Systematic Evaluation of the Night Vision Integrated Performance Model (NV-IPM)

by

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1. ABSTRACT

The night vision integrated performance model (NV-IPM) is a U.S. Army developed software used for modeling optical systems. In the United States and many other countries, NV-IPM is used as the design tool for proposing and modeling new sensor designs for fighter jets, rotorcraft, combat vehicles, and soldier sights.[1] It follows the radiometric transfer process by modeling a source and target, and propagating the light from the source to the optical system where it is detected and analyzed. This paper presents a brief background summary on the radiometric transfer process and then presents two examples of how the process is modeled in NV-IPM. The first example uses a thermal imager with a military vehicle target. The second example uses the same target with a visible band camera and includes two different illumination sources. Using the examples, the various design components in NV-IPM are analyzed, including a discussion on important parameters for each component and possible use cases. The discussion on the parameters follows along with the first example problem. The second example adds only some additional discussion but serves to demonstrate more of the available trade techniques. Loops, which are NV-IPMs version of variables, are added to the various parameters in the second example to demonstrate the trade capabilities that make NV-IPM an important analysis tool. The performance metrics used in NV-IPM are also discussed, including the Johnson criteria, the target task performance (TTP) metric, and the national imagery interpretability rating scale (NIIRS). Performance calculations are performed and presented for each of the two examples. The paper also includes an additional short discussion on the benefits of using NV-IPM beyond what was discussed in the examples. The paper concludes with commentary on areas of improvement within NV-IPM, including its treatment of boost filters, image clutter and deep-learning image processing algorithms.

2. INTRODUCTION

The Night Vision Integrated Performance Model (NV-IPM) is an engineering tool developed by the U.S. Army Combat Capabilities Development Command (DEVCOM).[2] This group is made up of scientists and engineers that work to create and support new technologies for the United States military. Within DEVCOM is the Command, Control, Communications, Computers, Cyber, Intelligence, Surveillance and Reconnaissance (C5ISR) Center's[3] Night Vision and Electronic Sensors Directorate (NVESD).[4] Over the years, many of the optical performance models that are used within the U.S. military and other government related entities have been developed by NVESD. The most current of these optical performance models is the Night Vision Integrated Performance Model. NV-IPM "is a software package created by C5ISR Center's Night Vision and Electronic Sensors Directorate to provide a flexible and extensible engineering design environment for imaging system development.[5]"

Figure 1. NV-IPM logo from the NVESD webpage.[5]

NV-IPM represents a trade and analysis tool for analyzing the optical properties of a system. It models the radiometric process from source to human eye in order to calculate the overall optical system performance. NVIPM allows for multiple optical systems under various conditions and environments to be modeled at once, allowing for quick trades between optical systems. It is an important tool for both system level decision making and individual design analysis and refinement.

NV-IPM was released in May, 2013[6], but was under development starting in 2010.[7] Prior to NV-IPM, NVESD had released several other optical design engineering tools. However, each of these performance models was built around a specific imaging technology and it was necessary to use each one individually based on the characteristics of the optical design. There were four main performance models that handled each of the general optical systems used within the U.S. military.[8] The Night Vision Thermal Model and Image Processing (NVThermIP) tool was used only for mid wave infrared (MWIR) and long wave infrared (LWIR) systems, which are the predominantly emissive optical bands. For the reflective band cameras, NVESD had developed the Solid-State Camera and Image Processing (SSCamIP) model. In addition, NVSED had two different performance models for working with Image Intensifier (II) tubes. The first, Image Intensified Camera and Image Processing (IICamIP), was for II tubes that connected to actual detector arrays. The second, Image Intensified Night Vision Device (IINVD), was developed for II tubes that were part of direct view goggles, and thus included the optical system of the human eye with no detector. With multiple performance models, each designed to handle a different type of system, NVESD developed NV-IPM in order to combine the four previous models into one single interface. That new model was designed to handle imaging scenarios from each of the above models and also be better equipped to capture new imaging and sensor technologies.[7]

3. RADIOMETRY BACKGROUND

Performance models like NV-IPM are important for optical system design because they allow the user to model complicated radiometric transfer scenarios. Many benign examples can be solved by hand, but more complex scenarios quickly become difficult to solve in that manner. Regardless of the complexity, NV-IPM is capable of modeling the radiometric process starting at the source and ending at the eye of the viewer. There are some additional scenarios where NV-IPM is not yet capable of properly modeling the optical system. Such scenarios will be discussed at the end of section 6. To understand the process NV-IPM goes through to calculate performance metrics for an optical system, a brief review of the radiometric process is necessary. The systems handled by NV-IPM can be roughly divided into two main categories, which will be treated separately. The first of the two scenarios is a single path radiometric transfer problem. This is one where the optical device is imaging an emissive target. The second is a double path transfer problem. In this case, there is a target that is being illuminated by a separate source. This type of problem lies in the domain of the reflective portion of the optical spectrum.

3.1 Single Path Problem

The first of the two problems to be discussed is the single path or emissive target problem. Figure 2 demonstrates an example of this problem setup.

Figure 2. A representation of a possible single path problem where the target (a tank) is emitting photons that are being imaged by the optical system on the helicopter. Image taken from *Introduction to Infrared and Electro-optical Systems*, figure 1.4.[9]

In a single path problem, the source and the target are one in the same. The target is at some temperature greater than zero and thus emits photons. The target can be represented by a blackbody emitter and have its emittance found by integrating Planck's curve for the target blackbody temperature over the desired waveband. Depending on if the target is Lambertian or isotropic, the photons will be emitted outward from the source into a hemisphere, a complete sphere, or somewhere in between. The emittance of the target can be converted, based on the emission solid angle, into a target radiance. The target radiance can be used for various forms of radiometric transfer or can be converted into a target intensity to be propagated to the optical system. There will then be a solid angle that is subtended by the optical system from the target that represents the photons that will be captured by the optical system. Some of the photons that travel in this subtended solid angle will be lost to scattering or atmospheric absorption. The remaining photons are captured by the optical system and focused to an image. It is necessary to account for the transmission of the optical system itself as it also causes a loss of photons reaching the detector. Once the photons reach the detector, they are converted into an electrical signal, which can happen in a variety of ways, depending on the type of detector. The image on the detector, represented by this electrical signal, can then be adjusted, enhanced, or edited based on the digital post-processing of the electro-optical system. For systems using machine learning or other algorithmic processing, the signal is processed via those algorithms and the system reacts according to the received signal. For systems with a display and a viewer, the image is processed and displayed onto a screen. The observer is then able to view the image and the eyes and brain do the final processing of the image. For optical systems with only an eyepiece, there will be no digital image processing, only processing from the brain and eye. While there are various options for what a single path problem may look like, all of them follow the same general process. The photons are emitted from a source characterized by a blackbody temperature and an emissivity, which could possibly be a spectral quantity. The photons pass through an atmosphere with some being lost to various mechanisms of scattering or absorption. The photons within solid angle subtended by the optical system are captured and focused to an image. This image is processed, whether digitally or organically, to be used for decision making.

3.2 Double Path Problem

The double path problem follows the same general form as the single path problem, with only a change to the source of the photons that are imaged by the optical system. In the single path problem, the target was also the source of the photons that were being imaged. In the double path problem, these photons originate from another source and are reflected off the target before being imaged by the optical system. A representation of this is seen in figure 3.

Figure 3. A representation of a possible double path problem. The target is being illuminated by multiple sources. The photons from these sources are being reflected off the target into the optical system. Image taken from *Introduction to Infrared and Electro-optical Systems*, figure 1.3.[9]

There are numerous sources that could represent the origin of the light being reflected off the target. The sources shown in the figure above are the sun, the moon, and the stars. However, other possible sources could include manmade lights (flashlights, car headlights, indoor illumination, laser illuminator, etc.), luminescent sources, or airglow[10]. It is necessary to recognize that the light from the source will also be subject to transmission losses as it propagates to the target before the additional losses during propagation from the target to the optical system. Often, these transmission losses are not equivalent to transmission losses from target to optical system, and therefore require their own modeling. It is also important to note that, even though this general setup is roughly described as a two-path problem, the source illumination is not limited to only a single source to target relationship. For example, industrial lighting from a city may illuminate a cloud layer that, in turn, illuminates a source that does not have a direct path to the original city lights, making it visible to an optical system. There is an additional path in this process – the city lights to the clouds and the clouds to the target – but it would still be referred to as a double path problem.

4. RADIOMETRY MODELING IN NV-IPM

NV-IPM follows the same radiometric process described above in its calculations. NV-IPM begins with modeling the source and the target, which may differ depending on the type of problem. It then models the atmosphere and imaging environment. From there, the optical properties are considered before moving to the detector, digital processing, display, and eye. To demonstrate the many complexities of NV-IPM modeling, two examples will be set forth. The first will represent a possible single path problem model. In addition to describing the specifics for the given example, additional possible modeling components will be discussed with commentary on when and why each additional component may be required. This discussion will be much more robust for the single path problem since many components will be common between the single path and double path problems. For the double path problem, some specifics to reflective band modeling will be discussed, in addition to highlighting some of the ways that NV-IPM allows for users to make quick system level trades and multilayered analysis.

4.1 Single Path

The single path problem to be described in this section will represent a LWIR thermal camera imaging a vehicle of military interest from the 12 tracked vehicles that are commonly used for discrimination tasks.

4.1.1 Sources and Targets

The source for this example is a thermal source defined by its temperature and temperature variation. The target temperature is used to solve for the target spectral emissive radiance using Planck's Law, given by equation 1. For this problem, a terrestrial target of temperature 300K is used.

$$L(\lambda, T) = \epsilon(\lambda)\frac{2hc^2}{\lambda^5}\left(\exp\left(\left(\frac{hc}{kT\lambda}\right)-1\right)\right)^{-2} \tag{1}$$

The spectral emissive radiance for the 300K blackbody equivalent temperature source is shown in figure 4.

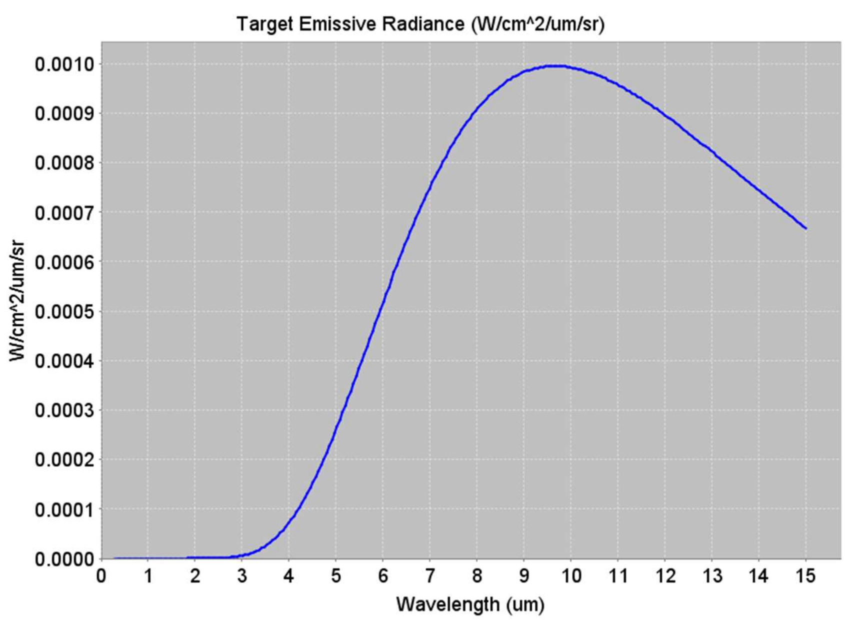

Figure 4. Target emissive radiance as a function of wavelength for a 300K blackbody equivalent target.

