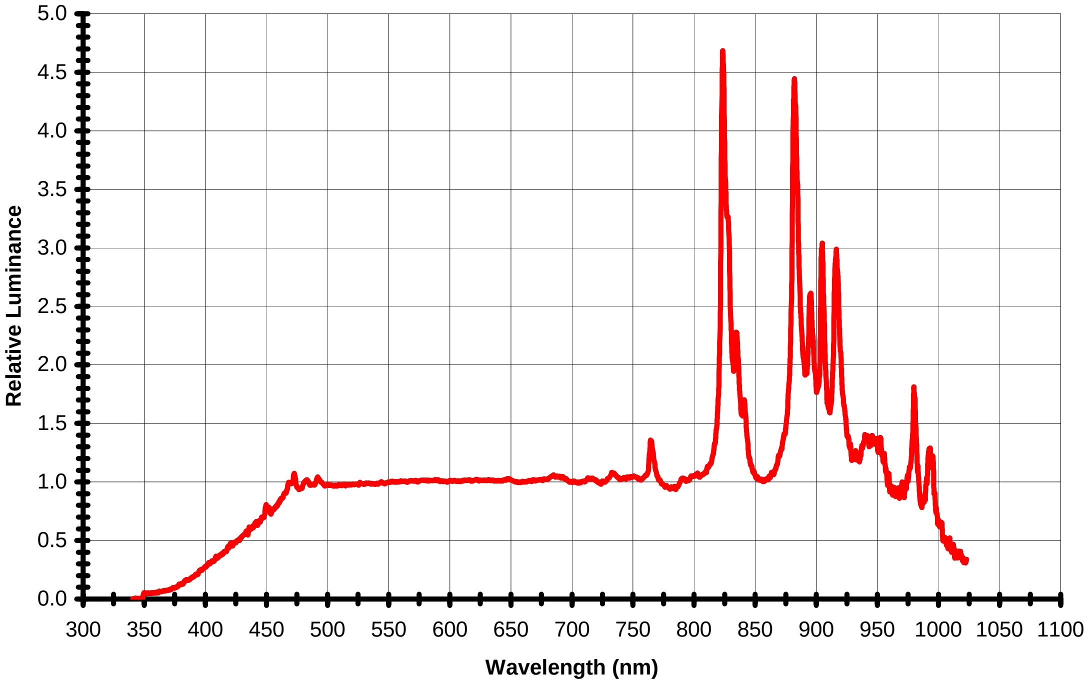

Figure 1. Xenon Arc Lamp Powered PTFE Integrating Sphere Relative Spectral Output (Normalized at 550nm)

2.2 Visible

As shown above in Figure 1, the Xenon arc lamp not only provides ultraviolet energy but is also an excellent source of visible radiation as well. If the imager under test does not include any response in the ultraviolet a simpler alternative source of visible energy is the Quartz Tungsten Halogen (QTH) lamp. This type of light source is simple to control and readily available commercially making it an attractive alternative to the Xenon arc lamp for visible energy. Utilizing a

QTH lamp is much the same process as the arc lamp. Radiation is directed by a silver-coated reflector through a variable attenuator and into a PTFE coated integrating sphere. A calibrated photodiode within the sphere maintains closed loop control of the output by feeding back to the attenuator drive. The final uniform stable output of the sphere is then used to backlight the imaging plane. See Figure 2 for typical relative spectral output of a QTH lamp coupled to a PTFE coated integrating sphere.

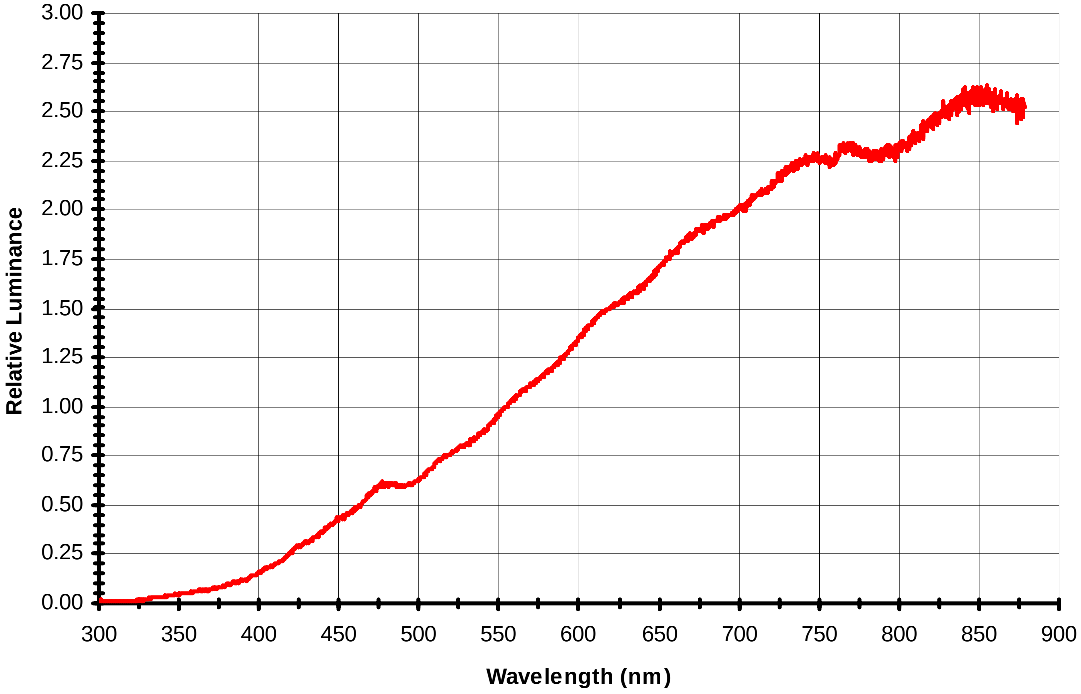

Figure 2. QTH Lamp Powered PTFE Integrating Sphere Relative Spectral Output (Normalized at 550nm)

2.3 Infrared

To provide the thermal radiation required for infrared imagery analysis a blackbody will be employed. The geometry and temperature specification of the blackbody are dictated by the spectral response of the infrared sensor under test. Typical blackbody geometries include the flat plate extended area source, grooved plate extended area source, and cavity source. Operational temperature range is specified independently of blackbody geometry. Each type of blackbody design has advantages and drawbacks. The extended area source allows for uniform illumination of larger targets while the cavity type source provides superior emissivity. See Figures 3 and 4 for typical emissivity curves of flat and grooved plate extended area sources, and cavity source, respectively.

