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Terahertz imaging system performance model for concealed-weapon identification

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The U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) and the U.S. Army Research Laboratory have developed a terahertz (THz) -band imaging system performance model for detection and identification of concealed weaponry. The MATLAB-based model accounts for the effects of all critical sensor and display components and for the effects of atmospheric attenuation, concealment material attenuation, and active illumination. The model is based on recent U.S. Army NVESD sensor performance modeling technology that couples system design parameters to observer-sensor field performance by using the acquire methodology for weapon identification performance predictions. This THz model has been developed in support of the Defense Advanced Research Project Agencies' Terahertz Imaging Focal-Plane Technology (TIFT) program and is currently being used to guide the design and development of a 0.650 THz active-passive imaging system. This paper will describe the THz model in detail, provide and discuss initial modeling results for a prototype THz imaging system, and outline plans to calibrate and validate the model through human perception testing. © 2008 Optical Society of America

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1. Introduction

Events over the past decade or so, most notably the militant attacks on civilians in London (July 2005), Madrid (March 2004), and New York and Washington, D.C. (September 2001), have led to the increasing need for more effective personnel and accessory security screening. Although techniques exist and are now being utilized for the detection of a variety of threats

such as handheld weapons or concealed explosives, most rely on x-ray imaging-inspection, portal and handheld metal detection technology, and manual search with random chemical-trace-detection sampling [1]. These techniques are currently deficient in two key respects: they provide essentially no stand-off detection capability, and the associated technology is expensive and can typically be deployed only in fixed, controlled environments. Other deficiencies include a limited ability to detect weapons that contain small amounts of metal, ceramic weapons, or explosive materials, especially when concealed

under a suspect's clothing. While emerging technologies such as backscatter x-ray and millimeter-wave imaging may provide additional capabilities, they will still have notable limitations. The backscatter x-ray technology produces ionizing radiation which raises health concerns for personnel use; the millimeter-wave technology, while potentially portable, has limited spatial resolution and thus limited stand-off capability.

The potential of imaging systems designed to operate in the terahertz (THz) electromagnetic spectrum (typically defined as ranging from 0.3 to 10 THz [2]) is twofold. The higher frequencies of THz radiation relative to millimeter-wave radiation yield higher spatial resolutions and thus greater imaging stand-off potential but are able to penetrate many nonconducting, nonpolar materials such as clothing, paper, cardboard, and plastic packaging (between approximately 0.3 and 1.0 THz [3,4]) with only moderate attenuation. Above approximately 1.0 THz, the spectral signatures of many explosive solid materials are available for capture [5] by using, e.g., THz time-domain spectroscopy (THz-TDS) for imaging [4]. Recent advances in THz generation and detection technologies [6] enable the design and development of more compact and potentially portable THz imaging systems. Substantial stand-off threat detection–discrimination will be a crucial aspect of all future THz-based security imaging systems intended to effectively counter today's asymmetric terrorist threats. Accurate modeling of such systems will play a significant role in the development of system technology, system architectures, and security procedures.

The objective of this research has been to develop an imaging system performance model for the THz band applied to concealed-weapon identification (ID). The performance model has been designed to allow the calculation of observer–imager performance for conceptual designs using either active or passive illumination, scanning or focal-plane-array (FPA) detector technologies, and arbitrary, but definable, display scenarios. The model will also allow for imager design and imager evaluation. The model has been designed to incorporate the effects of target and background source phenomenology including atmospheric and concealment-material (e.g., clothing) radiation transmission.

Sensor characterization is seen in three ways: theoretical models, field performance, and laboratory measurements (Fig. 1). Theoretical models are developed that describe sensor sensitivity, resolution, and human performance for the purpose of evaluating new conceptual sensors. Acquisition models, and other models, are developed to relate the theoretical models to field performance. This link allows theoretical models to be converted to field performance quantities (e.g., probabilities of detection, recognition, and ID). Field performance is measured in the field so that the theoretical models can be refined and become more accurate with advanced sensor developments. Since field performance activities are so expensive, methods

Fig. 1. Imaging system relationships.

for the direct measurement of sensor performance are developed for the laboratory. Field performance testing of every imaging sensor built, including buy-off, acceptance, and life-cycle testing is prohibitive. Laboratory measurements of sensor performance are developed such that, given these measurements, the field performance of a system can be predicted.

Every successful military sensor program has all three of these sensor elements: a theoretical model for sensor performance, a conversion for field performance, and laboratory measurements. This research provides the sensor theoretical model. Conversion for field performance and the link to laboratory performance measurements will be addressed as future work.