In addition to specifying the target temperature, it is also necessary to specify a background temperature for the scene around and behind the target. For this example, a background temperature of 300K is again used. Since the same temperature is used for both the target and the background, nothing is visible unless there is a target temperature variation or background temperature variation specified. In this example, a target temperature variation of 3K is given. The target and background spectral radiance values, plus the differential target radiance are used to determine the target and background mean signals. In addition to the temperatures, it is also necessary to define the emissivity, or in the case of NV-IPM, the reflectivity, of the target. In general, by conservation of energy, the reflectivity, the absorptance, and the transmissivity will sum to one for an object.[9]

$$\alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 1 \tag{2}$$

For infrared targets, it is assumed that transmissivity is extremely low. In addition, for targets at thermal equilibrium, the absorptance and the emissivity are equal. Thus, equation 2 can be reduced to what is shown in equation 3.

$$\varepsilon(\lambda) + \rho(\lambda) = 1 \tag{3}$$

NV-IPM uses this approach for defining the emissivity of a target or background. The reflectivity of the target or background is defined as a function of wavelength. Any values that are not specified are assumed to have a reflectivity of zero and thus an emissivity of one. In this way, a target can easily be specified as a spectral graybody by defining non-unity values for reflectivities at wavelengths that correspond to the target spectrum. For this example, both target and background are assumed to be blackbodies with an emissivity of one for all wavelengths. Finally, it is important to specify the characteristic dimension of the target. The characteristic dimension is defined in equation 4.

$$m = \sqrt{A_{tgt}} \tag{4}$$

The area used in the calculation represents the average area of the target over all aspects.[11] Tables 5.7 and 5.8 in *Introduction to Infrared and Electro-optical Systems*[9] are especially useful for determining appropriate values for target characteristic dimensions. This value becomes important for calculating performance metrics like the Target Task Performance (TTP) metric, which is discussed in section 6.

The assumptions detailed above work for many imaging scenarios but fall short when calculating target signals for targets with temporal dependencies or targets that are smaller in angle than the instantaneous field of view (IFOV) of the camera. Each of these cases is treated separately within NV-IPM. For targets that have a time dependent blackbody temperature, a flash target can be used. This component is the same as the simple target described above except that it has two additional parameters: target temperature profile and target profile delay. The profile input allows the user to specify the target blackbody equivalent temperature as a function of time. The delay input can shift the temperature profile along a temporal axis to represent a delay (or in the case of a negative input, an already ongoing process) for the target temperature profile. This becomes necessary when there are targets being imaged that have temperature variations on timescales that cannot be justifiably be considered steady state.

Targets that have an angular subtense smaller than the IFOV of the camera are said to be unresolved. Unresolved targets, represented by the point target component, cannot be properly described in terms of target emittance, since they approximately have no emission area. Instead, the target is described by its intensity in units of W/sr. Such a target might be useful in infrared search and track (IRST) systems that are imaging targets at extremely long distances where the target signal is smaller than one pixel.[12] For these cases, NV-IPM requires an additional cuton and cutoff wavelength for the target and a target intensity.

4.1.2 Atmospherics

Once the target has been modeled, the next step in NV-IPM for creating an optical system model is to represent the atmosphere. The target will emit an optical signal that will have been degraded by the presence of an atmosphere model, both in transmission losses and added blur. For any atmosphere model in NV-IPM, it is necessary to specify four parameters: (1) the altitude of the system, (2) the atmosphere temperature, (3) the range to target, and (4) the sky-to-ground ratio. The altitude of the system, given in units of length, defines the height of the optical system from the ground. The atmosphere temperature is the blackbody equivalent temperature of the atmosphere. The range to target defines the slant range, as shown in figure 5.

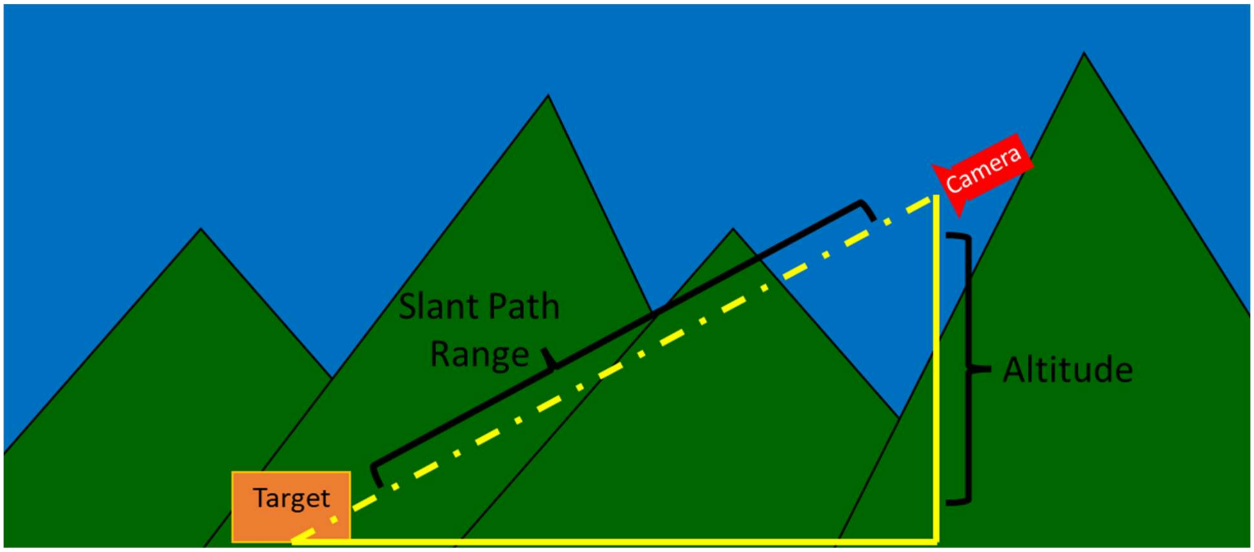

Figure 5. Demonstration of how NV-IPM handles the range to target specification. This value is the slant range, or absolute distance, from the target to the optical system. The relationship between the slant path range and the ground path range is dependent on the specified altitude.

The final parameter that is common among all atmosphere types is the sky-to-ground ratio. This value represents the ratio of light that is scattered into the imaging path from other sources, like sky irradiance, compared to the amount of light that is scattered out of that same path due to transmission losses.[11] A value of 1 is used for this problem, meaning that the amount of light that is scattered into the imaging path is the same as the amount of light that is lost out of the path. Combined with the scattering factor, this value represents the path radiance for the atmosphere between the source and the target. For each propagation of light, whether from target to optics in this single path example or source to target and target to optics as in the double path example, it is important to consider this path radiance caused by light sources having light scattered into the imaging path. This additional radiance causes, first, a decrease in the target contrast, second, the electron wells to fill faster, and third, an increase in the noise of the system.[9] For the propagation path from the target to the optics, the path radiance can be handled using the sky-to-ground ratio, the scattering factor, which is an advanced parameter, and then looking at the extraneous signal output. However, NV-IPM does not model this path radiance for the source to target path. In order to do this or other more advanced atmospheric calculations for the source to target path beyond bulk transmission loss, additional work in a program such as MODTRAN is necessary.

Additional parameters are required depending on the type of atmospheric model used. The simplest of the models is a broadband application of Beer's law, as shown in equation 5.

$$\tau(R) = \tau_{1km}^{R} \tag{5}$$

Thus, the total atmospheric transmission is the one kilometer transmission to the power of the range. The value is considered broadband because it is constant for all wavelengths. This can be adjusted to account for the spectral component of the transmission by instead using the spectral Beer's law component, which is defined in equation 6.

$$\tau(R,\lambda) = \tau(\lambda)_{1km}^{R} \tag{6}$$

For the broadband component, only the one-kilometer transmission is required as an additional input. For the spectral component, the one-kilometer transmission is input as a vector with respect to wavelength. For the example demonstrated here, a broadband Beer's Law is used with a per kilometer transmission of 0.85.

It is also possible to input a user-defined transmission table. NV-IPM allows for the creation of a table that gives a bulk transmission for all ranges as a function of wavelength. This becomes useful for creating user modified moderate resolution atmospheric transmission (MODTRAN) tables, which is discussed in the double path example. MODTRAN calculated atmospheric transmissions are also discussed in that example.

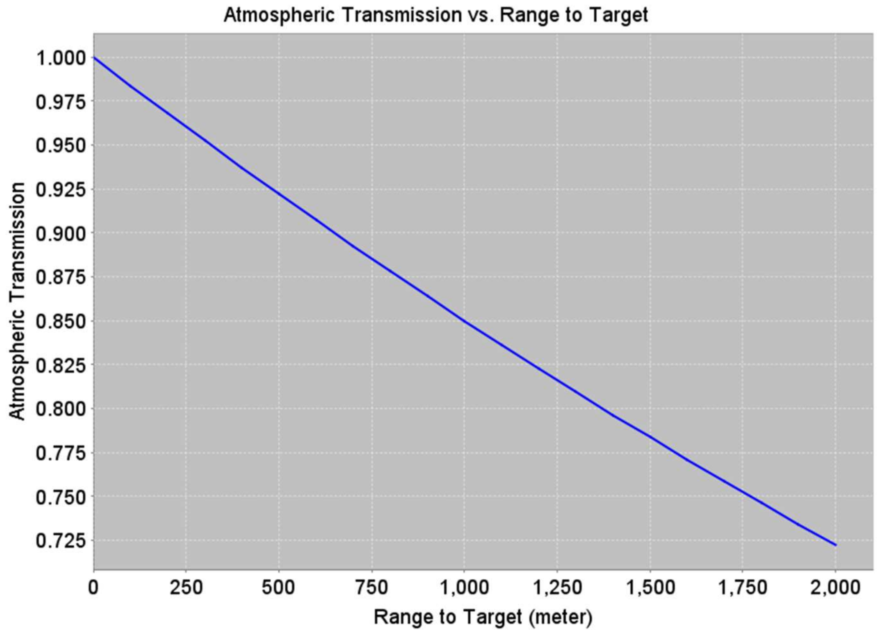

Figure 6. Atmospheric transmission as a function of range for the single path example. Transmission is determined according to broadband Beer's law (equation 5).