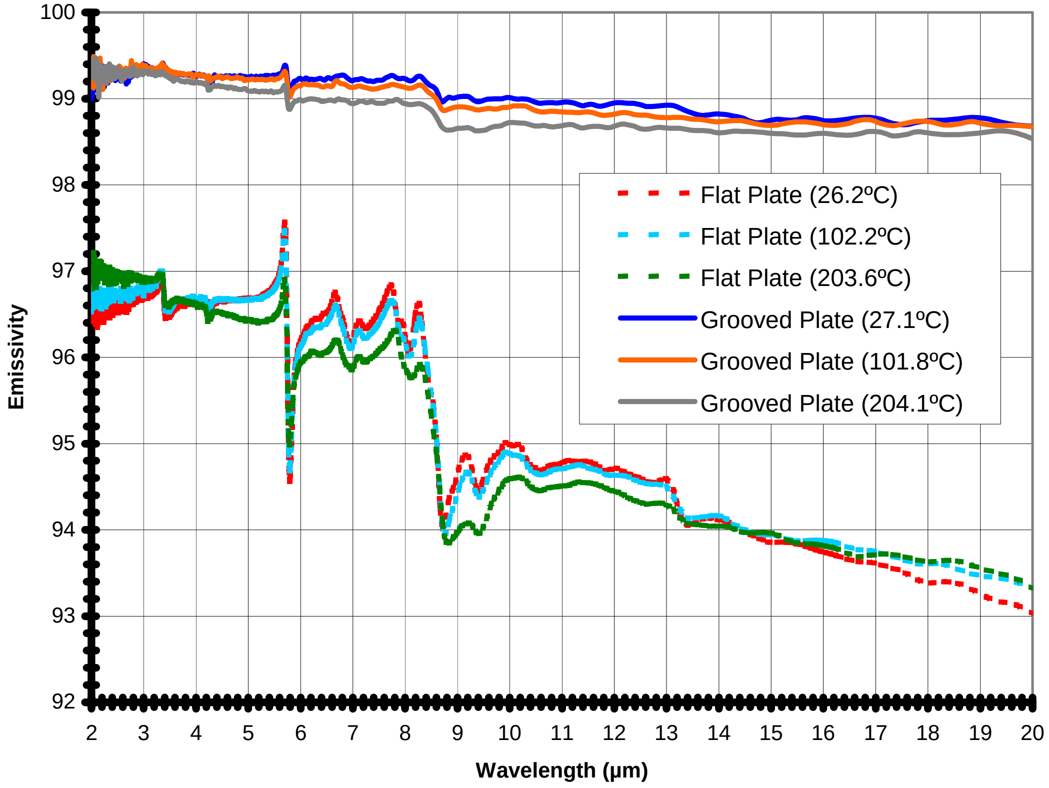

Figure 3. Flat and Grooved Plate Extended Area Source Emissivity

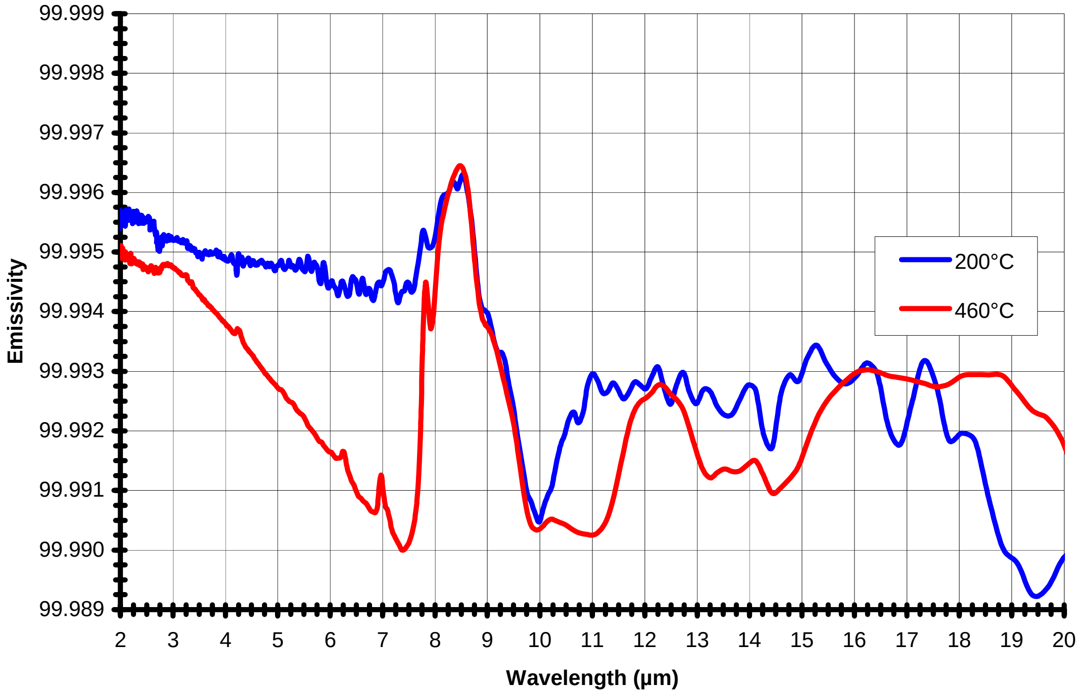

Figure 4. Cavity Source Emissivity

3. TEST TARGETS

The crux of any image analysis system is the test target. The radiation source shines through the target and the projection optics present the target to the camera under test. The target pattern defines the test image and much of the subsequent analysis. Although many patterns have become standard, custom designs can vary widely. Regardless of the pattern layout, target construction dictates the spectral region over which the target can be utilized.

3.1 Clear Aperture

The best substrate for target pattern transmission is no substrate at all. Clear aperture targets can be employed across all imaging spectral regions and are limited only by absorption bands of the ambient atmosphere. Typically these type of targets are made of metal such as a copper or aluminum alloy. Metal substrates provide both a structurally and thermally stable base. When using targets in the infrared it is important to not only know how much thermal radiation is passing through the target but also how much is being emitted by the target background. Metal target substrates promote good heat transfer from the pattern features to the target support structure where the temperature can be monitored and the thermal contrast can be calculated.

The best way to construct a clear aperture target is from a single piece of metal. This type of construction affords the most robust design and best thermal stability. Unfortunately since this design is tied to machining fabrication operations feature sizes and tolerances are limited. Using a traditional machining operation to create the general target features and then switching to Electro Discharge Machining (EDM) to create the target pattern yields the best results, yet still can not maintain high enough precision for all clear aperture target designs.

For precise target pattern geometries with tight tolerances or small feature sizes a photo-etching process is utilized. Since the etching process is only viable on thin substrates the target now becomes an assembly consisting of a machined metal holder and a photo-etched metal inlay. The inlay is permanently bonded to the holder, which is designed to support the inlay as close to the pattern as possible to enhance structural and thermal stability.

3.2 Transmissive Substrate

If specific pattern geometry, such as floating opaque aspects, prevent the use of a clear aperture target than a transparent substrate must be employed. Most all standard infrared image tests utilize targets that lend themselves to the clear aperture target design thus the transmissive substrate model will typically only apply to the ultraviolet and visible spectrums. Ultraviolet Grade Synthetic Fused Silica is a good substrate for these types of targets. The target pattern is created on the fused silica by first coating the entire substrate with metal and then using a photo-etching process to remove the metal from the areas where transmission is desired. To achieve contrast levels other than unity it is possible to vary the thickness of the initial metal plating.