This paper will first provide an overview of the architecture used in the development of the THz performance model, followed by a detailed description of its components. Preliminary modeling results for a prototype THz imaging system will be provided and discussed. Finally, plans to calibrate and validate the model through human perception testing will be outlined.

2. THz Performance Model Architecture

The overall goal of this effort was to develop a MATLAB-based [7] imaging system performance model for the THz band applied to concealed-weapon ID. The model has been designed to allow the calculation of observer–imager performance using either active or passive target illumination or self-emission, scanning or FPA detector technologies, and arbitrary, but definable, display scenarios. The model has been designed to account for the effects of target and background source phenomenology including atmospheric and concealment-material (e.g., clothing) radiation transmission.

The overall approach was to adapt the latest U.S. Army Night Vision and Electronic Sensors Directorate (NVESD) sensor modeling technology to the THz regime. The approach essentially requires coupling of a THz radiometric transfer model with the latest Army task performance model for humans viewing dis-

played images, along with THz-specific detector technology parameters. The THz model must then be calibrated and verified through human perception experiments on simulated and/or real THz imagery.

While the U.S. Army NVESD currently releases several different models for different sensors, at their core, they are essentially all the same. Conceptually, the performance models accept inputs that describe sensor characteristics, target-background phenomenology, radiometric propagation properties, and detection, recognition, and/or ID task difficulty factor(s) along with display characteristics, to generate probability of performance as a function of range curve(s) (see Fig. 2). Mathematically, the models consist of three primary equations: the system contrast threshold function (CTF), the target task performance metric, and the target transform probability function (TTPF). These equations follow from two fundamental assumptions: that target acquisition performance is related to the image quality through the sensor, and that image quality is related to threshold vision of the observer through the sensor.

Threshold vision of the observer in the absence of a sensor can be defined in terms of the CTF of the eye, which defines the response of an observer to a sine wave grating. In this model, we utilize an empirical equation for CTF developed by Barten [8] that accounts for the variability associated with different observers, light levels, and display sizes. This equation is a curve fit to an ensemble of CTF measure-

ments and is given by

$$\text{CTF}_{\text{eye}}(f) = \left(a f e^{-bf} \sqrt{1 + c e^{bf}} \right)^{-1}, \quad (1)$$

where f is the spatial frequency in cycles per degree,

$$\alpha = \frac{540 \left(1 + \frac{0.7}{L} \right)^{-0.2}}{1 + \frac{12}{w \left(1 + \frac{L}{3} \right)^2}}, \quad (2)$$

w is the size of the display in degrees, L is the display luminance in candelas per square meter,

$$b = 0.3 \left(1 + \frac{100}{L} \right)^{0.15}, \quad (3)$$

and c is 0.06.

In an imaging system, the CTF of the eye is degraded by the blur and noise of the sensor. Vollmerhausen [9] has shown that this degradation of the CTF is predicted by the following equation;

$$\text{CTF}_{\text{sys}}(f) = \frac{\text{CTF}_{\text{eye}}(f)}{H_{\text{sys}}(f)} \left[1 + \alpha^2 \frac{\sigma^2(f)}{L^2} \right]^{1/2}, \quad (4)$$

where CTF_{sys} is the degraded CTF of the observer through the sensor system, H_{sys} is the modulation

Fig. 2. (Color online) Performance model architecture. Note that the task difficulty factor(s) are determined independently through human perception testing.

transfer function (MTF) of the system, σ is the standard deviation of the perceived noise on the display, L is the average display luminance, and α is an empirically determined calibration constant. The perceived noise on the display is given by

$$\sigma^2(f) = \int_{-\infty}^{\infty} S_n(\xi) |H_{\text{Post}}(\xi) H_{\text{Per}}(\xi, f)|^2 d\xi, \quad (5)$$

where S_n is the power spectral density of the noise source, H_{Post} is any filter in the sensor that occurs after the point where noise is generated, and H_{Per} is a filter describing the perception process. H_{Post} generally includes the MTFs associated with the display and the eye. General expressions for these filters can be found in the NVESD NVTherm manual [10]. The perceptual filter is a bandpass filter designed to mimic the spatial frequency channels of the human visual system. In psychophysical tests, it has been shown that it is only the noise within an octave of the center frequency that interferes with the perception of a sine wave. In the model(s), an expression introduced by Barten [11] is used and is given by

$$H_{\text{Per}}(\xi, f) = \exp \left[-2.2 \log^2 \left(\frac{\xi}{f} \right) \right], \quad (6)$$

where ξ is spatial frequency and f is the center frequency of the filter.