The last portion of the atmosphere that is modeled in NV-IPM is the turbulence modulation transfer function (MTF). The turbulence is defined by the index structure parameter (c_n^2). The index structure parameter is a function of location and time. When thermal transfer between the air and the earth is low, index structure parameter will also be low.[11] This means that the blur added to the system from turbulence will be low. A useful chart for determining relative index structure parameters is included in the NV-IPM help documentation. These values can have a range from 1E-17m$^{-2/3}$ to 1E-12m$^{-2/3}$ with the latter representing a significant blurring of the image with range. This larger value may represent the case of imaging across a hot desert or similar landscape where turbulence will cause significant image degradation. The input index structure parameter is then adjusted based on the altitude, the range, the path direction, and the reference height. The latter two are additional parameters that are required when calculating the turbulence MTF. The path direction determines whether the camera is above or below the target of interest based on the specified altitude of the system. The turbulence contribution to the system blur changes depending on the specified path direction. The scaling of the index structure parameter is also dependent on the reference height at which the parameter was measured. If there is no altitude specified, it is assumed that the path direction is horizontal, and both the aforementioned parameters are ignored. Ultimately, the effective index structure parameter that has been adjusted to match the setup of the optical system is used to determine the turbulence MTF, as defined in equation 7.

$$MTF_{turb}(\xi) = \exp\left(-57.4 * \frac{3}{8} * \xi^{\frac{5}{3}} * C_n^2 * \lambda^{-\frac{1}{3}} * R\left(1 - 0.5\left(\frac{\lambda\xi}{D}\right)^{\frac{1}{3}}\right)\right) \tag{7}$$

In the above equation, lambda is the diffraction wavelength for the optical system, R is the range, and D is the optical aperture diameter. This MTF equation makes two important assumptions. The first is that the electro-optical system is functioning with a relatively short exposure time and, second, that the object is in the realm of the farfield approximation for the majority of the imaging time. For a camera with a long exposure time or for targets in the nearfield, equation 7 needs to be modified. NV-IPM does not consider these other cases, but the MTF for such systems can be found in *Introduction to Infrared and Electro-optical* Systems, equations 6.25 and 6.26. For this problem, turbulence is to be ignored, so an index structure parameter of 1E-17 m$^{-2/3}$ is selected. This is sufficiently small to simulate no added blur due to turbulence.

4.1.3 Optics

The next portion of the radiometric process that is modeled by NV-IPM is the optical system. The basic optical system, as used in the example presented here, is defined by four elements. The first is the entrance aperture of the system. Second is the average optical transmission. Third is the optical focal length. Last is the temperature of the optics. For system level trades, these values can be adjusted based on general project requirements or guesses on what the system will look like. For more mature system analysis, these values can be taken from lens design software or, in the case of the optical transmission, other computational software. Additional optical components allow the system to be adjusted to better match an actual optical system. For example, many optical systems are not diffraction limited, due to the presence of defocus, aberrations, etc. In addition, motion blur, or line of sight jitter may also degrade the system performance. NV-IPM has built in MTFs that model each of these cases. It is important to note that the MTF labelled "Optical Aberration MTF" is only for modeling spherical aberration in an optical system and does not account for other aberrations. If it is necessary to precisely represent the aberration MTF performance of a known optical system, the MTF values can be saved from the optical design software and put into a "Generic MTF" component in NV-IPM. These MTF components are in units of cy/mrad and not cy/mm as is traditional in optical design software. Often, the MTF is measured at the focal plane in programs like Code V or Zemax. If it is necessary to convert the MTF to cy/mrad from cy/mm at the focal plane, the MTF can be scaled by the focal length in meters. In addition to the MTF components listed above, it may be necessary to model other MTF contributions as well. NV-IPM has Gaussian, exponential, and sinc MTFs that can be used to model many of those situations that may arise.

It is also possible to model other elements that may be present in an optical system. The first of these additional NV-IPM components is the aperture stop component, which allows for additional apertures that may be present elsewhere in the system (i.e., before an eyepiece) to be represented. For cooled thermal optical systems, it is necessary to have either a cold shield or a warm shield. The cold or warm shield is necessary to limit the angle where radiation is able to reach the cooled detector and thus prevents stray radiation from reaching the detector.[13] This parameter is defined by the transmission, emissivity, and temperature of the shield in addition to the reflected temperature. For systems that require photometric units and not radiometric units, the third additional component that can be added to the system is a radiometric conversion. This will allow the radiometric units to be converted to photometric units based on a normalized response that is defined by the user. This is important for systems that may use an eyepiece in place of a detector and it is necessary to account for the response of the eye in these cases. The final of the additional components to be discussed is the eyepiece component. In place of a detector and electronics, it is possible to simply use an optical eyepiece. This component is defined by an aperture, focal length, transmission, and temperature, just like the generic optical system. It is also possible to specify a vertical or horizontal MTF for the eyepiece based on its design.

For this example, an f/1 optic with an entrance aperture of 50mm is used. The optics are assumed to be at 300K, which would make them in thermal equilibrium with the rest of the environment. With no actual optical design to work with, the optical transmission is assumed to be 0.8. No additional MTF components are used.

4.1.4 Detectors

The next component of the uncooled camera model is the detector. There are many different options in NV-IPM for modeling the camera detector. For this example, and for many design cases, a generic staring detector is used. The staring array is defined by many different inputs that will vary drastically depending on the specific detector being used. It is necessary to first specify the response waveband for the detector. Next, the pixel dimensions, measured NETD, time constant, and fixed noise parameters are defined. Finally, the measurement f-number, transmission and frame rate are recorded. These values are necessary to scale the system noise where the measurement values from the detector do not match the optical design being modeled in NV-IPM (i.e., the f-number). For this example, a U8000 uncooled infrared sensor from DRS is used as the detector.[14] Parameters were taken from a public released specification sheet of the sensor. Parameters that were not recorded in the specification sheet were given generic values from NV-IPM. Camera responsivity is from 8μm to 14μm.

In addition to a basic staring array, NV-IPM can also represent various other specific types of detectors. One of these specific detectors is a photocathode. In NV-IPM, this detector type was made to support electron bombarded charge coupled devices (EBCCD) from legacy IICamIP[11]. NV-IPM also has a new method for handling II tubes with a detector labelled "tube." This represents a photomultiplier low light device that is coupled with a phosphor screen. This component is defined by various factors specific to II tubes, including the equivalent background input (EBI), noise factor, tube geometry, gain, spectral response, time constant, and device MTF.

Beyond II tube modeling, NV-IPM also is capable of modeling scanning detectors, both sampled and continuous. These two detector types are characterized by the same parameters with one exception. The continuous scanning array uses only a horizontal field of view definition while the sampled array needs to be given a sample count in the horizontal direction and a sample rate per IFOV. These arrays are used together with the scanning detector component to properly model the scanning detectors. It is also important to note that, for the continuous scanning array, it is necessary to combine the array with the electronic low pass filter to limit the horizontal noise bandwidth.

Lastly, there is a selection of specialty detectors built into NV-IPM that represent specific detector types that may be useful to the user. The first of these specialty devices is the detector with gain. While not necessarily a specialty device, this component represents a detector with a noise electron gain process. This is useful when modeling detectors such as electron multiplying CCDs (EMCCDs).[15] Other specialty detectors within NV-IPM include the Detector Rule 07 (which represents a CdHgTe detector[16]), the Detector Dynamic Range (which models a generic detector where the temperature dynamic range can be specified), the Color Detector (which represents a typical RGB detector that is being used monochromatically), and the Sub-Pixel Standalone. The Sub-Pixel Standalone is used in conjunction with the regular detector component and is important for properly handling unresolved targets. This was developed to replace the IRST Detector component that was used in previous versions of NV-IPM.[11]

4.1.5 Electronics and Post-Processing

For optical systems that use a detector array and not a direct view optic, the components that follow the detector are for describing the electronics and post-processing of the camera. For this example, only one of these components is used. The component used is the root sum of squares (RSS) contrast. This allows the user to specify a desired contrast for the display which is used to define a new zero level for the incoming signal.[11]

$$L_{min} = \frac{c_{des}(\mu_{tgt} - \mu_{bg}) - \sqrt{(\mu_{tgt} - \mu_{bg})^2 + \sigma_{tgt}^2}}{2c_{des}} \tag{8}$$

$$\mu_{out} = \mu_{in} - L_{min} \tag{9}$$

Nominally, this component is set so that pre-modified contrasts that are greater than the desired value are not "degained" to meet the specified contrast level.[11] This can be adjusted if desired by the user in the advanced parameters section of the component. For this example, the RSS contrast is set to 0.2.

Another post-processing component that can be used is the digital filter. This component works to model digital post-processing for an image by enhancing spatial frequencies in the image via use of a filter kernel. The digital filter makes the important assumption that the filter kernels are separable and can be described in terms of a single vertical kernel and separate horizontal kernel. In many cases, this may not be practically true, so caution must be used when applying this component to the system. A second digital filter used by NV-IPM is the Weiner deconvolution filter. This filter makes use of the Weiner deconvolution theorem to remove blur and noise from an image. This filter looks to minimize the mean-square error of a processing filter that is convolved with the noisy image in an attempt to restore the original object without noise or blur.[17]

In addition to the two digital filters, NV-IPM is also able to model dither. Dither, sometimes referred to as super-resolution, is the means by which the sample spacing of a sampled detector is decreased by shifting the detector on the sub-pixel level so that the sampling frequency can be increased. This is especially effective in systems that are sampling limited because it allows the sampling cutoff frequency to increase based on the number of dither points. The camera is often dithered in a single direction, which is called 2-point dither, or along two directions, which is referred to as 4-point dither. This method requires a single frame at each location and thus decreases the frame rate by the number of dither points. For a camera operating at 120Hz using a 4-point dither, the effective frame rate would be only 30Hz. NV-IPM may also decrease the effective frame rate of the system by the addition of the frame average component. This can be added in place of or in addition to the components above. Frame averaging works to decrease the temporal noise in an imaging system but will make no difference in the camera fixed noise. The user is able to specify the number of frames that will be averaged.

The next class of post-processing components within NV-IPM all focus on adding gain to the system. The first of these gain components is the amplifier gain. This component allows the user to specify the gain value while also inputting an additional amplifier noise term that is applied uniformly across all wavelengths. The next gain component is the constant gain level. This component works very similar to the RSS contrast level used in this example problem, except that the gain is calculated only once and then used as a constant for all ranges. The constant gain requires a desired contrast input. It then calculates the gain necessary for that contrast at the first range value and then keeps a constant gain for all ranges. This differs from the RSS contrast that finds a different gain to keep the constant contrast for all ranges. The last of the gain components is the modulation contrast level. This tool functions the same as above, but instead is specified by a modulation contrast.

The final group of post-processing tools in NV-IPM is for pixel interpolation. Often, the display used to match a detector does not have the same resolution as that detector. If there is a higher resolution on the display, then it is possible to interpolate the signal from the detector and use the full resolution of the display. Each of the pixel interpolations does this, but in a unique way. For example, bilinear interpolation will average two adjacent pixels in both vertical and horizontal directions and then create a number of intermediate pixels based on the interpolation order specified. The bicubic interpolation uses a weighted average of six nearby pixels in each direction to interpolate new pixels based on the interpolation order input by the user. It is also possible for the user to define a general interpolation method that can be used in place of the built-in methods. For this example, a bilinear pixel interpolation of factor two in both x- and y-directions was used. It is important to note that the interpolation components require integer factors only for calculation of the MTF contributions of the interpolation. Thus, direct scaling of a detector resolution to a display resolution may not be possible to model precisely.

The user is also able to add a component that specifies a camera system being used in single frame mode where only a single still frame is presented to the observer. In this case, all temporal noise is converted into fixed noise because there is no longer a time dependence between frames.

4.1.6 Display and Observer

Once the camera has been modeled up to the detector and post-processing, it is possible to begin to analyze several system level performance metrics. These components will be discussed later since it is necessary to treat first the display and observer models that are required for predicative performance metrics.

Once the image has been processed via the methods discussed above, the image is then displayed for the viewer. NV-IPM offers several options for displays that cover most of the practical cases the designer will encounter. For this example, an LCD display is used. The LCD component in NV-IPM is first defined by an average and minimum luminance. The brightness of the display is extremely important for calculations in the observer model that will be discussed further on. In addition to the brightness specifications, the pixel size and pitch in both directions is also specified. The resolution of the display is determined by the detector resolution and the interpolation components that are used. For this example, an average luminance of 10fL is used with a minimum luminance of 0fL. The pixel size is 0.2mm in both directions with a 100% fill factor. It is important to note that the LCD component is used to model any sort of new display technology, including OLED displays. However, in modelling these other display technologies, the user is limited to only the available parameters within the LCD component. NV-IPM does not have an explicit way to model anything other than an LCD screen.