4. OPTICS

In an effort to simplify and maintain continuity between the testing of the various spectral regions of interest only a single optical exit path must exist. To achieve this, the projection optics specified must be capable of transmitting and resolving all radiation from the ultraviolet through the infrared. Behind the focal plane the ultraviolet, visible, and/or infrared radiation sources can either be switched into position as required, united with a beam combining refractive element, or even fused together.

4.1 Quality

All energy comes to the same focus when using reflective optics. Refractive systems can employ corrective elements in an attempt to flatten, or color-correct, the spectral shift of the lens but are still subject to errors often toward the ends of the spectrum of interest sacrificing signal fidelity. When faced with a broad spectrum such as ultraviolet through infrared, refractive optics can be plagued with errors most all of which can be remedied by employing an all-reflective system. See Figures 5 and 6 for the reflectance of a typical evaporated aluminum film mirror.

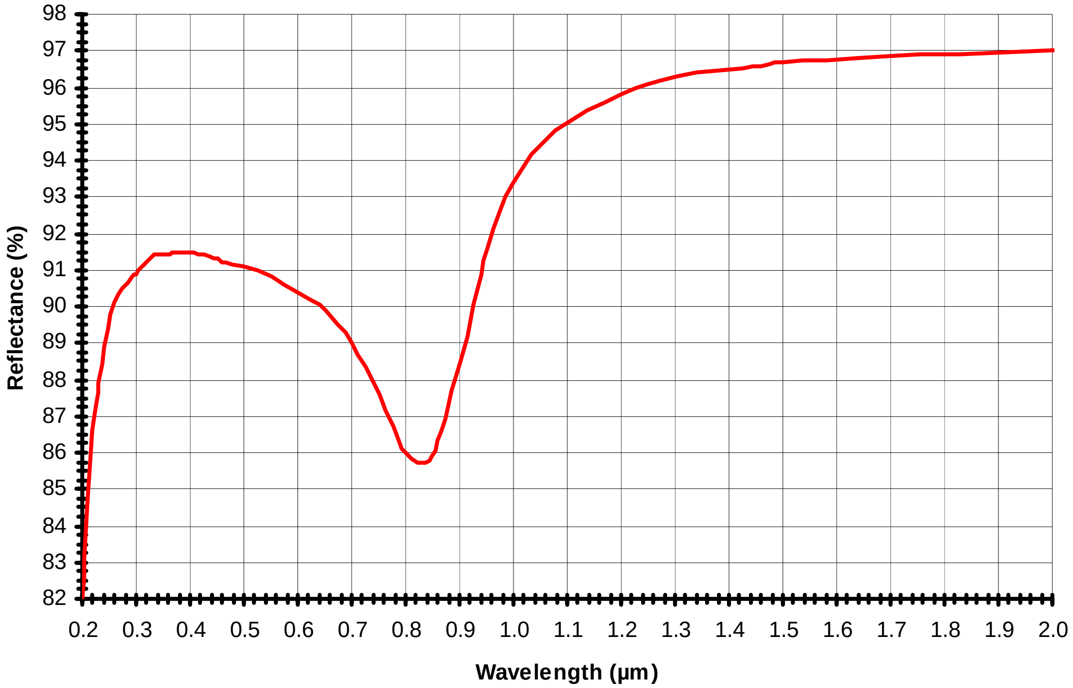

Figure 5. Reflectance of Aluminum Film Evaporated at High Vacuum (Ultraviolet through Short Wave Infrared)

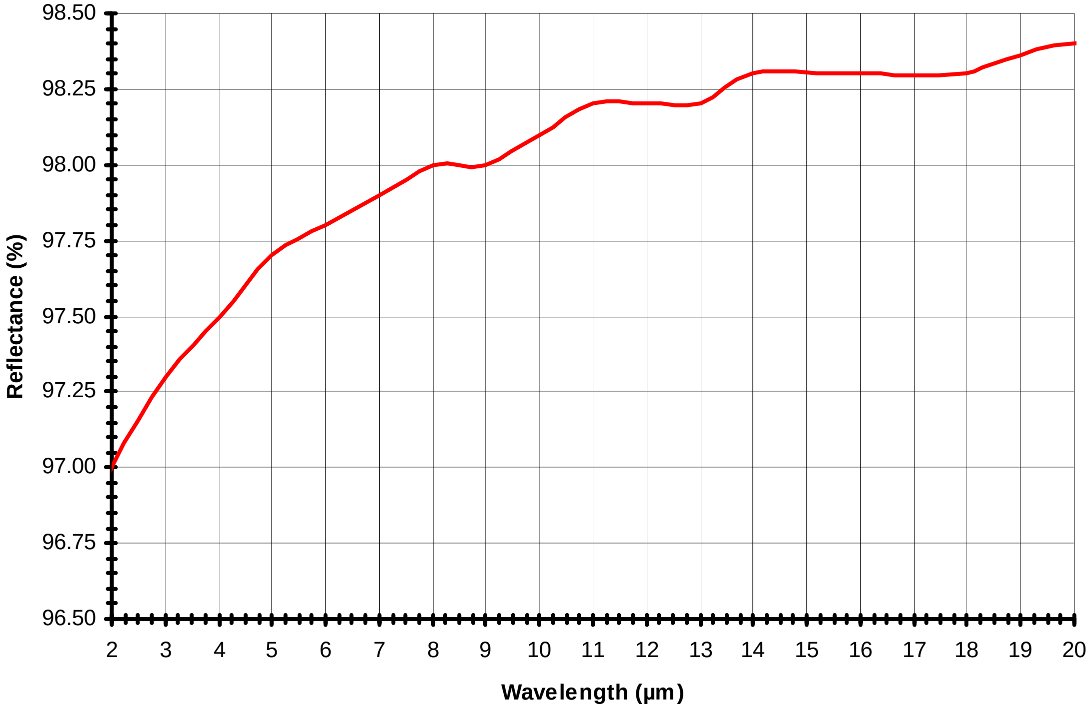

Figure 6. Reflectance of Aluminum Film Evaporated at High Vacuum (Infrared)

The theoretical maximum resolution of an optical element is defined by the Rayleigh Criteria as one half the diameter of the airy disk. See Equation 1 below.

$$r = \frac{(1.22)(\lambda)(f)}{D} \tag{1}$$

where

r = radius of airy disk (theoretical maximum resolution)

λ = wavelength of incident radiation

f = focal length of optic

D = diameter of optic

In practical applications the mirror is not of perfect quality and the actual limiting resolution is dictated instead by the wavefront error. This mirror specification is typically measured by an interferometer at 633nm. In order to specify an element that will perform to 1/4wave (peak to peak) into the ultraviolet (200nm) it is required to specify the mirror with 3.2 times less error or approximately 1/13wave @ 633nm. It is only necessary to specify the mirror to the shortest wavelength of interest. For example, the 1/13wave @ 633nm mentioned above will exhibit 4.7 times less error in the infrared or 1/61wave @ 3000nm.