Again, assuming that threshold vision is related to image quality, performance should be related to some metric applied to the system CTF. The standard approach since 1958 has been to use limiting frequency (see Fig. 3) as a measure of image quality. This is the basis of the Johnson criteria [12]. Recently, Vollmerhausen [13] has introduced the target task performance (TTP) metric. This metric has significantly improved the accuracy of predictions especially with regard to effects present in modern sensors. The TTP metric is defined by the root integral of excess contrast weighted by the inverse of the CTF, or

$$\text{TTP} = \int_{f_{\text{lo}}}^{f_{\text{limit}}} \sqrt{\frac{C_t}{\text{CTF}_{\text{sys}}(f)}} df, \quad (7)$$

where C_t is the target-to-background contrast ratio and the limits of integration are determined by

Fig. 3. Relationship between system CTF, limiting frequency, and excess contrast.

$$\text{CTF}_{\text{sys}}(f)|_{f_{\text{lo}} f_{\text{limit}}} = C_t, \quad f_{\text{limit}} > f_{\text{lo}}. \quad (8)$$

Note that if the CTF is taken as equal to the target contrast, then the TTP reduces to the Johnson limiting frequency (since f_{lo} is approximately zero). In a manner analogous to the Johnson limiting frequency approach, range performance is dictated by the effective number of cycles on the target, which is calculated by

$$V(R) = \frac{\sqrt{A_t}}{R} \text{TTP}, \quad (9)$$

where A_t is the area of the target and R is the range to the target.

The TTPF gives the probability of an observer performing a task (detection, recognition, or ID) as a function of both the effective cycles on target and a predetermined set of criteria for that task. Since the effective number of cycles on the target in Eq. (9) is a function of range, the TTPF gives the range performance for a given task. The TTPF is given by

$$P_{\text{task}} = \frac{\left(\frac{V(R)}{V_{50}(\text{task})} \right)^E}{\left\{ 1 + \left(\frac{V(R)}{V_{50}(\text{task})} \right)^E \right\}}, \quad (10)$$

where V_{50} is the number of effective cycles needed to perform a given task (with a 50% probability of success). E is an exponent determined by fitting Eq. (10) to perception experiments. For our preliminary modeling, we used a value of E that had previously been determined from perception experiments with infrared imagery, namely,

$$E = 1.51 + 0.24 \left(\frac{V(R)}{V_{50}} \right). \quad (11)$$

Note that in the older literature on NVESD models, N and N_{50} replace V and V_{50} in Eqs. (10) and (11). The switch to the V and V_{50} notation (value and value₅₀) was done to prevent confusion with the older Johnson cycle criteria.

The methodology described here, while developed for thermal and electro-optical sensors, is applicable to any sensor that provides a display to an observer. The only things that change are the way target contrast is mapped into display luminance (radiometry) and the task difficulty.

3. Terahertz Model Components

As previously stated, the NVESD imaging system performance models and the subject THz imaging system performance model consist mathematically of three primary equations: the system contrast threshold function (CTF_{sys}), the target task performance metric (TTP), and the target transform probability function (TTPF). The following sections

provide detailed descriptions of all of the components that make up the three primary model equations.

A. Image Blur

Image blur, described in Eq. (4) as $H_{\text{sys}}(f)$, consists of spatial blurring from the system optics, the detector size and shape, display system parameters such as the pixel size and shape, the pixel pitch, viewing distance, electronic zoom, average display luminance, and the human eye. Each of these spatial blurring elements are described in the spatial frequency domain as MTFs and are multiplied together to generate the system MTF, $H_{\text{sys}}(f)$.

For this model, the optics MTF is assumed to be the diffraction-limited MTF generated from a circular focusing element and is described (in one dimension) by

$$H_{\text{diff}}(\xi) = \frac{2}{\pi} \left\{ \cos^{-1} \left(\frac{\xi}{\xi_{\text{cut}}} \right) - \left(\frac{\xi}{\xi_{\text{cut}}} \right) \left[1 - \left(\frac{\xi}{\xi_{\text{cut}}} \right)^2 \right]^{1/2} \right\},$$

$$\xi \leq \xi_{\text{cut}}, \quad (12)$$

where

$$\xi_{\text{cut}} = D_{\text{ap}} / (\lambda \times 1000). \quad (13)$$

D_{ap} is the diameter of the circular focusing element (aperture) in meters, λ is the wavelength of the imaging radiation in meters, and ξ is in units of cycles per milliradian [14].