In place of an LCD screen, it is still possible to model a cathode ray tube (CRT) display. These have been mostly replaced with other display types and thus this component would only be selected when the use of a CRT display was guaranteed. The final display type is an LED direct view display. These displays are used with continuous scanning systems, and thus are not used for this example model.

Once the display has been represented, the observer model is the final component of the system design. The diffraction wavelength of the observer is input, in addition to the number of eyes used by the observer. For a rifle scope or similar optical design, only a single eye is used. In the case of this example, two eyes are used to view the display. The diffraction wavelength is set for the observer at 550nm, which is a standard value. The diffraction wavelength is used when the limiting aperture for either the exit pupil or the eyepiece, depending on the system, is smaller than the pupil. MTF correction is necessary when this is the case but is ignored when it is not. The observer model is important when calculating performance metrics like Johnson criteria or the target task performance (TTP) metric as they are both based on the contrast threshold function (CTF) of the eye. The equations for determining the CTF of the eye are taken from the NV-IPM help documentation and listed below.

$$CTF_{eye} = \frac{\sqrt{2/N_{eye}}}{a\xi * \exp(-b\xi)\sqrt{1 + 0.06 * \exp(b\xi)}} \tag{10}$$

$$num = 540\left(1 + \frac{0.7}{L}\right)^{-0.2} \tag{11}$$

$$denom = 1 + \frac{12}{w(1 + \xi/3)^2} \tag{12}$$

$$a = \frac{num}{denom} \tag{13}$$

$$b = 0.3\left(1 + \frac{100}{L}\right)^{0.15} \tag{14}$$

Here, ξ is the spatial frequency in cycles per degree, N_{eye} is the number of eyes being used by the observer, L is the average display luminance, and w is the apparent target angle. It is not intuitive based on the equations above, but the CTF of the eye is inversely proportional to the average luminance. Thus, increasing the average luminance will decrease the CTF of the eye, which, assuming all other parameters are held constant, will improve task discrimination performance.

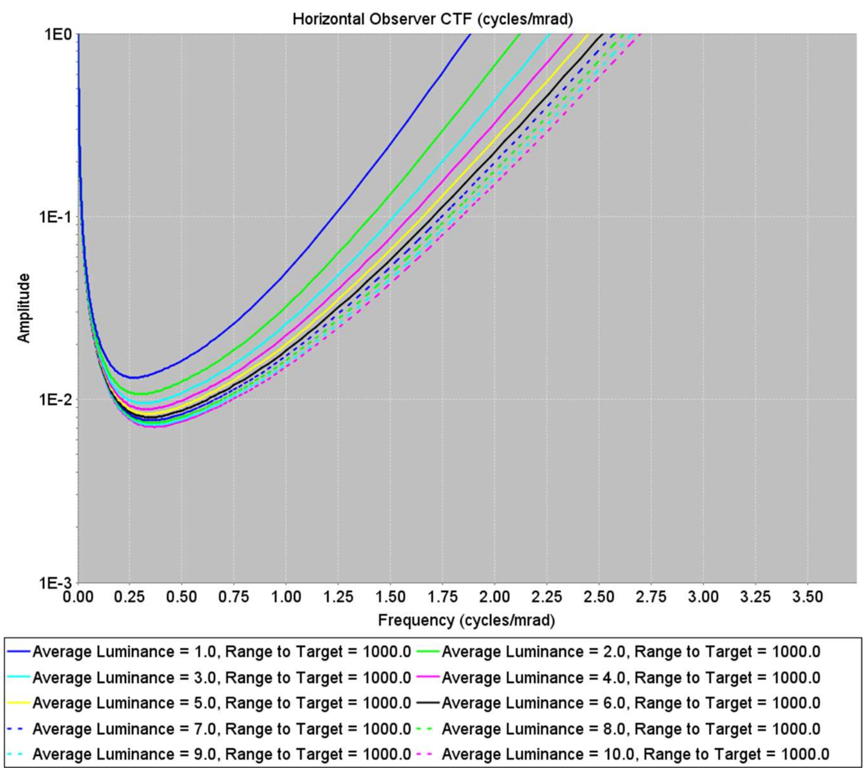

Figure 7. CTF of the eye v average display luminance for the first example problem. As luminance increases, the CTF decreases, which improves the observer-based performance metrics discussed in section 5.

The importance of the CTF and its relation to performance metrics will be discussed in the performance modeling section.

4.2 Double Path

Now that the general components and their corresponding characteristics have been discussed to some length, the second example problem will demonstrate some of the capabilities that make NV-IPM an important trade and analysis tool. For example, NV-IPM uses what are referred to as loops to serve as variables where the analysis will be repeated for each combination of parameters in a loop. Many different scenarios can be designed and traded quickly by creating loops for various parameters. The data can then be compared and traded depending on how the user wants to analyze them. The most common loop used in NV-IPM, which is used in both examples that are presented in this report, is for the range parameter. Often, performance is observed at many ranges, and this is handled using an NV-IPM loop. Additionally, loops are used in both examples to examine the probability of detection, recognition, and identification using the TTP metric, which is discussed later. For the second example, a loop will also be created so that the entire optical system can be modeled in both direct sunlight and full moon illumination conditions.

It is also important to note that many of the design parameters that are used in both problems can be selected via the NV-IPM setup wizard. It is recommended that, with the creation of each new system, the wizard be used to create the general model that can then be modified by the user. For example, the setup wizard allows the user to quickly create the range loop by selecting the maximum range and the increment used for calculations. This is a very convenient and simple way to begin the design process.

4.2.1 Sources and Targets

This example will represent a double path problem where the source and the target are not the same. Thus, we are in the reflective band domain for the model. To begin, it is necessary to specify an ambient source that will provide the illumination for the target. In this problem, we want to compare the optical performance of the system with direct sunlight and full moon illumination conditions. To do this, the first of the two components is added to the component tree. To add the second component, the full moon source can be dragged into the component tree and then created as a new loop. As mentioned above, multiple ambient sources can be selected using the setup wizard instead of starting with a blank model. The ambient sources vary in their nominal emittance. For example, the emittance of the direct sunlight source is going to be much greater than the emittance of the full moon source. Note the several orders of magnitude difference between the spectral emittance of the two sources.

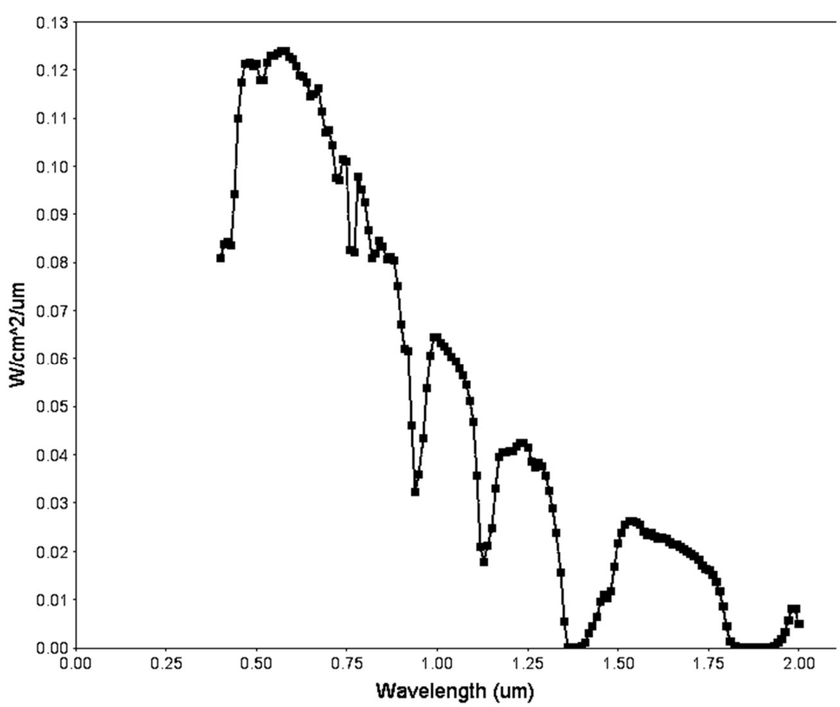

Figure 8. Spectral emittance for the direct sunlight ambient source.

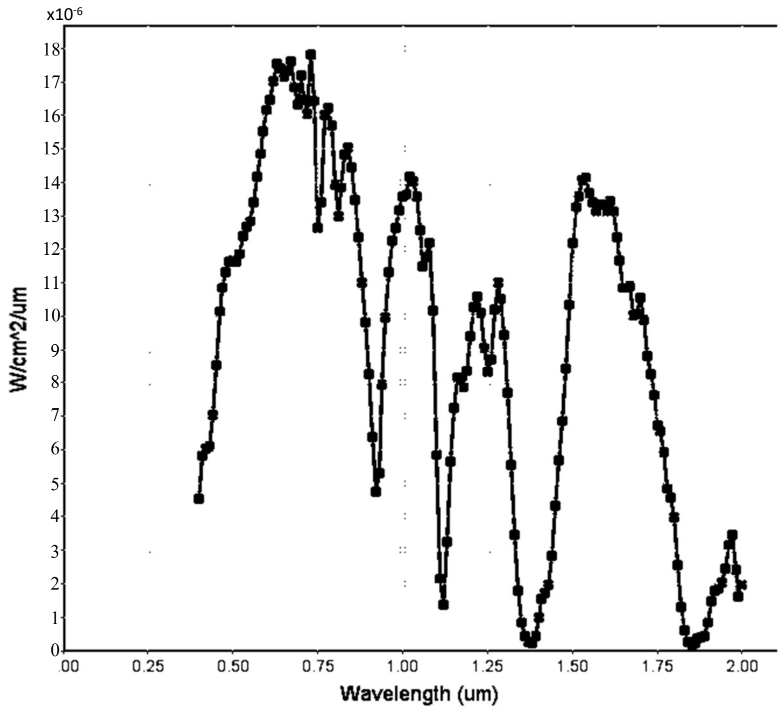

Figure 9. Spectral emittance for the full moon ambient source.

The user can also select from overcast, quarter moon, or starlight ambient sources.

In addition to the given ambient sources, there are several other options that are available to describe the illumination used in the system. The first of these additional sources is the active source component. This can be used to represent any active illumination source that is defined by a spectral emittance. Another option is to define the illumination with a blackbody photopic source. This component is defined by a blackbody temperature in Kelvin and a photopic illumination in foot candles or lux. The blackbody temperature is used to find the spectral components of the source and the photopic illumination scales the output of the source. In place of the blackbody photopic source, an extended blackbody can also be used when the range to and size of the blackbody are known.

Beyond blackbody sources, NV-IPM is also able to model both CW and pulsed lasers. Both of these require an atmospheric transmission per kilometer, a laser wavelength, and a laser divergence. Since an atmospheric transmission per kilometer is required, the transmission of the wavelength is assumed to follow Beer's law, as written in equation 5. The pulsed laser also requires a pulse duration and an energy per pulse while the CW laser requires only a laser power in watts. The laser components are important for modeling semi-active laser (SAL) systems where the target is illuminated by a designating laser.