After each optical element has been specified correctly and verified to meet those specifications it is prudent to confirm system performance empirically. Simply measuring the autocollimated blur spot diameter can verify optical system performance. This test involves projecting a pinhole of white light of known diameter focused at the target imaging plane through the optical system off of a flat mirror positioned at the exit port back through the optical system and focused back on the target plane where it is captured and measured. See Figure 7. The diameter of this captured spot is a culmination of the pinhole diameter plus two times the blurring affects of optical system. Making the conservative assumption that the projected pinhole diameter is infinitesimally small and throwing its dimension out of the calculation the limiting resolution, according to the Rayleigh Criteria, is 1/4 the autocollimated blur spot diameter.

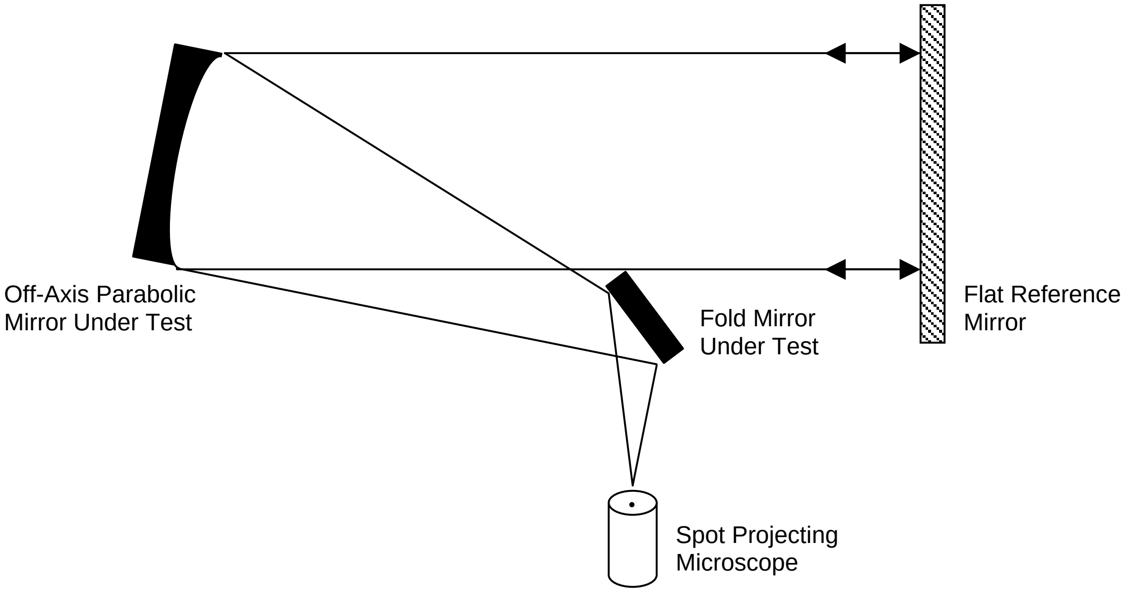

Figure 7. Autocollimated Blur Spot Diameter Test Setup

4.2 Radiation Source Switching

To provide ultraviolet through infrared energy two radiation sources may be required. A Xenon arc lamp will provide spectral coverage from the ultraviolet through the visible and a blackbody will cover the infrared. The simplest method of testing a multi-spectral imager using shared optics is merely a process of switching either source into position behind the target plane. Both sources can be mounted on a motorized slide which can quickly transport either into position behind the imaging plane for consecutive ultraviolet/visible and infrared sensor testing, see Figure 8.

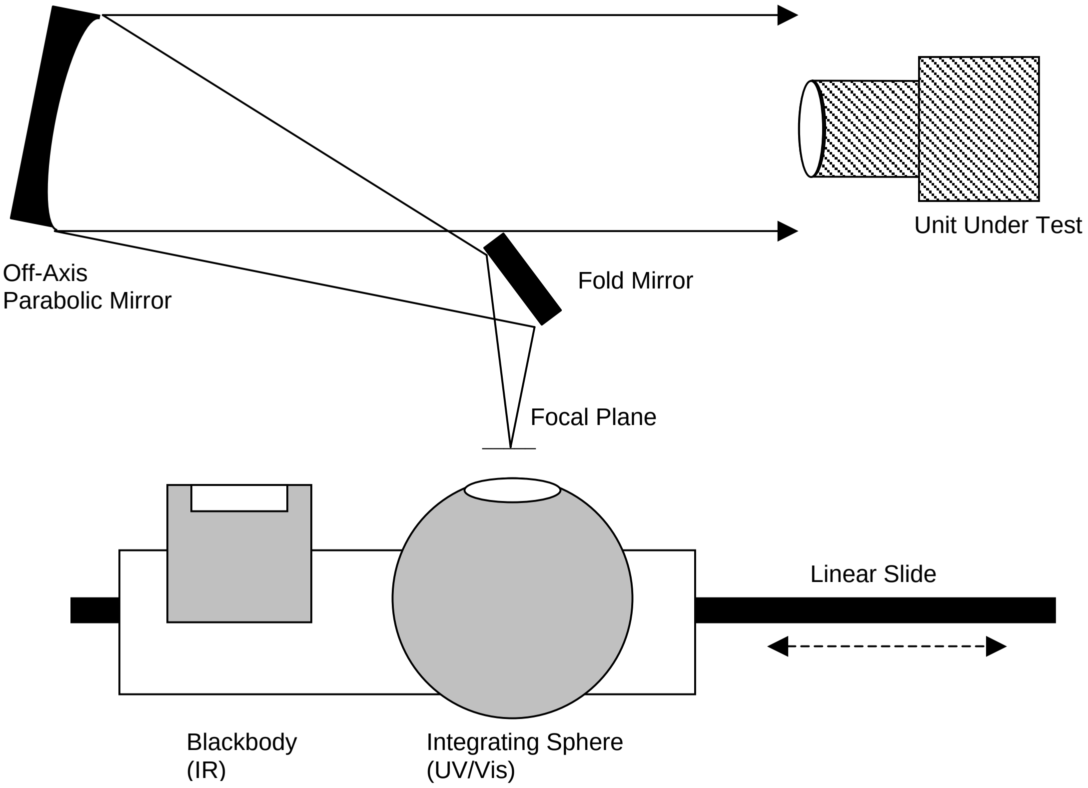

Figure 8. Switching Source Optical Diagram

4.3 Radiation Source Combining

If simultaneous ultraviolet, visible, and infrared image testing is required than the Xenon arc lamp and blackbody can both be mounted behind the imaging plane and their radiation paths united with a beam combiner to illuminate the target, see Figure 9. The blackbody source is situated in the reflected path and the Xenon arc lamp is located in the transmission position. See Figures 10 and 11 for typical beam combiner reflectance and transmission, respectively. Spectral focus shifting induced by the refractive beam combiner has no effect on the overall system focus since the beam combiner is located behind the target plane, out of the collimator optical path.