The detector MTF depends on the detector size and shape. For a square detector, the MTF is described (again, in one dimension) by

$$H_{\text{det}_{\text{sp}}}(\xi) = \text{sinc}(\text{DAS}_x \xi), \quad (14)$$

where

$$\text{sinc}(\pi x) = \sin(\pi x) / \pi x, \quad (15)$$

and DAS_x is the detector angular subtense in milliradians [15].

For a circular detector, the MTF is described by

$$H_{\text{det}_{\text{sp}}}(\rho) = \frac{2J_1(2\rho r)}{2\rho r}, \quad (16)$$

where J_1 is a Bessel function of the first kind (order 1) and r is the detector radial angular subtense in milliradians [16].

For single-detector, scanned imaging systems, an antenna horn will typically be used to couple the THz radiation into the detector element. For this case, the effective aperture size of either a square or circular antenna horn is approximated by

$$A_{\text{eff}} = G_{\text{max}} \frac{\lambda^2}{4\pi}, \quad (17)$$

where G_{max} is the gain of the antenna [17]. A_{eff} is

used as the detector size in computing the detector MTF.

The display MTF depends on the pixel size and shape. For a square pixel in a flat-panel display, the MTF is described (in one dimension) by

$$H_{\text{disp}}(\xi) = \text{sinc}(X_{\text{angle}}\xi), \quad (18)$$

where X_{angle} is the pixel size dimension converted to an equivalent angular space in the sensor's field of view [15].

For a pixel in a CRT display, a Gaussian intensity distribution is assumed; the MTF is described by

$$H_{\text{disp}}(\xi) = \text{Gaus}(\sigma_{\text{angle}}\xi), \quad (19)$$

where σ_{angle} is the pixel spot size dimension converted to an equivalent angular space in the sensor's field-of-view [15].

Electronic zoom is accomplished by using bilinear interpolation which, adds an interpolation MTF component. The model can simulate 2×, 4×, or 8× zoom, which is often used to increase system magnification and to reduce any out-of-band spurious response effects from aliased, undersampled configurations [15].

The human eye MTF used in the subject model is described in [15], and is dependent on the average display luminance and the system magnification.

B. Image Noise

In the calculation of the perceived noise on the display [Eq. (5)], the term for the power-spectral-density of the noise source, S_n , is a spatiotemporal quantity with nominal units of $\text{fL}^2 \text{s mrad}$. For this model, S_n is the power spectral density of the detector noise and is given by

$$S_n = \frac{(\text{NEP}_{\text{det}})^2}{P_{\text{spbw}}}, \quad (20)$$

where NEP_{det} is the noise equivalent power (NEP) of the detector in $\text{W/Hz}^{1/2}$, and P_{spbw} is the one-dimensional pixel spatial bandwidth in cycles/mrad. S_n now has units of $\text{W}^2 \text{s mrad}$. To properly map detector noise to display noise, the average display luminance (L) in Eq. (4) must be equated to the incident average THz-band power *received* by the detector and is given by

$$L = P_{\text{detIFOV}} \eta_{\text{ant}}, \quad (21)$$

where P_{detIFOV} is the average power received by the detector instantaneous field of view (IFOV), and η_{ant} is the coupling efficiency of the antenna structure. For this model, H_{post} in Eq. (5) comprises the display MTF, the human eye MTF, and the interpolation MTF.

The calibration factor, α^2 , in Eq. (4) subsumes a temporal eye integration component that is assumed to be essentially constant over a broad range of eye illumination levels. If detector noise is temporally

varying at a fairly rapid rate through the sequential display of changing image frames, then the eye-brain system temporally filters detector noise in the same way as eye noise. If, however, a snapshot (single frame image) is captured and then displayed repeatedly at a fairly rapid rate, eye integration is no longer as effective in reducing noise, and the noise term in Eq. (4) must be scaled by a factor given by

$$t_{\text{scale}} = \frac{t_{\text{eye}}}{t_{\text{act}}}, \quad (22)$$

where t_{eye} is the integration time of the eye and t_{act} is the actual detector frame integration time [18].

The dependence of the eye on display luminance can be approximated by

$$t_{\text{eye}} = 0.0192 + 0.0633(L)^{-0.17} \quad (23)$$

where L is the display luminance in foot-Lamberts and t_{eye} is the eye integration time in seconds [18].