As with many of the other components, there is also a generic source option that allows the user to define a source by its known mean and standard deviation. This can be specified differently for the target and the background, allowing the user more freedom in defining various source types.

Once the sources that are being used have been selected, it is required that a target and background be selected. The target components for a reflective band system are defined the same as they are for an emissive band system. The characteristic dimension, reflectivity, temperature, temperature variation, and cuton and cutoff wavelengths are all required. When using the setup wizard, there are multiple presets for specific targets with measured reflectivities. These presets are not available outside the setup wizard. For this example, a target with a characteristic dimension of 3.11m was used, corresponding to a military vehicle. The reflectivity used was a preset for dark brown paint.

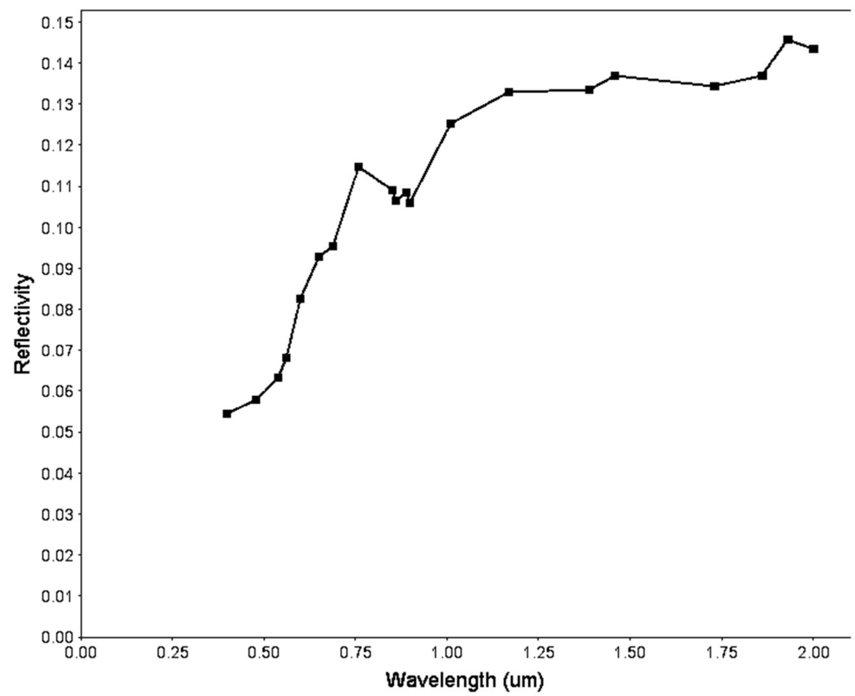

Figure 10. Target reflectivity as a function of wavelength for the NV-IPM dark brown paint preset.

The background component is defined by the same inputs as the target, minus the characteristic dimension. Again, it is possible to input user defined values or use a preset from the setup wizard. For this example, a background preset for Arizona sand dunes was used.

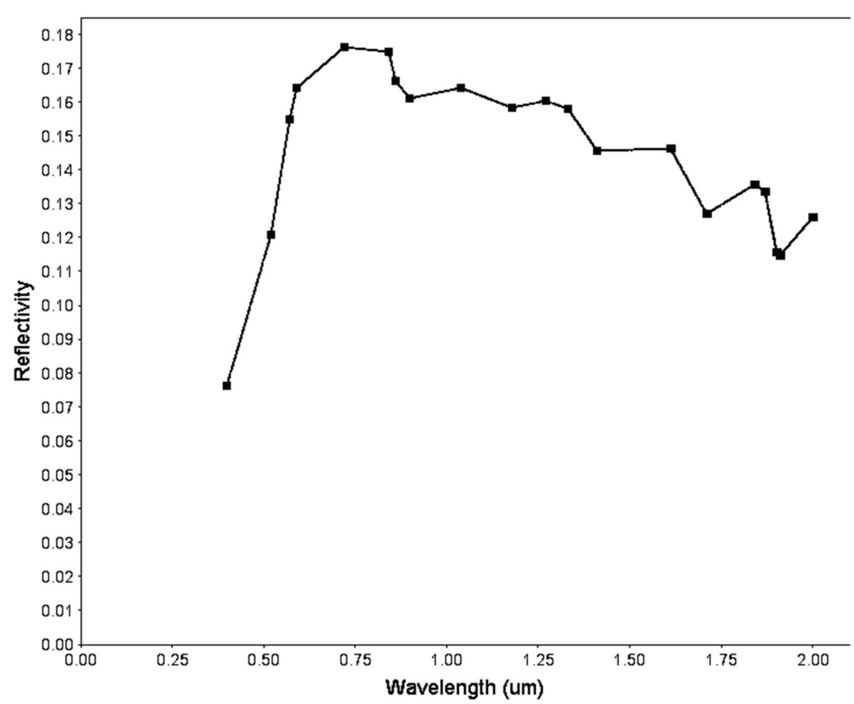

Figure 11. Background reflectivity as a function of wavelength for the NV-IPM Arizona sand dunes preset.

4.2.2 Atmospherics

The next step of the camera model is to define the atmospheric model. In the first example, a simple application of Beer's law was used to model the transmission loss due to atmosphere. In this example, a MODTRAN preset was used. MODTRAN is a separate program developed by Spectral Sciences, Inc., in partnership with the Air Force Research Lab.[18] It is used for analysis of atmospheric contributions toward optical measurements. This program is not included in NV-IPM but requires a separate license. However, there are MODTRAN preset transmission tables built into NV-IPM that are available to the user. When selecting the MODTRAN database component, the atmosphere, aerosol, and cloud models are specified from a set list of options. The various combinations of these options each have a unique transmission table that was calculated in MODTRAN and saved into NV-IPM. These presets represent several generic atmospheric models that will cover many of the scenarios that are required for analysis. It is not possible to edit these presets within the program. However, there may be some cases where changes are desired based on additional known transmission degradations. In this case, there is a process that allows the user to edit these tables, but it requires the addition of a second atmosphere component. As mentioned in the first example, NV-IPM has a generic transmission table component that allows the user to define bulk transmission as a function of wavelength which will be used for the work around.

In order to create a modified MODTRAN transmission table, the initial step is to get the transmission values from the generic MODTRAN component and save them into a secondary program, like Microsoft Excel. First, in the outputs section of the MODTRAN database component, the atmospheric transmission box must be selected. Next, it is necessary to complete an analysis run. This can be done with a dummy set of components after the atmosphere component or the actual desired system model. Once the analysis run is complete, the atmospheric transmission output can be selected. The results for the atmosphere used in the second example problem are shown in figure 11.

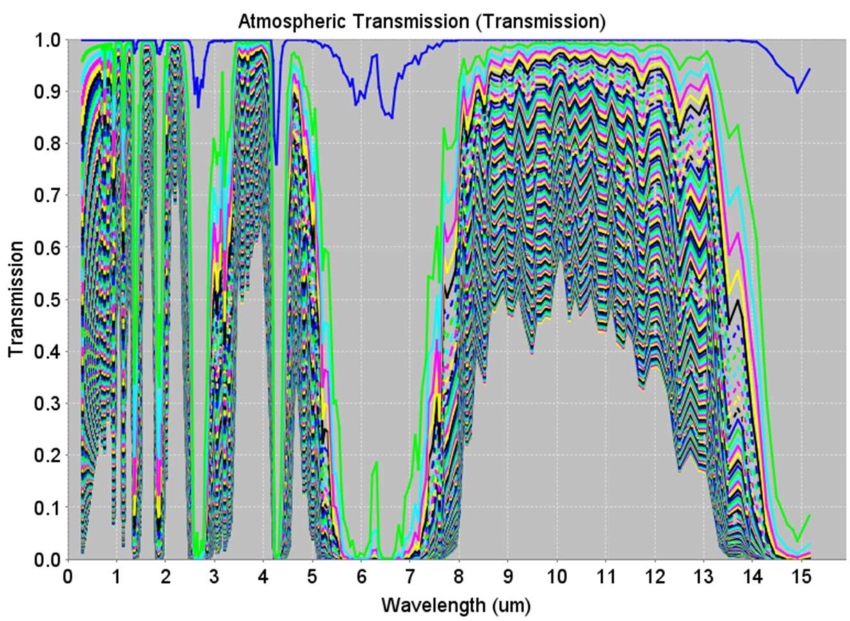

Figure 12. MODTRAN transmission table from NV-IPM. This transmission table represents a 1976 US Standard atmosphere model with rural 23km visibility and no cloud model. The range increases from the top line at 1m to the bottom line at 10km in increments of 100m.

After the atmospheric transmission table has been produced, the next step is to copy the transmission table for each range. At each range, a table of spectral transmission values is available by selecting the box with three dots at the right of the main analysis window. This table can be copied and pasted into another program for storage. Unfortunately, it is necessary to repeat this exercise for each range value.

Once these values have been saved, the transmission tables can be modified, but then they must be estimated in terms of a spectral transmission per kilometer to be used with the spectral Beer's law component. The new optical model can be built in NV-IPM, this time with a spectral Beer's law component in addition to the original MODTRAN component. This component allows the user to input a spectral transmission, but not as a function of range. Thus, why the modified MODTRAN table must be estimated as a per kilometer transmission. The new modified spectral values can be added to this component to mimic the modified MODTRAN table. Unfortunately, without access to MODTRAN directly, it is not possible to create a new spectral and range dependent transmission table. If the user has access to MODTRAN, it is possible to export the resulting atmospheric transmission and then import that file into NV-IPM.

For his example, a 1976 US Standard atmosphere model was used. The aerosol was set to rural 23km visibility with no cloud model. The altitude, atmosphere temperature, and sky-to-ground ratio are all identical to the previous example. Range values are from 1m to 10km in 100m increments. Turbulence was assumed to be negligible, so an identical index structure parameter was used.

4.2.3 Optics

The optical setup is defined the same as in the previous example. A 50mm aperture with a 100mm focal length represents the system. An 80% transmission is assumed with a blackbody equivalent temperature of 300K.

As an important note, it is common for an optical designer to consider multiple aperture sizes and focal lengths when initially beginning the design of an optical system. General rules of thumb and fundamental relationships are well known for the effects that changing the above parameters have on an optical system. However, it is extremely easy to get quantitative comparisons between these optical designs in NV-IPM. Loops can be created for various aperture and focal length combinations. Performance metrics can then be determined for these combinations, even if the rest of the system or use cases are not known. The result will be a relative, yet quantitative, comparison between possible optical systems.

4.2.4 Detectors

Detector options were previously discussed in the first example. For the double path problem, an ON Semiconductor MT9T034 1/3-Inch CMOS digital image sensor was used in the model.[19] The known parameters that were taken from the specification sheet were input into NV-IPM. Additional parameters that were not listed were given generic values from NV-IPM.

In the single path problem example, the cuton and cutoff wavelength are parameters within the microbolometer component that are specified. With the generic detector component, there is not a parameter available for either of these values. Instead, the responsivity of the camera is defined by the spectral quantum efficiency (QE) parameter. This allows the user to define the QE of the camera as a function of wavelength and thereby define the wavelength bounds available to the camera for performance calculations. For this example, the monochromatic option from the ON Semiconductor detector was used and the QE plot was taken from the specification sheet. The resulting QE plot in NV-IPM is shown in figure 13.