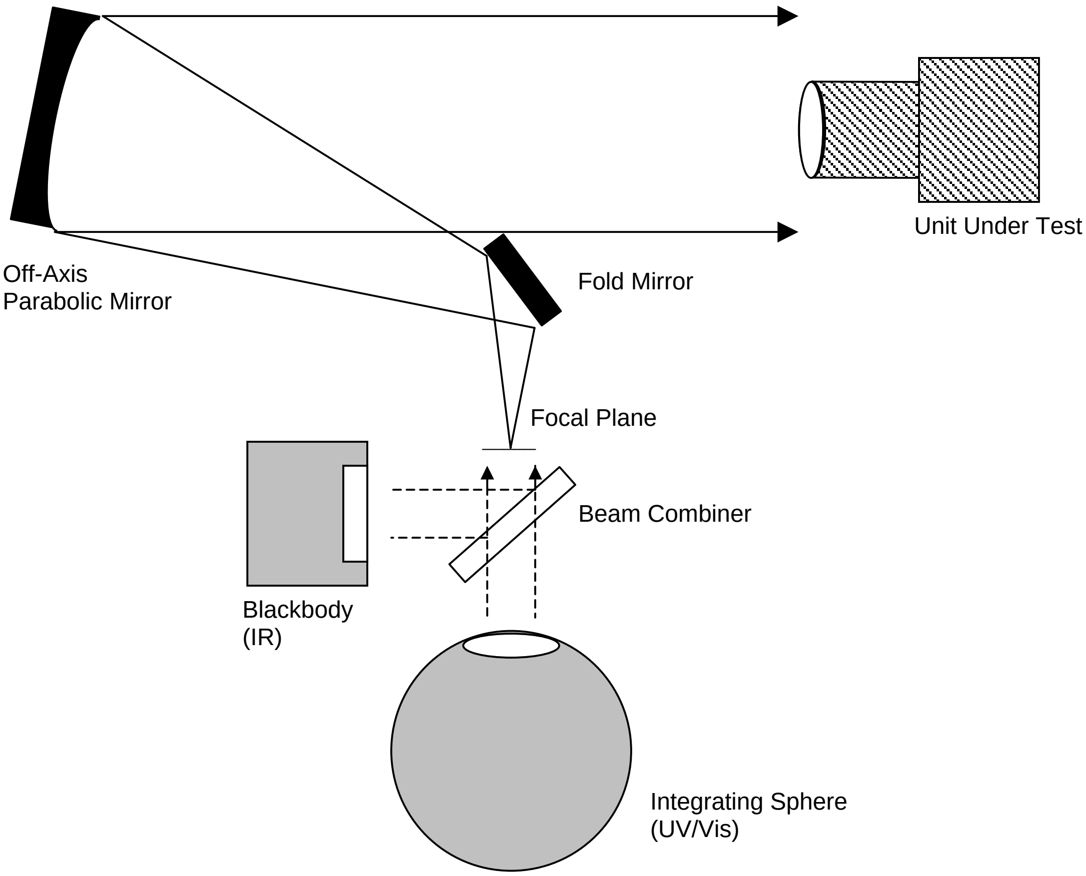

Figure 9. Combined Source Optical Diagram

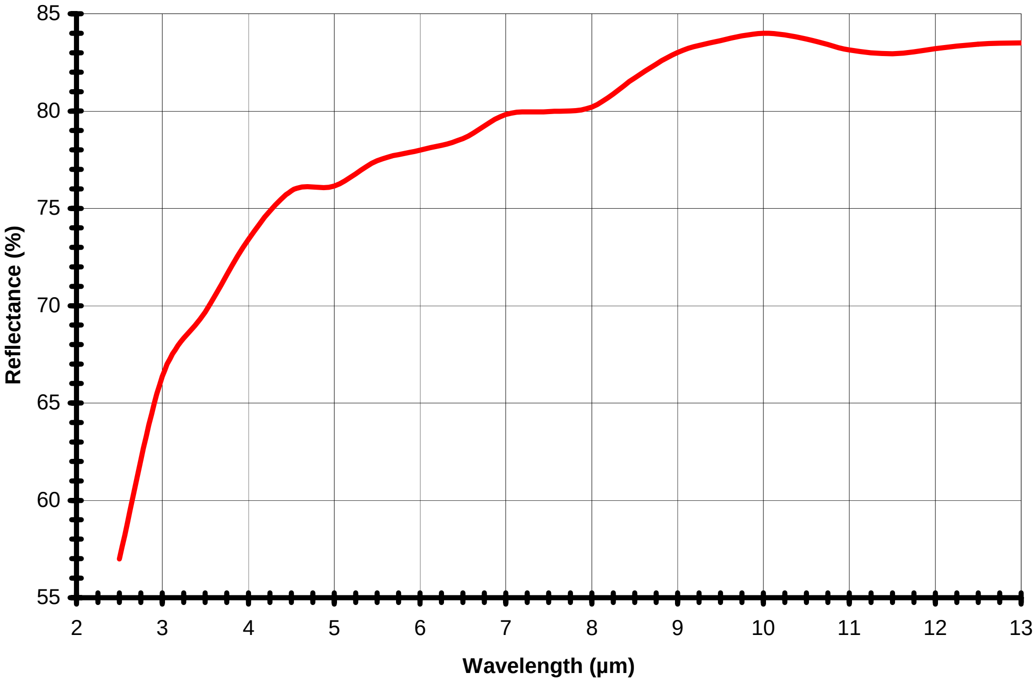

Figure 10. Typical Beam Combiner Reflectance

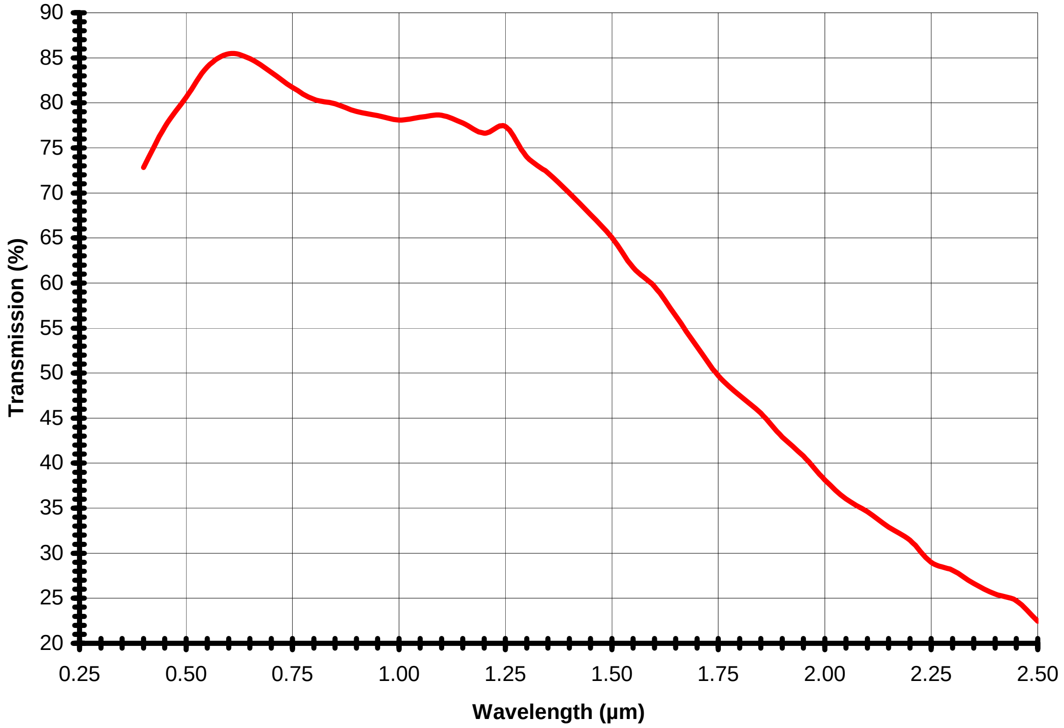

Figure 11. Typical Beam Combiner Transmission

4.4 Fused Radiation Source

To maintain the highest spectral fidelity it is desired that the target projector system not contain any refractive elements. In order to accomplish simultaneous visible and infrared testing employing only reflective optics, a fused source is required; see Figure 12. The design of this patent pending source consists of a unique surface that is both highly emissive in the infrared region and greatly reflective in the visible spectrum. See Figures 13 and 14 for the emissivity and reflectivity of such a surface, respectively.