C. Radiometry

The radiometric transfer process developed for this THz imaging system performance model is designed to accurately compute radiant power from the scene into the system detector(s) from either active illumination or passive emission while accounting for the propagation effects of atmosphere and any target concealment material located between the target and sensor. The model includes a capability to define source beam propagation characteristics for the active-illumination case and to define both target and background reflectivity properties through a parameterized specular-Lambertian reflection model.

Development of the radiometric transfer process began with the construction of a formal mathematical procedure to track power exiting the horn antenna of a source to the target and back to another horn antenna

receiver-detector via a focusing mirror. This procedure treats the target reflectance as a weighted sum of a Lambertian surface and a Gaussian function to model the specular component. Figure 4 illustrates this process. Note that, because the mathematical forms of the illuminating beam and the target reflectance do not always allow correlation (convolution) to be done in closed form, numerical correlation was performed. This formal, numerical procedure was used to calculate power onto the detector for several active-illumination configurations and several passive-emission cases at a fixed sensor-to-target distance of 10 m. These data are given in Section 4.

For ease of implementation and flexibility of use, a second, less-rigorous radiometric transfer process was developed for active illumination. This process is based on a radar radiometric transfer approach [19], and is the one currently used in the MATLAB-based imaging system performance model. Referring to Fig. 5, the radiation transfer process begins with a description of the THz source beam propagation characteristics. The source beam is characterized by an initial spot size and a divergence angle representative of a beam exiting either a horn antenna or a horn antenna with collimating optics. The beam is then propagated through the atmosphere and through any target concealment-obscurant material to the target plane a distance R away, and the target-background irradiance is calculated. The target-background irradiance at range R is calculated from

$$E_{\text{tgt plane}} = \frac{P_{\text{source}} \tau_{\text{atm}} \tau_{\text{obsc}}}{A_i}, \quad (24)$$

where $E_{\text{tgt plane}}$ is the target-background irradiance in watts per square meter, P_{source} is the source power in watts, τ_{atm} is the atmospheric transmission through range R , τ_{obsc} is the concealment-obscurant material transmission, and A_i is the target-background illumi-

Fig. 4. (Color online) Illustration of the formal, horn-antenna radiation transfer process: illustration of (a) the numerical correlation (outer curve) of the source beam (middle curve) with the target reflectance (inner curve), and (b) the return irradiance across a 12 in. focusing mirror (upper curve) and the weighting of that irradiance by the pattern of a 22 dB gain receiver-detector horn antenna (lower curve). The power received by the detector is the integration of the product of the two functions.

Fig. 5. (Color online) Illustration of the present radiometric model for active target-background illumination. Note that the input aperture is that of either a lens or a mirror focusing element.

nation area in square meters given by

$$A_i(R) = \pi \left(\frac{\alpha}{2} \times R + \frac{B_d}{2} \right)^2, \quad (25)$$

where α is the source divergence full angle in radians, B_d is the initial beam spot diameter in meters, and R is the range in meters.

Next, the power reflected from the target plane into the detector's IFOV is calculated from

$$P_{\text{refl}} = E_{\text{tgt,plane}} A_{\text{do}}(R) R_{\text{normal}}, \quad (26)$$

where R_{normal} is the reflectivity of the target or background at normal incident angle and $A_{\text{do}}(R)$ is the detector area in object space given by

$$A_{\text{do}}(R) = \pi \left(\frac{\text{IFOV}}{2} R \right)^2, \quad (27)$$

and where IFOV is the detector's IFOV.

The reflected power, P_{refl} , is then propagated back through any target concealment-obscurant material and through the atmosphere to the receiver aperture located a distance R away, and the receiver aperture irradiance is calculated. The irradiance at the receiver aperture is given by

$$E_{\text{aperture}} = \frac{P_{\text{refl}} \times \tau_{\text{atm}} \times \tau_{\text{obsc}}}{4\pi R^2} \times \text{Gain}, \quad (28)$$

where Gain is the reflective gain from the target or background surface given by

$$\text{Gain} = \frac{4\pi}{\Omega_{\text{refl}}} \quad (29)$$

and Ω_{refl} is the solid angle of the reflected beam

(reradiated power) in steradians. For specular reflections, Ω_{refl} is taken to be twice the full width at half-maximum (FWHM) planar angle of the surface reflectivity measured in radians; for Lambertian reflections, Ω_{refl} is π steradians, yielding Gain = 4.