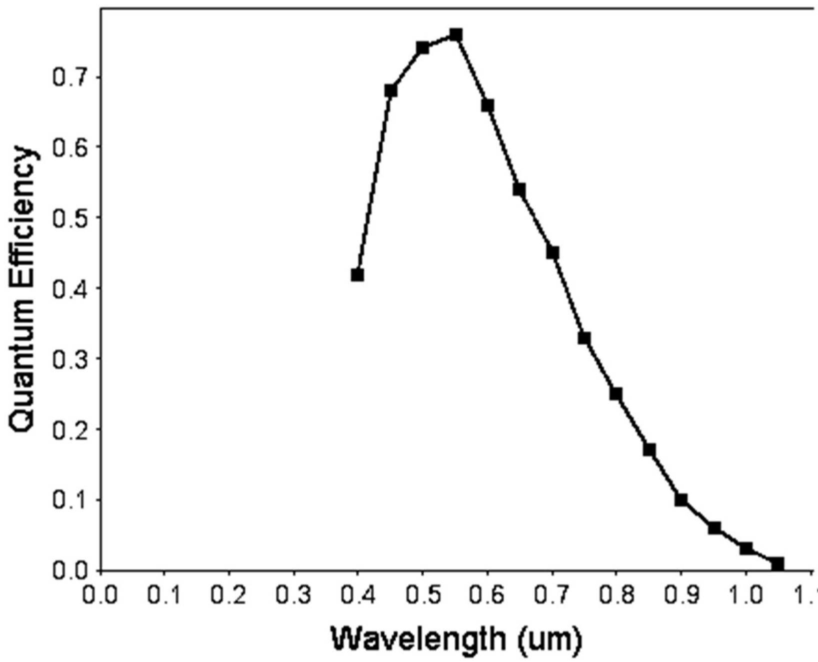

Figure 13. Spectral quantum efficiency for the ON Semiconductor detector[19] used for the double path problem.

4.2.5 Electronics and Post-Processing

For this example, no additional electronics or post-processing components were used.

4.2.6 Display and Observer

The final components of the model are once again for the display and the observer. The same LCD component used in the first example was repeated here. Additionally, the observer model is the same.

One of the main points of this second example problem was to compare the functionality of the optical system during full daylight hours to full moon equivalent illumination. Previously discussed was the derivation of the CTF of the human eye, but this CTF calculation is only a portion of the system CTF calculation used in predictive performance calculations. The system CTF is shown in equation 15.

$$CTF_{sys}(\xi) = \frac{CTF_{eye}(\xi)}{MTF_{sys}(\xi)} NF(\xi) \tag{15}$$

With a completed model, all of these required values are known. The difference in source illumination between the two lighting conditions necessitates that the CTF for full moon illumination will be much greater across all spatial frequencies. This will severely hurt the overall system performance, as discussed in the following section.

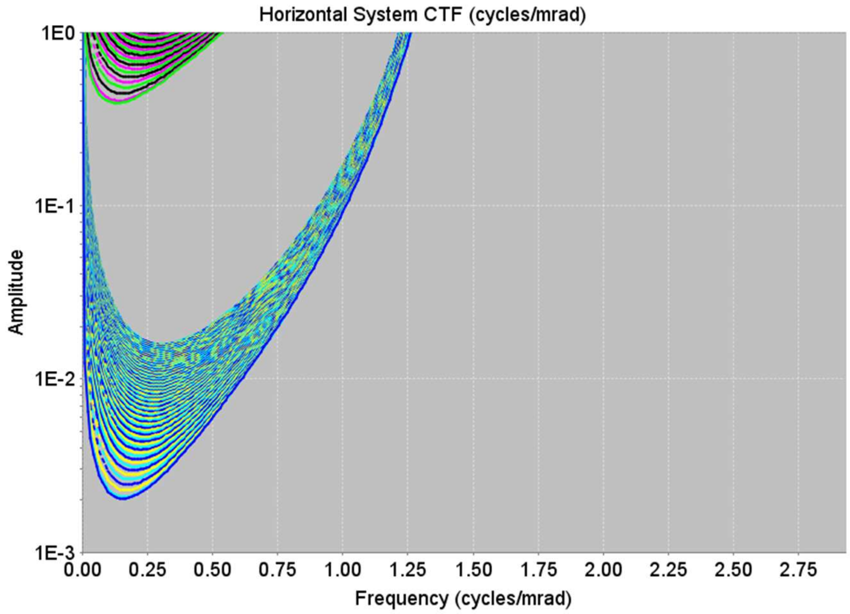

Figure 14. System CTF for the second example problem. The small upper bundle of curves represents the full moon source while the lower bundle represents the direct sunlight source. Within each bundle, the range is represented moving from the bottom curve at 1m to the top curve at 10km.

It is important to note that CTF curves are given an upper bound of one because a contrast ratio greater than one is not possible. The amplitude represents the minimum contrast for a sinusoid of the given angular frequency that is visible at the defined viewing distance. Thus, a value of one essentially means that maximum contrast would be required for that sinusoid to be visible. In cases where the CTF for a given set of parameters at an angular frequency is greater than one, its value is replaced by one. Thus, many of the long ranges with the full moon illumination would be expected to not be visible since they are one for all spatial frequencies. A more rigorous derivation and explanation of CTFs is available in chapter 13 of *Introduction to Infrared and Electro-Optical Systems*[9].

5. PERFORMANCE MODELING IN NV-IPM

With a completed discussion on the design and analysis components, it is now important to cover performance modeling in NV-IPM. In this section, each of the listed performance metrics includes a discussion on the derivation of that metric with examples taken from the models presented in section 4.

5.1 Johnson Criteria

The first performance metric to be analyzed is the Johnson criteria. Its inclusion is more important from a historical perspective and to better understand the TTP metric that is described in section 5.2. The Johnson criteria is a method for determining the probability of task completion for detection, recognition, or identification developed in the 1950's by John Johnson. The criteria use the idea of finding the highest frequency, just resolvable sinusoid under certain conditions at a given range. The initial tests involved placing bar chart targets of various frequencies next to actual targets of interest. When it was possible to detect, recognize, and identify the target, the frequency of the just resolvable bar target was noted for each task. This was repeated many times with different targets. After completion of the testing period, it was determined that the number of just resolved bar target cycles across the smallest target dimension was roughly constant. Thus, the number of cycles required for each of the discrimination tasks were determined. These numbers of cycles were based on the 50% probability for task completion.[13] These are referred to as N50 values. The more difficult the discrimination task, the larger the N50 value for that task.

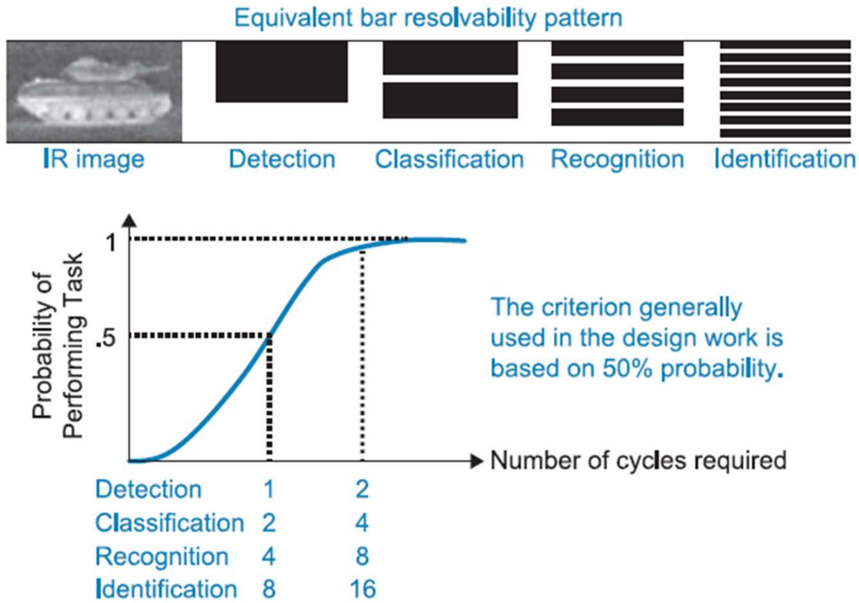

Figure 15. Depiction of the number of cycles on target for a given IR image. The N50 values for each discrimination task are included. Values of N that are double their respective N50 values show the probability of task completion. Image is taken from *Field Guide to Infrared Systems, Detectors, and FPAs*.[20]

To determine the actual probability of completion for a given task based on the Johnson criteria, the system CTF must first be determined. Next, the apparent contrast of the desired target is plotted with the system CTF. The highest contrast for which the system CTF is less than or equal to the apparent target contrast is found to be the limiting frequency, normally in units of cycles per milliradian. This is equivalent to the initial method used by Johnson detailed above. By multiplying by the angular subtense of the target, it is possible to find the number of cycles on target.

$$N = \xi_J * \left(\frac{x_{\lim}}{R}\right) \tag{16}$$

Once this is known, the probability of task completion is determined.

$$p = \frac{(N/N_{50})^{A+B(N/N_{50})}}{1 + (N/N_{50})^{A+B(N/N_{50})}} \tag{17}$$

The values A and B define the steepness and shape of the psychometric function that relates the observer's ability to discriminate targets to the original image quality.[11] These values change depending on the conditions of the system, and thus require some familiarity to properly determine. Additional information on matching legacy models is available in the NV-IPM help documentation.

After 25 years of using the Johnson criteria, a new predictive performance metric, the TTP metric, was developed to account for many of the flaws in the Johnson criteria. It is much more common to use the TTP metric for determining task probabilities, but an understanding of the Johnson criteria is important as the TTP metric builds on the work by Johnson and functions much in the same way as his original model.

5.2 Target Task Performance (TTP) Metric

One of the biggest flaws of the Johnson criteria was that it weighted all frequencies evenly when determining the cycles on target, as shown in equation 16 above. Work by Richard Vollmerhausen and Eddie Jacobs from the Modeling and Simulation Division of NVESD produced the more commonly used TTP metric. With the development of new detector technologies, the Johnson criteria becomes insufficient for analyzing new systems because, being based on only the limiting frequency, it often predicted constant performance over different technologies when testing proved the contrary. Vollmerhausen recognized the importance of including the excess contrast available at frequencies lower than the limiting frequency.[21]

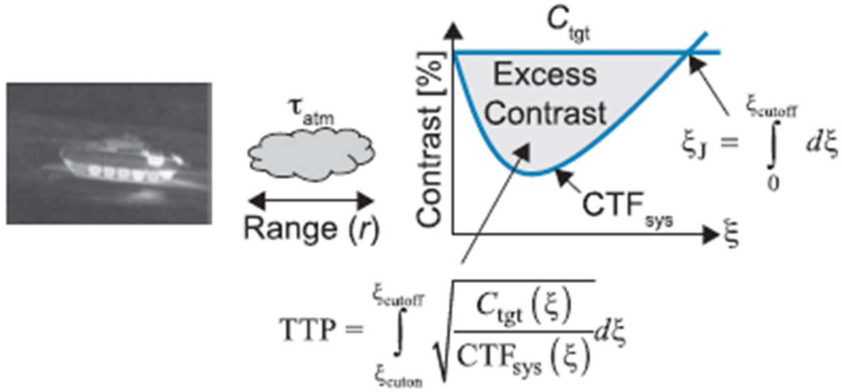

Figure 16. Representation of the method used to determine both the limiting frequency for Johnson criteria calculations (ξ_J) and the TTP metric. It is important to note that in the limiting frequency integral, all of the frequencies are given an equal weight while in the TTP metric, the frequencies are weighted according to the available excess contrast. Image taken from *Field Guide to Infrared Systems, Detectors, and FPAs*.[20]

The TTP metric gives additional weight to the excess contrast at each of the lower frequencies, as seen in equation 18.[22]

$$TTP = \int_{\xi_{cuton}}^{\xi_{cutoff}} \sqrt{\frac{C_{tgt}(\xi)}{CTF_{sys}(\xi)}}\, d\xi \tag{18}$$

With the additional weighting of the excess contrast, the TTP metric is much more capable of making performance predictions for a greater number of detector technologies and over a wider range of applications. Once the TTP is calculated, it can be converted to a V number that is similar in principle to an N number from the Johnson criteria.[21]

$$V = \frac{\sqrt{A_{tgt}}TTP}{R} \tag{19}$$

Another difference between the TTP metric and the Johnson criteria is that the target dimension used for the TTP metric is the square root of the area of the target presented over the average of all aspects, not just the limiting dimension of the target. It was determined that this characteristic dimension better represented the performance of the system over using just the limiting dimension.[20] This V number is then turned into a probability of task completion based on the determined V50 via the target transfer probability function (TTPF).[21]

$$TTPF = \frac{(V/V_{50})^{E_{TTP}}}{1 + (V/V_{50})^{E_{TTP}}} \tag{20}$$

$$E_{TTP} = 1.51 + 0.24(V/V_{50}) \tag{21}$$

Again, similar to the development of the Johnson criteria, V50 values were experimentally determined to represent the V that corresponds to a 50% likelihood of task completion. Much work has gone into experimentally determining appropriate values for V50 corresponding to different discrimination tasks for various target sets.[9] Table 1 is taken from the NV-IPM help documentation and shows some of the recommended values that may be of interest to NV-IPM users.