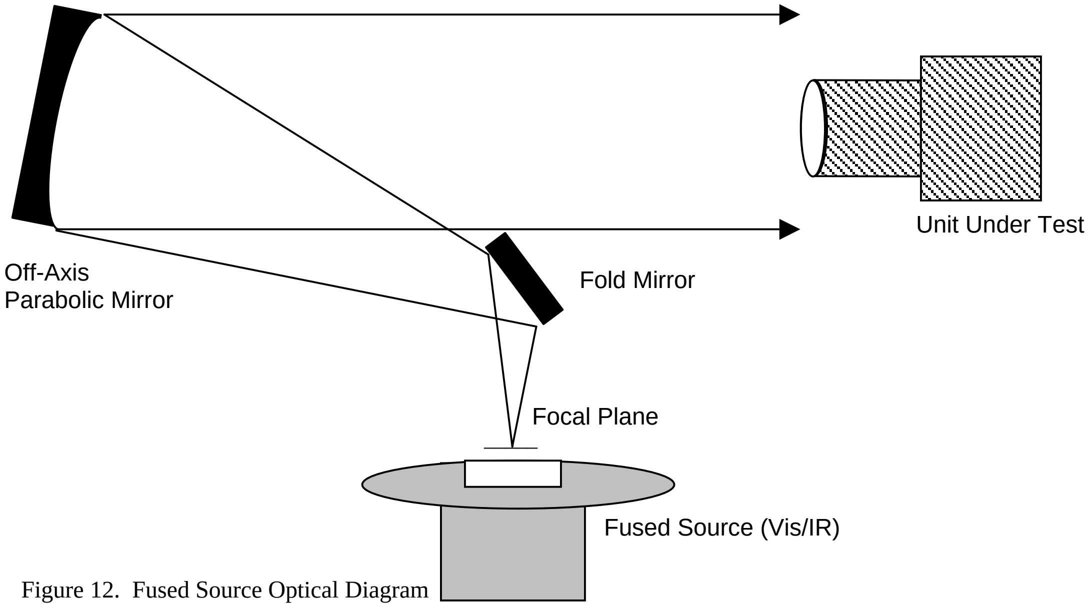

Figure 12. Fused Source Optical Diagram

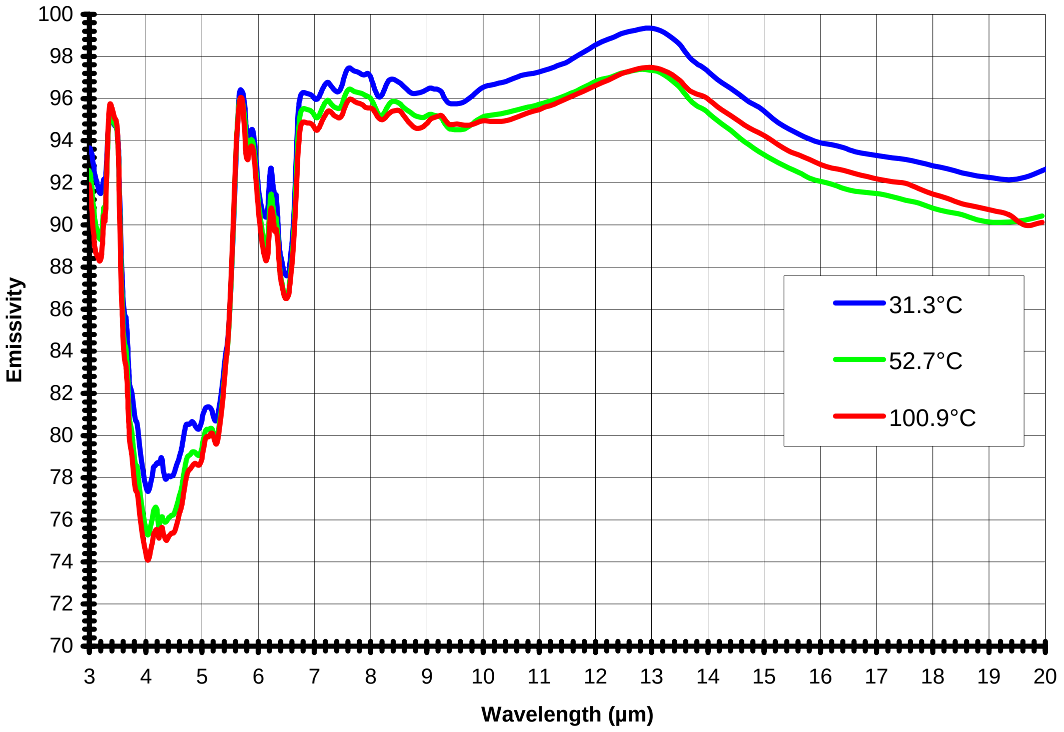

Figure 13. Fused Source Emissivity

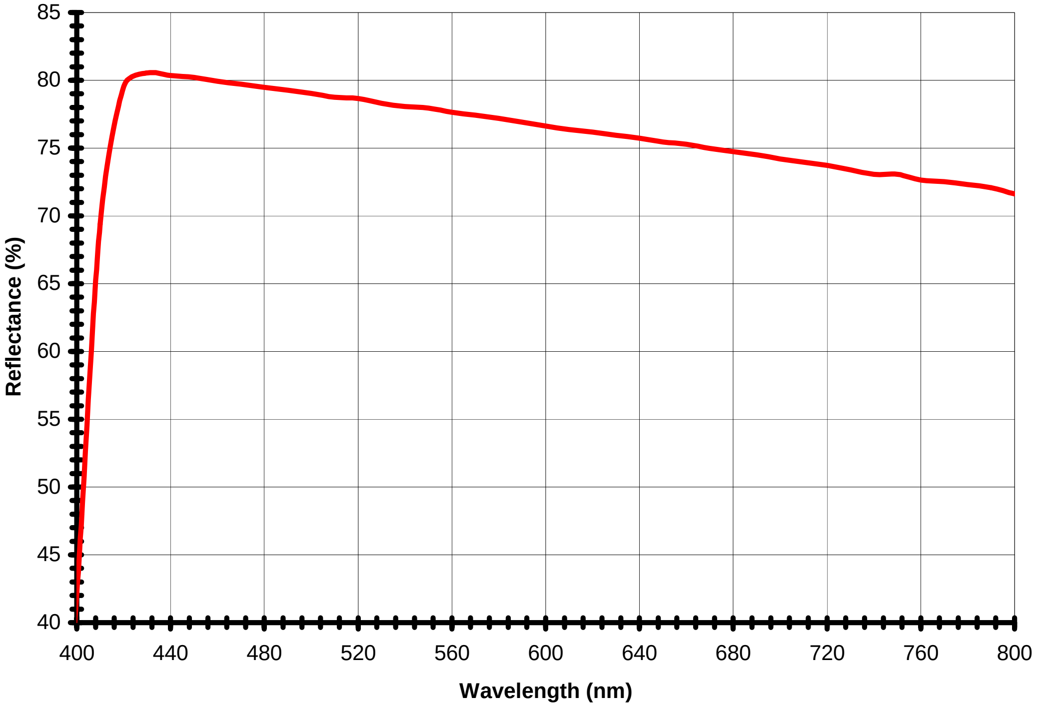

Figure 16. Fused Source Reflectivity

5. SOFTWARE

The key to test automation and ease of use for the operator is application software. An appropriate application suite will control and monitor all test hardware and facilitate the analysis of acquired test images. Automation software minimizes the possibility of error by consolidating pertinent test methodology and requiring only minimal operator interaction.

5.1 Control

An ultraviolet, visible, and infrared sensor test system consists of various components that need to be controlled and monitored. Both the Xenon arc lamp and the blackbody radiation sources are closed loop control systems that necessitate output value settings and system ready signals. Multiple targets are often mounted in a motorized wheel facilitating quick and precise target changing and alignment. Interaction with the wheel motion controller involves position set point and ready status. When using a system that involves radiation source switching the slide position setting can be set and monitored. If a beam combiner is utilized it may also be mounted on a user controlled motorized stage providing the option of removing one source channel and the associated spectral fidelity effects. Fused sources require both visible and infrared independent output control.

5.2 Analysis

There are many industry standards for camera testing and image analysis. Some apply to imagers with response in specific spectral regions and others are more universal in definition. The following is a sample of tests that are applicable across the ultraviolet through infrared region: Uniformity, Modulation Transfer Function (MTF), Focus, Distortion, Intrascene Dynamic Range (IDR), Signal to Noise Ratio (SNR), and Sensitivity.

The Uniformity Test is an analysis of an image captured with an open target at the imaging plane. The image is interrogated pixel by pixel and the maximum, minimum, mean, and standard deviation are reported. This test is useful in identifying singular or pattern defects in the sensor under test.

The MTF Test is a resolution analysis based on the interrogation of a knife-edge transition. See Figure 15 for an example test image. The edge spread function (ESF) is created by analyzing video lines traversing the edge. The line spread function (LSF) is the derivative of the ESF and thus represents the slope of the transition. MTF is the Fourier Transform of the LSF and provides modulation per frequency. See Figure 16 for an example of MTF testing results. The Focus Test makes use of a real-time video MTF analysis and promotes focus optimization by peaking MTF response.