Finally, the power incident on the detector is calculated to be

$$P_{\text{detIFOV}} = E_{\text{aperture}} \times A_{\text{aperture}} \times \tau_{\text{aperture}}, \quad (30)$$

where A_{aperture} is the area of the aperture in square meters and τ_{aperture} is the transmission of the aperture.

Power incident on the detector from a source reflection in a target region comprises power from the target's specular reflection component and power from the target's Lambertian reflection component. The relative amounts of power reflected as specular and Lambertian are user definable.

Power incident on the detector from a source reflection in a background region comprises power from the background's specular reflection component and power from the background's Lambertian reflection component. Again, the relative amounts of power reflected as specular and Lambertian are user definable.

D. Image Contrast

Given the radiometric transfer process described above, image contrast in the MATLAB-based imaging system performance model is defined as

$$\text{Contrast}_{\text{image}} = \frac{|P_{\text{detIFOV}}(\text{Target}) - P_{\text{detIFOV}}(\text{Background})|}{P_{\text{detIFOV}}(\text{Target}) + P_{\text{detIFOV}}(\text{Background})}. \quad (31)$$

It should be noted that the underlying assumption in the above definition of image contrast is that the atmosphere causes little to no scattering of THz-band

radiation, and thus causes no reduction in image contrast. This assumption arises from the facts that there is strong molecular absorption of THz-band radiation from atmospheric water vapor and that the wavelengths of THz-band radiation are too long relative to the sizes of most atmospheric particulates (including fog and mist particles) for any significant scattering to occur.

4. Preliminary Modeling Results and Discussion

Modeling results for both passively emitting and for actively illuminated targets and backgrounds are given in the following sections. In order to compare the benefits of active illumination over only passively emitting targets and backgrounds, the formal radiometric transfer process described in Subsection 3.C was used to compute power at the input aperture for several actively illuminated cases and power into the receiving detector for several passive-emission cases. Performance modeling results for several actively illuminated scenarios were computed using the subject MATLAB-based imaging system performance model. All active-illumination calculations were based on a 650 GHz, commercially available source generating 0.5 mW of output power.

A. Radiometric Results

The results of the radiometric calculations described above are given in Tables 1 and 2. All calculations are based on a sensor-to-target distance of 10 m (refer to Fig. 5). For the active-illumination cases, the target is assumed to be a metal surface with a normal reflectivity of 0.95; the reflected radiation is assumed to have the angular properties given in Fig. 4(a). For the passive-emission cases, the target-source emission is assumed to be a 300 °K blackbody Lambertian surface with emissivity (ϵ) = 0.7. The broadband radiant exitance $E(\text{W}/\text{m}^2)$ was calculated by using a spectral band from 0.5 to 1.0 THz; for the narrow-band case, the radiant exitance was calculated by using a spectral band from 0.645 to 0.655 THz. Except where indicated, attenuation due to the atmosphere was included in all calculations.

Because of the weighting of the irradiation pattern across the 12 in. focusing mirror by the acceptance pattern of the receiver-detector horn antenna [see Fig. 4(b)], power onto the detector for the active illumination cases is only approximately 20% of the power at the input aperture. Even so, approximately 2 orders of magnitude more power can be delivered to the receiver detector by using a noncollimated, active illumination source than detecting only broadband

passive radiation. Comparing the focused, Gaussian-spot, active-illumination case to the passive, narrow-band case yields an approximately 6 order of magnitude increase in power onto the detector for the active-illumination case.

B. Active-Illumination Performance Prediction Results

Performance modeling of concealed-weapon identification (ID) was performed for a prototype, active-illumination system using relevant system parameters and the subject MATLAB-based imaging system performance model. The prototype system is based on a Virginia Diodes [20] heterodyne 650 GHz source-receiver subsystem using an optical configuration consistent with the radiometric model shown in Fig. 5.

Parameters that remained fixed (except where noted) for all simulations are as follows: basic system parameters, focal length 1.0 m; display parameters, type CRT, pixel pitch 0.24 mm, detector pixels displayed 160×120 , interpolation factor 2 (4 $\times$ zoom), viewing distance 45.72 cm, display luminance 30.0 cd/m²; illumination parameters, XMTR power 0.5 mW; atmospheric parameters, attenuation 30.0 dB/km; detector/noise parameters, antenna coupling efficiency 0.50; obscurant parameters, transmission of obscurant 0.7; target parameters, critical dimension 7.62 cm, ID task difficulty criteria 20.8 cycles. Only the Lambertian components of the target and background reflective properties were utilized in these simulations; the specular components will be included in future simulations as sufficient phenomenological data become available. Spatial sampling was adequate to avoid aliasing for all simulations.