Table 1. Recommended V50 values for various target sets and discriminations tasks. The table is taken from the NV-IPM help documentation.

Target Set	Task	Aspect	Band	ΔT (K), Contrast (%)	Characteristic Dimension (m)	V50
12 Tracked Vehicles	ID	All Aspects	Thermal	4	3.1	13
Military Vehicles	Rec	All Aspects	Thermal	4	3.1	9
Vehicles (Moderate Clutter)	Det	All Aspects	Thermal	4	3.1	2
Humans (Moderate Clutter)	Det	All Aspects	Thermal	3	0.75	2
Human Activities	ID	Front Aspects	Visible/SWIR	30%	0.75	6.5
			Thermal	3	0.75	6.5
Two-Handheld Objects (Weapon/Non-Weapon)	Rec	Front Aspects	Visible/SWIR	30%	0.25	3*
			Thermal	2	0.25	4
		All Aspects	Visible/SWIR	30%	0.25	7.5*
			Thermal	2	0.25	10
Two-Handheld Objects	ID	Front Aspects	Visible/SWIR	30%	0.25	5
			Thermal	2	0.25	5
		All Aspects	Visible/SWIR	30%	0.25	12.5
			Thermal	2	0.25	12.5

For both example problems, the TTP metric was the main performance metric used to determine probability of task completion. As shown in the chart, a characteristic dimension of 3.11m was used for both examples, corresponding to a vehicle of military interest. V50 values of 2, 9, and 13 were used to represent detection, recognition, and identification, respectively. The probability of task performance as a function of range for the single path problem is shown in figure 15 while the same plot for the double path problem is shown in figure 16.

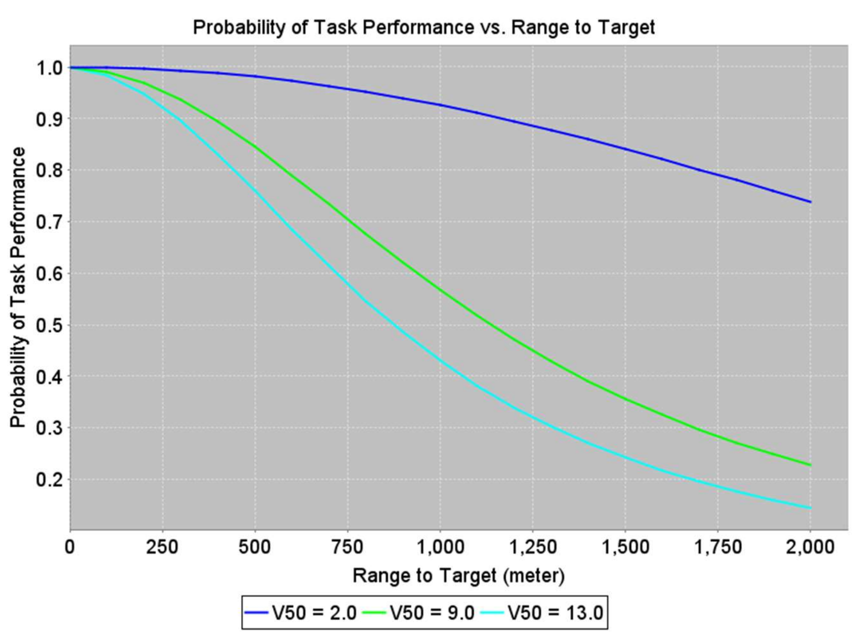

Figure 17. The probability of task performance is shown as a function of range for detection, recognition, and identification for the single path, thermal target problem.

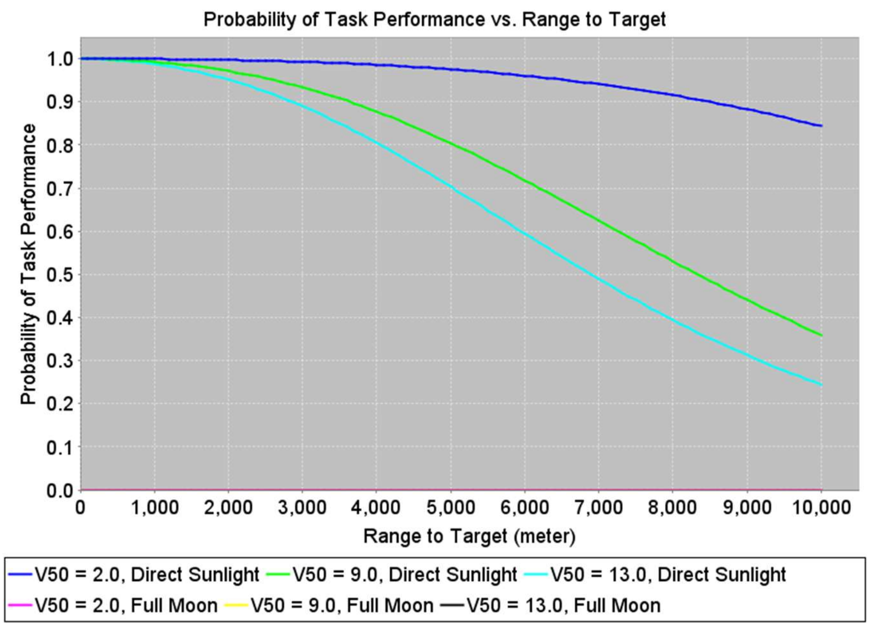

Figure 18. The probability of task performance is shown as a function of range for detection, recognition, and identification for the double path, reflective target problem.

Both plots follow the same trend. The probability of detection is much higher than recognition or identification for all ranges. In the double path example, there is a second set of curves that are zero for all ranges at the bottom of the plot. This set of curves corresponds to the probability of task performance for the full moon illumination source. Since this illumination is so much smaller than the direct sunlight illumination and the reflectivity of the target is so small, almost no illumination reaches the camera. This was seen in the system CTF curves from figure 12. Since there is so little illumination, the TTP value for all ranges is extremely small. Essentially, due to blur and noise in the camera added to the very small amount of illumination, the target will not be visible at night.

Another useful capability within NV-IPM for determining performance capabilities using the TTP metric is the TTP metric backsolver. This allows the user to determine the range at which a specific probability is reached for each desired V50 value. In the double path problem, this can be used to solve the range at which a 90% probability of task completion is reached for each of the desired tasks.

Table 2. Range for task probability of 90% with 3.11m reflective target with direct sunlight illumination.

Task	V50	Range
Det	2	8.488
Rec	9	3.633
ID	13	2.856

5.3 National Imagery Interpretability Rating Scale (NIIRS)

The next predictive performance metric that can be used in NV-IPM is the National Imagery Interpretability Rating Scale (NIIRS). The NIIRS was developed in the 1970's as a way to quantitatively determine the interpretability of an image in cases where scale and resolution were insufficient.[23] The NIIRS has traditionally been used with surveillance aircraft, but more currently has been developed for unmanned aerial vehicles (UAVs).[9] In the NIIRS model, there are 10 levels of interpretability, going from 0 to 9. Each level has a set of descriptions corresponding to image quality. Table 14.11 in *Introduction to Infrared and Electro-optical Systems* demonstrates an example set of NIIRS criteria.[9]

There are various sets of descriptions for NIIRS levels depending on the application, i.e., military or civilian.[23] For example, from table 14.11, a NIIRS level of 6 is described by:

1) "*Distinguish between models of small helicopters.*"
2) *"Identify automobiles as sedans or station wagons."*
3) *"Identify the spare tire on a medium-sized truck."*

NIIRS levels are calculated using the general image quality equation (GIQE). This equation is based off the image scale, image resolution, and system signal to noise ratio (SNR). The GIQE will give a NIIRS value for the given optical system, which differs from the probability outputs of the Johnson criteria and TTP metric.

The GIQE is not based off an observer looking at an image of a screen. Thus, it is required that the NIIRS component be placed after the detector and image processing components but before the display components in NV-IPM. In addition, the GIQE, as calculated in NV-IPM, requires the ground sample distance (GSD) of the system and necessitates that the camera system be given some altitude. Without it, NV-IPM will exit calculations with an error. For both examples, no altitude was specified, therefore the NIIRS is not used as a performance metric.

5.4 Other Metrics

In many cases, it is not practical in a system to assume that there will be an observer making decisions based on the output of the optical system, as is the requirement with the Johnson criteria and TTP metric. In these cases, it may not be appropriate to determine system performance using either of these metrics. There are often other system parameters that are equally important for determining complete system performance. In NV-IPM, these additional metrics can be found as outputs within existing components or included as probes. Probes are components that can be placed inside the system and have the corresponding performance metrics measured at that location in the system. Several of these probe performance metrics are discussed in the following sections. There are some additional noteworthy performance models that are not available within NV-IPM. The first of these is the TRM3 model developed in Germany which uses a modified Johnson criteria that accounts for the phase difference between the camera and the imaged 4 bar target.[9] The second of these additional models is the triangle orientation discrimination (TOD) model from the Netherlands. This model required the imaging of a triangle, instead of a bar target, that could be oriented with its apex in any of the 4 basic directions. A forced-choice experiment required the observer to decide which direction the triangle was oriented. Performance determination was based on the ability of the observer to correctly identify this orientation.[9]

5.4.1 Noise Equivalent Temperature Difference (NETD)

The first of the other performance metrics that is discussed is the noise equivalent temperature difference (NETD). This metric is an output for the basic detector component. NETD represents the sensitivity of the optical system and is defined as the temperature difference between target and background that leads to a SNR of 1.[9] In NV-IPM, the NETD is defined as the target to background differential temperature divided by the target standard deviation all multiplied by the root sum of squares (RSS) for all noise sources.[11]

$$NETD = \frac{\Delta T_{tgt}}{\sigma_{tgt}} \sqrt{\sum_{i=0}^{N} n_i^2} \tag{22}$$

NETD is a common performance metric that is specified and measured for thermal imagers. Lower NETDs correspond to better sensitivity in a system since smaller variations in temperature can be measured. As seen in figure 17, as the range decreases and the optical system approaches the target, it is possible to measure smaller temperature differences. NETD decreases as it passes through atmosphere and signal is lost which explains the trend seen in the figure.