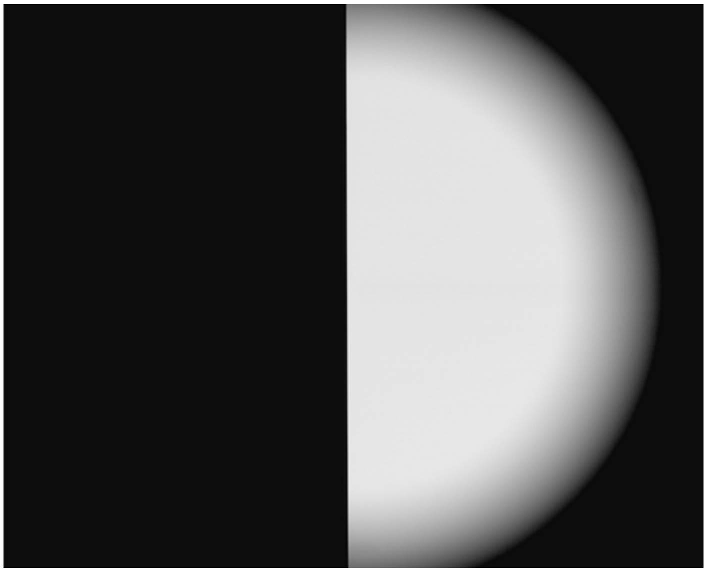

Figure 15. Sample Knife-Edge Test Image

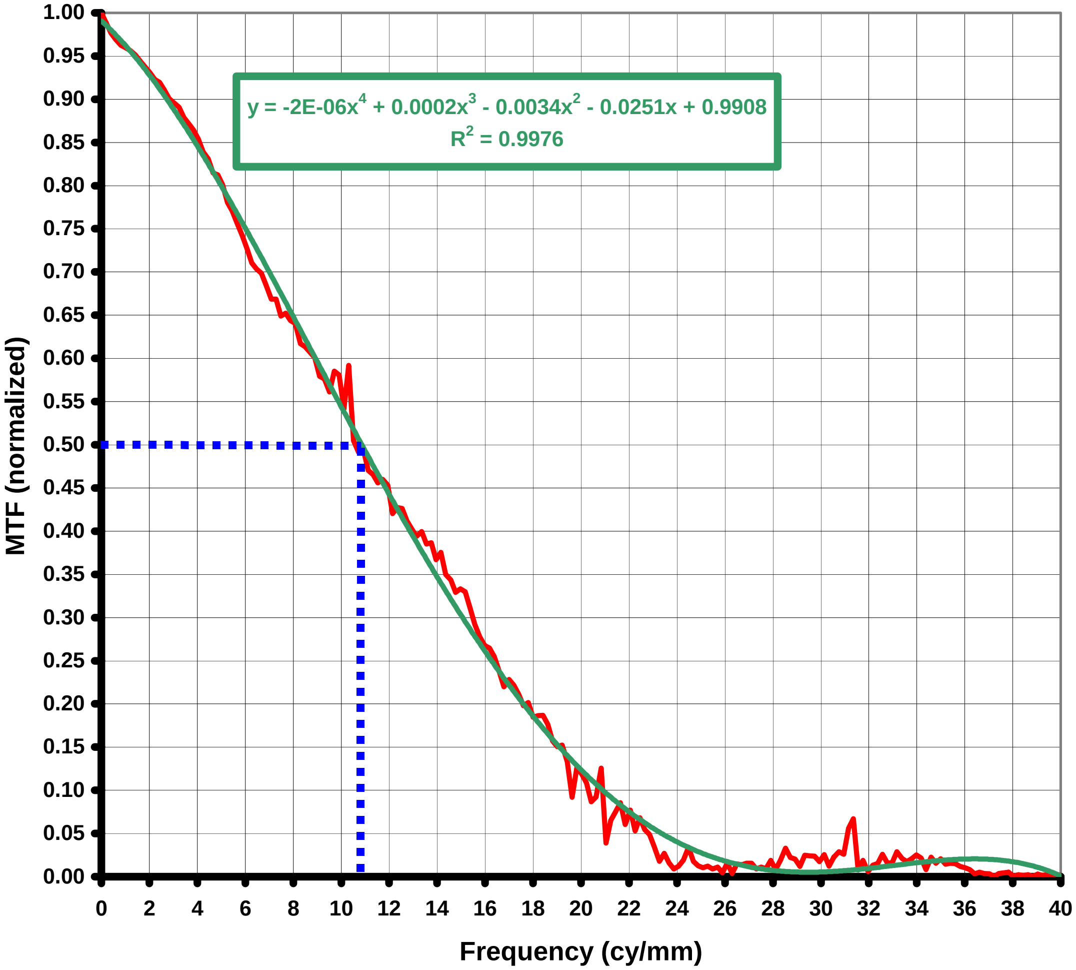

Figure 16. Sample MTF Plot

Distortion is analyzed using a pinhole array target. After an image is captured a defined dot matrix is overlaid on the picture in an effort to assist in the visual assessment of distortion errors. This test is useful in identifying barrel and pincushion type errors in the imager collecting optics.

IDR is the measure of the dynamic range within a single captured frame. Signal and background areas of a sample frame are analyzed at camera saturation. IDR is the ratio of signal pixel level to background noise.

SNR is a measure of sensitivity at a given luminance level. Signal and background regions of a knife-edge target are analyzed and their ratio calculated. By acquiring SNR data at various luminance levels it is possible to derive ISO film speed equivalent ratings. See Figure 17 for an example of SNR and Sensitivity Testing results. Using the luminance value at SNR:40 (excellent image) and SNR:10 (acceptable image) in conjunction with the effective f-number and sensor integration time the Recommended Exposure Index (REI) can be calculated and correlated to film speed by referring to ISO 12232.

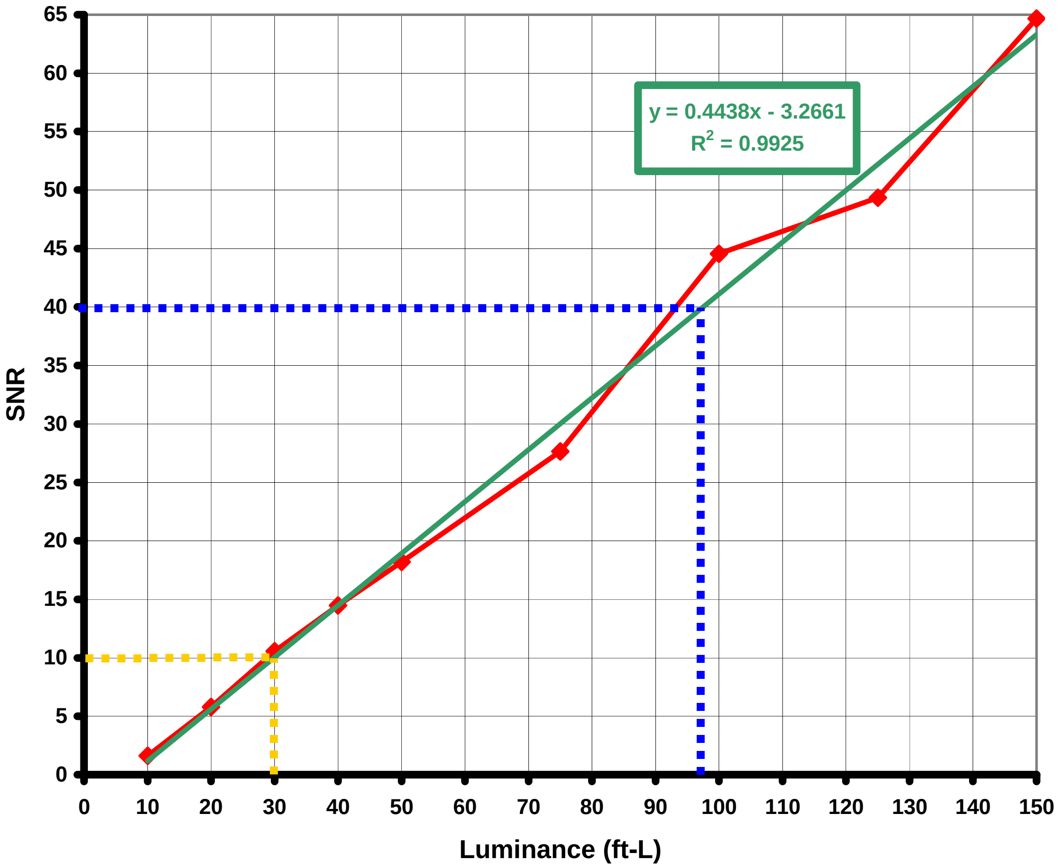

Figure 17. Sample SNR and Sensitivity Plot

6. CONCLUSION

Using an automated multi-spectral test system on shared optics is the best way to approach ultraviolet, visible, and infrared sensor testing. By specifying targets and optics capable of use across the full spectrum of interest the unified test fixture becomes a simpler alternative to dedicated band limited hardware. With only two radiation sources it has been shown how ultraviolet through infrared can be covered either by source swapping or beam combining. If source swapping is not practical and spectral fidelity is critical an innovative new single fused source design can be employed. Utilizing a software control and analysis suite promotes consolidation of methodology and thus good testing continuity across all types of image quality analysis. As the future undoubtedly brings more broadband and multi-spectral camera systems into production, for both military and commercial use, test systems will strive for and be selected for use on maximum spectral coverage.

REFERENCES

1. RCA Corporation, Electro Optics Handbook, RCA Commercial Engineering, New Jersey, 1974.
2. W. Wolfe, G. Zissis, *The Infrared Handbook*, Environmental Research Institute of Michigan, Michigan, 1985.
3. Mazzetta, J. and Scopatz, S., “Automated Testing of Ultraviolet, Visible, and Infrared Sensors Using Shared Optics,” Proc. SPIE 6543-37 (2007).