Figure 6 illustrates one of the main graphical outputs from the MATLAB-based imaging system performance model and contains performance predictions for a best-case, maximum-performance scenario where several system parameters have been chosen to yield maximum results. Optimized parameters are as follows: basic system parameters, main aperture diameter 1.0 m (f -number 1.0), detector size 0.5 mm (minimal impact from the detector MTF); target parameters, target reflectivity 0.9, background reflectivity 0.0 (contrast ratio 1.0). From the chart in the bottom-right quadrant of Fig. 6, the maximum range that an object with a critical dimension of 7.62 cm (approximately 3 in.) can be identified is predicted to be approximately 55 m (with a 50% probability of success), for the case where there is no system noise, no atmospheric attenuation, and no target-concealing

Table 1. Summary of Active-Illumination Radiometric Results

Condition	Peak Irradiation at Target ($\mu\text{W}/\text{m}^2$)	Peak Irradiation at Input Aperture ($\mu\text{W}/\text{m}^2$)	Power at Input Aperture (μW)	Beam Radius at Target (cm)	Beam Radius at Input Aperture (cm)
No collimation	63	13	0.90	95	110
Gaussian collimation	49,300	1400	85	13	75
Gaussian spot	988,000	1900	112	3.1	67

Table 2. Summary of Passive-Emission Radiometric Results

Condition	Target Exitance $\mu\text{W}/\text{m}^2$	Image Plane Irradiance $\mu\text{W}/\text{m}^2$	Power onto Detector (μW)	Beam Radius at Target (cm)	Beam Radius at Input Aperture (cm)
Passive, no atmosphere	59,100	1330	22×10^{-3}	Lambertian	Lambertian
Passive (effective std.)	55,300 (35,900)	810		Lambertian	Lambertian
Passive (effective fog)	55,300 (25,900)	580	1.6×10^{-3}	Lambertian	Lambertian
Passive Narrow Band (effective std.)	856 (742)	16.7	45×10^{-6}	Lambertian	Lambertian

material(s) (obscurants). This represents a maximum practical bracketing performance for an object of this size, using nearly realistic system parameters with a 1 m main aperture diameter.

The curve sets in Fig. 7 represent performance predictions from several model simulations to show the impact that main aperture size and target-to-background contrast ratio have on ID performance. In both curve sets, the performance predictions are for the case where there is no system noise, no atmospheric attenuation, and no target-concealing material(s) (obscurants). In Fig. 7(a), the target-to-background contrast ratio and the system focal length are held constant at values of 0.3 and 1.0 m, respectively. In Fig. 7(b), the main aperture size and the system focal length are held constant at values of 0.33 and 1.0 m, respectively. Other simulations (not examined here) show that range performance can also be strongly affected by the detector IFOV.

The following two sets of performance simulations explore the effects of active-illumination beam shaping on ID performance for the single-element, scanned imaging system configuration; the third set of performance simulations explores the effect of active scene illumination on ID performance as required for FPA detector-based imaging systems. The following simulation parameter(s) remained fixed for all three of the following sets: basic system parameters, main aperture diameter 0.3048 m (f -number 3.3), detector size 1.8 mm; target parameters, target reflectivity 0.9, background reflectivity 0.3. [The target parameter values were chosen to approximate a highly reflective metal target (weapon) and a less reflective background (human skin)].

Fig. 8 gives the probability of ID versus range results using a 22 dB gain horn antenna (beam divergence 70 mrad) on the output of the active-illumination source. For these simulations, the NEP was set to $5.0 \times$

Fig. 6. (Color online) Example graphical output from the MATLAB-based imaging system performance model.

Fig. 7. (Color online) ID range performance as a function of (a) aperture size (f -number), (b) target-to-background contrast ratio.

$10^{-13} \text{ W/Hz}^{1/2}$ (the estimated NEP for the Virginia Diodes heterodyne receiver), and the detector integration time was set to 10 ms. Note that, for the ranges shown, atmospheric attenuation has little impact on range performance.

Figure 9 gives the probability of ID versus range results using collimated active illumination (beam divergence $2\times$ the detector IFOV). Again, the detector NEP was set to $5.0 \times 10^{-13} \text{ W/Hz}^{1/2}$.