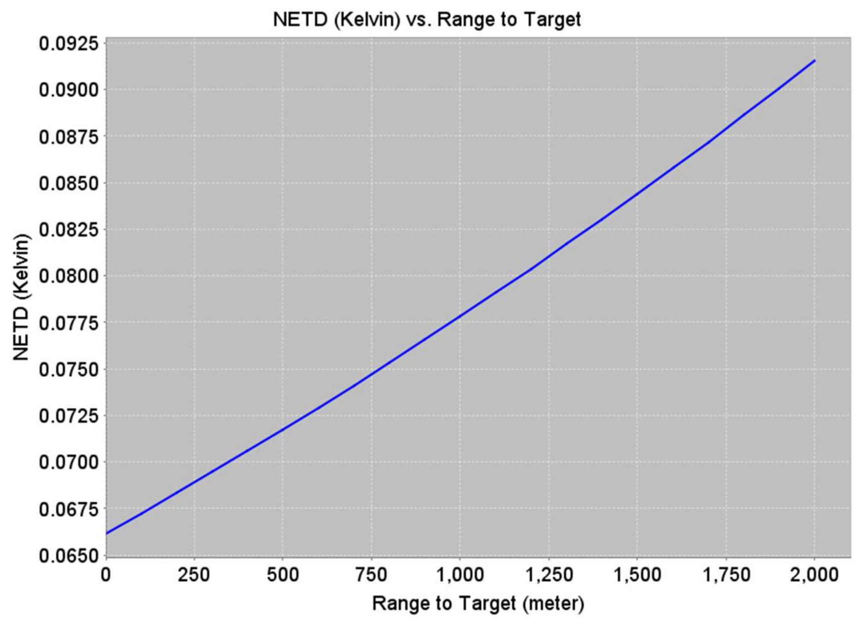

Figure 19. NETD plotted against range for the thermal target example.

5.4.2 Signal to Noise Ratio (SNR).

Next, is the signal to noise ratio. The SNR probe component can be placed in the component tree in various locations to measure the SNR at that location. For example, the SNR probe may be placed right after the detector with a second probe after the post-processing components to quantify the SNR improvement due to these components. In systems where there is not an observer making decisions based on images presented to them, SNR may be used by computer algorithms to make these types of decision. For the second example problem, an SNR probe is placed after the detector to measure the SNR before any electronics or post-processing.

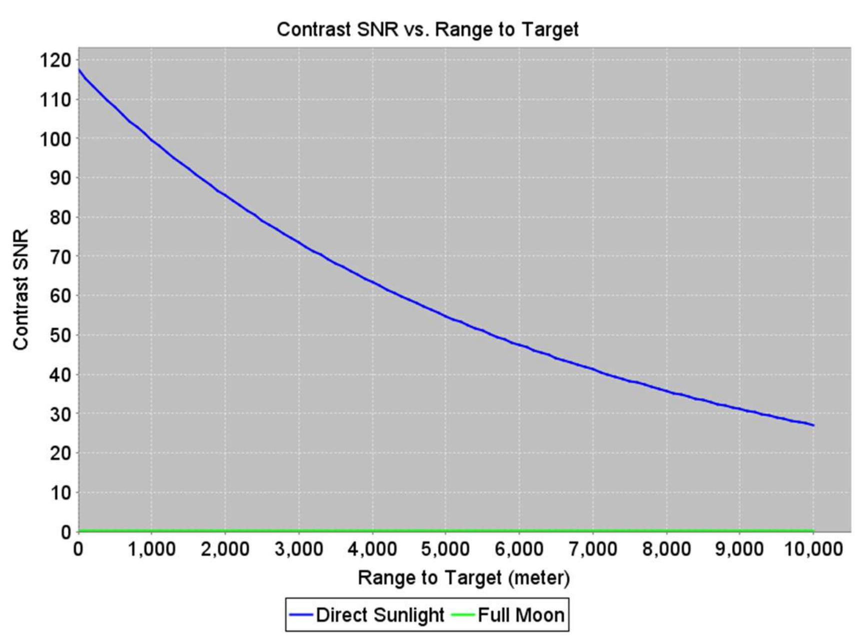

Figure 20. System SNR for the double path problem. For the full moon source, SNR is zero for all ranges. The model parameters and noise values are from the example detailed in section 4.2.

The output gives the SNR as a function of range for the illumination loop that was defined at the beginning. As expected, the SNR for the direct sunlight decreases with increasing range. Due to the lack of illumination from the full moon source, the SNR is effectively zero for all ranges.

In addition to SNR, the SNR probe can also evaluate other parameters, including the detectivity of the detector, the noise equivalent irradiance, the noise equivalent power, or the NETD. These parameters are further defined in the NV-IPM help documentation.[11]

5.4.3 Modulation Transfer Function (MTF)

The final performance metric is the modulation transfer function (MTF). The MTF of the system defines the frequencies that are passed by the optical system and how those frequencies are attenuated. The MTF probe will measure the system MTF at the location the probe component is placed, in local units or angular units. The system MTF gives local units, i.e., cy/mm, while the system MTF (object) gives the MTF in what NV-IPM refers to as object space, in units of cy/mrad. The MTF is calculated in both the vertical and horizontal directions. For axisymmetric systems, these two MTFs should be identical. An MTF probe was placed next to the SNR probe in the double path example so that the MTF could be measured after the detector but before the display. The result is seen in figure 18.

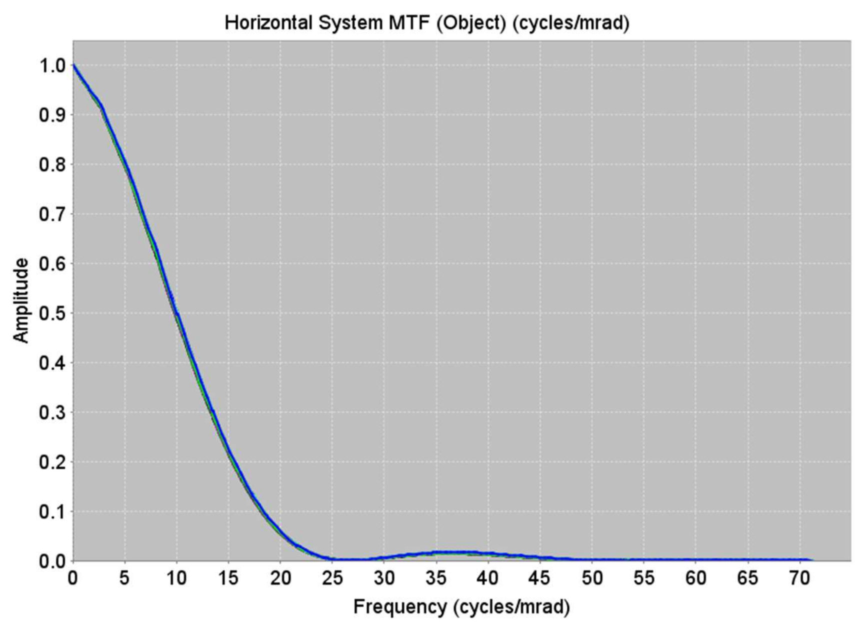

Figure 21. System MTF for the double path problem in object space, having units of cy/mrad. Curves for all ranges and both illumination levels are represented.

The MTF plot shows the system MTF for both illumination sources in the source loop calculated at each of the range values. Since the turbulence was approximated to be zero, there is almost no change in the MTF as a function of range.

6. NV-IPM IMPROVEMENTS AND CONCLUSIONS

NV-IPM is an extremely useful trade and analysis tool that is capable of handling many different design scenarios. In terms of user friendliness, the NV-IPM help documentation can assist a new user understand many of the components and general design processes. Included with NV-IPM are various examples and training tutorials that walk users through the basics of starting a new system and making important design trades. Compared to other engineering software, the built-in documentation is well done and easy to navigate. NV-IPM excels at working with complicated scenarios that would otherwise be difficult to analyze. The variety of components makes it possible to design a system model that closely matches a real model. Overall, NV-IPM is an effective tool for making engineering decisions.

Regardless of the many attributes that make NV-IPM so useful, there are still areas for improvement. As is important with all engineering tools, it is necessary to understand that poor inputs that do not properly model a system will not give correct outputs. It is essential that the user recognize this principle. Accuracy and consistency are requirements for creating models with useful outputs. Additionally, while confidence can be had in the capabilities of NV-IPM, no amount of modeling should ever replace laboratory and field testing. This is especially true in NV-IPM when it comes to the boost filters that are available. These boost filters provide an MTF improvement around a desired frequency, but provide little gain at low and high spatial frequencies.[9] These filters, when modeled in NV-IPM, often provide an overly optimistic assessment of the final performance metrics. Special care is required when working with these components so that proper decisions are made. Prior knowledge of the boost filter performance benefits will help create a more accurate model when working with these components.

NV-IPM does not have a built-in way to account for image clutter when making task performance predictions. Clutter has had an important effect on probability calculations and was discussed in the context of the development of the TTP metric. In his discussion on the topic, Vollmerhausen recognized that clutter can hurt task performance probabilities, and claimed it can hurt target acquisition ranges by a factor of four.[21] Yet, he did not include this as part of the development of the TTP metric. Thus, it is left to the optical designer to decide the incorporation of clutter to the predictive performance models. With the example of the TTP metric, this may look like scaling the nominal V50 value for a given task on the assumption that clutter will affect it by the scaled amount. Regardless of the approach, this falls purely to the designer as NV-IPM has no way to directly incorporate clutter into its analyses.

NV-IPM is also not yet well equipped to handle the implementation of deep-learning algorithms to calculate task performance probabilities. This, however, is a fundamental flaw of both the Johnson criteria and the TTP metric as both depend on an observer making decisions after seeing images from an optical system. Both metrics are based on the CTF of the eye, which necessitates the inclusion of an observer model. There are now many applications in which an observer is not involved in the decision-making process, but rather a computer makes decisions based on the post-processed image. For example, government contracted defense manufacturers do not include live feed from missile seekers to observers in front of a monitor to make decisions on target acquisition. This general family of systems is often referred to as automatic target recognition (ATR) models.[9] As is, the type of task performance probabilities determined via the TTP metric are not available for this type of system, thus, the importance of using other performance metrics like NIIRS, SNR, or NETD. Normally, these additional parameters are taken from NV-IPM and must be applied into other programs so that task probability predictions can take place. This is not necessarily a flaw in NV-IPM, but rather a limitation where additional research can be done so that models like the TTP metric can be applied to deep-learning or similar optical systems. Of late, research is being done on this type of work to apply general performance predictions to ATR models. For example, work done by Jaffe, Zelinski, and Sakla published in an IEEE journal in November 2019 details the researchers attempts to train a neural network via deep learning to complete NIIRS level assignments to images. Jaffe, et al., concluded that there is still a possibly significant difference in the visual recognition performance of a deep-learning neural network compared to a human.[24] Without a reliable and widespread relationship between human and computer recognition performance, NV-IPM will not be able to accurately and precisely model performance predictions without the inclusion of a human observer. This leaves many opportunities for continued research on the generalized application of task performance metrics to ATR and other like systems.

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