Figure 10 gives the probability of ID versus range results using scene active illumination (beam divergence 90 mrad, just larger than the system field of view). For these simulations, the detector NEP was set to $1.0 \times 10^{-12} \text{ W/Hz}^{1/2}$, the detector size was set to 0.5 mm (each side), and the antenna coupling efficiency was set to 10% (values are estimates for present FPA technology).

One of the interesting results from the performance model simulations is that a scanning, active-illumination, THz imaging system that focuses most of the source radiation into the detector's IFOV is optimal; for ranges less than approximately 25 m, essentially all of the effects of system noise and atmospheric and target-concealment-material attenuation can be

eliminated [refer to Fig. 9(a)]. When the source radiation is *defocused* in a manner such that it just fills the system field of view (as required for a FPA-detector-based system), and lower-performance, FPA-technology system parameters are utilized, the present simulations predict a significant loss of range performance [primarily due to low detector signal-to-noise ratios (SNR's)]. It should be noted that these latter predictions are expected to change toward better range performance when the specular components of the target and background reflective properties are included in the simulations using optimal target-background orientations. For nonoptimally oriented target-background scenarios, ID range performance would be expected to decrease because a significant amount of illumination power would be reflected in a specular fashion away from the system's receiver-aperture.

5. Model Calibration and Validation

As a first step toward validating the subject THz imaging system performance model, the model needs to be calibrated with human perception testing. Perception testing is required for determining the discrimi-

Fig. 8. (Color online) Probability of ID versus range results using a horn output antenna: atmospheric attenuation set to (a) 30.0 dB/km, (b) 60.0 dB/km.

Fig. 9. (Color online) Probability of ID versus range results using a collimated output beam: detector integration time set to (a) 10 ms, (b) 52 μ s. In (b) an entire image frame could be captured in 1 s.

nation task difficulty parameter V_{50} . This parameter is very similar to the previous Johnson's criteria (N_{50}) and is measured by human perception testing of target ID in the spectral band of interest. Previous experience shows that this calibration is different for different bands. It is more difficult to identify objects in the infrared than in the shortwave or visible bands and may be even more difficult in the THz regime. It is expected that this calibration in the THz band will be sufficiently different from the criteria in the infrared and visible, that human perception testing is required for proper calibration. The procedure for deriving the calibration parameter involves collection of high-resolution radiometric images, segmentation of these images for contrast determination, blurring these images to limit the available spatial frequencies, and measuring the 50% probability-of-ID point associated with the collections of perceived frequencies. The V_{50} values are the calibration coefficients for application of the sensor model to the concealed-weapon ID problem in the THz regime.

6. Conclusions and Future Plans

A MATLAB-based imaging system performance model for concealed-weapon ID in the THz regime has been developed. The model accounts for the effects of image blur, image noise, the human response to displayed imagery, atmospheric attenuation, and target-concealment-material attenuation. The model has also been designed to account for the specular and Lambertian reflective properties of targets and backgrounds in this frequency region. Results from the radiometric calculations show a strong SNR advantage for systems that utilize active illumination versus passive-only systems. Results from the performance model simulations performed at 0.650 THz indicate that the *maximum* range that a target with a critical dimension of approximately 3 in. can be identified (using a 1 m receiving aperture) is approximately 55 m (with a 50% probability of success). Analysis of simulation data shows that range performance is a strong function of the size of the main imaging aperture, the target-to-background contrast ratio, and

Fig. 10. (Color online) Probability of ID versus range results using a scene-collimated, active-illumination output beam: detector integration time set to (a) 10 ms, (b) 1 s.

the detector IFOV. Other results from the performance model simulations indicate that a scanning, active-illumination, THz imaging system that focuses most of the source radiation into the detector's IFOV is optimal; for ranges less than approximately 25 m (with a source output power of 0.5 mW), all of the effects of system noise and atmospheric and target-concealment-material attenuation can be eliminated with such focusing. Alternatively, when the source radiation is *defocused* in a manner such that it just fills the system field of view, and lower-performance, FPA-technology system parameters are utilized, present simulations predict a significant loss of range performance due to low detector SNRs. These FPA-based predictions are expected to change toward better range performance when the specular components of the target and background reflective properties are included in the simulations using optimal target-background orientations. For nonoptimally-oriented target-background scenarios, ID range performance would be expected to decrease due to a significant amount of illumination power being reflected in a specular fashion away from the system's receiver-aperture. Future work is to include the calibration and validation of the subject performance model through systematic human perception testing and the incorporation of the specular characteristics of various targets and backgrounds into performance model simulations as the phenomenological data become available. Target-background orientation effects will also be addressed in future work.

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