NVEOD FLIR92 Thermal Imaging Systems Performance Model

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ABSTRACT

The Night Vision and Electro-Optics Directorate's FLIR92 model predicts minimum resolvable temperature difference (MRTD) and minimum detectable temperature difference (MDTD) for scanning and staring infrared sensors. FLIR92 retains unchanged the two-dimensional MRTD, and incorporates sampling effects and three-dimensional noise more thoroughly than the simple approximations used in the FLIR90 model. The FLIR92 MRTD predictions are shown to be valid for representative scanning and staring systems.

1.0 INTRODUCTION

In 1989, the Deputy Under Secretary of the Army for Operations Research, Mr. Walter M. Hollis, approved the U.S. Army Joint Research Plan on Search and Target Acquisition Simulation (ACQSIM). FLIR92 represents NVEOD's continuing contribution to this group in the area of advanced thermal imaging systems modeling. FLIR92 is a single-system linear filter model that predicts standard laboratory performance measures for scanning and staring thermal imaging systems. From basic system-level parameters, the model predicts component and total system MTF, system noise, MRTD, and MDTD. The principal function of the model is to predict whether or not a system achieves the required MTF, system noise, MRTD, and MDTD determined necessary to perform mission-specific target acquisition and discrimination tasks. To facilitate making range performance predictions, FLIR92 interfaces with the ACQUIRE model by creating a template data file for this model that includes either a two-dimensional MRTD or an MDTD. FLIR92 runs can be tailored to laboratory or field conditions.

At its initial release, FLIR92 will be a strict "D-star" model - the detector responsivity will have to be measured or predicted off-line and inserted into the model. This approach allows the model to remain free of material-specific algorithms and numerous subsystem-level parameters. Revisions to FLIR92 may include generic stand-alone models or linkable functions that predict detector responsivity.

The model is being validated successfully against a variety of scanning and staring systems. The scanning system validation database includes first generation, first generation derivative, and second generation sensors; the staring system validation database includes PtSi and HgCdTe sensors.

2.0 SYSTEM NOISE

The concept of system noise, meaning noise from anywhere within a system, is an integral part of FLIR92. Historically, MRTD models have generally relied upon the noise equivalent temperature difference (NETD) to describe the noise characteristics of thermal imaging systems. For first generation detector noise-limited systems, the classical NETD sufficiently characterizes system noise. For modern sensors, NETD has been demonstrated to be an inadequate characterization of system noise. There are two principal reasons for this. First, the definition of NETD requires that a standard reference filter be employed to simulate the "back end" system processing. In many sys-

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tems, the signal processing that the reference filter is supposed to replace has occurred prior to the NETD measurement, which is made typically at a video port just prior to the system display. Second, noise from signal processing and focal plane nonuniformities can contribute significantly to, or in some cases dominate, the total system noise, neither of which is represented in the NETD measurement.

Beginning with the FLIR90 model, and continuing in FLIR92, NVEOD incorporated into the MRTD and MDTD prediction a methodology that provides a comprehensive assessment of the noise characteristics of thermal imaging systems. The 3-D noise analysis methodology[1] isolates system noise into eight clearly definable directional components (Table 1). Note that the subscripts indicate the directions in which the noise components fluctuate (*t* temporal, *v* vertical spatial, and *h* horizontal).

TABLE 1. 3-D Noise Component Descriptions

noise	description	source
σ_{tvh}	random spatio-temporal noise	basic detector temporal noise
σ_{tv}	temporal row noise, *e.g.* line bounce	line processing, 1/f, readout
σ_{th}	temporal column noise, *e.g.* column bounce	scan effects
σ_{vh}	random spatial noise, *e.g.* bi-directional fixed pattern noise	pixel processing, detector-to-detector non-uniformity, 1/f
σ_{v}	fixed row noise, *e.g.* line-to-line non-uniformity	detector-to-detector non-uniformity
σ_{h}	fixed column noise, *e.g.* column-to-column non-uniformity	scan effects, detector-to-detector non-uniformity
σ_{t}	frame-to-frame noise, *e.g.* frame bounce	frame processing
S	mean of all noise components	

In FLIR92, σ_{tvh} replaces NETD and five of the remaining noise components are used to calculate correction functions that modify the MRTD and MDTD by the amount of system noise in excess of σ_{tvh}. In the model, the global mean, *S*, is not used, and the temporal component, σ_t, is not used because it is almost always negligible relative to σ_{tvh}, and its effect on MRTD and MDTD has not been investigated.

2.1 Random spatio-temporal noise - σ_{tvh}

The equation giving σ_{tvh} differs from the equation giving NETD only in the system noise bandwidth term. It is useful to write

1. J. D'Agostino, "The modeling of spatial and directional noise in FLIR90, part 1: A 3-D noise analysis methodology," *IRIS Passive Sensors Symposium*, March 1990.

$$\sigma_{tvh} = NETD \times \frac{\sqrt{\Delta f_P}}{\sqrt{\Delta f_N}} \qquad \text{(EQ 1)}$$

where the equivalent noise bandwidth is given by

$$\Delta f_N = \int_0^{\infty} S(\upsilon) H_{ref}^2(\upsilon) d\upsilon \qquad \text{(EQ 2)}$$

and the noise bandwidth at the system output port is given by

$$\Delta f_P = \int_0^{\infty} S(\upsilon) H_{elec}^2(\upsilon) d\upsilon . \qquad \text{(EQ 3)}$$

S is the detector noise power spectrum (normalized). H_{ref} is the standard NETD reference filter[2], and H_{elec} is product of all noise filtering MTFs existing prior to the measuring port. For scanning systems, H_{elec} includes the temporal electrical filters (electronic boost, electronic highpass, and electronic lowpass). For staring systems, H_{elec} is the MTF for the focal plane clock rate, $sinc(\pi \upsilon t_i)$, where t_i is the detector integration time.

σ_{tvh} is directly implemented in FLIR92 with

$$\sigma_{tvh} = \frac{4 f_{no}^2 \sqrt{\Delta f_P}}{\pi \tau_o \sqrt{A_D} \left(\int_{\lambda_1}^{\lambda_2} D(\lambda, 300) \frac{\partial}{\partial T_{300}} W(\lambda) d\lambda \right)} , \qquad \text{(EQ 4)}$$

where f_{no} is the optics f/#, τ_o is the optics transmittance, A_D is the detector area, $D(\lambda,300)$ is the detector spectral response. The temperature units in equation 4 are normalized to 300 K, and FLIR92 can scale to other background temperatures.

Because of the nature of noise modeling in FLIR92, care must be taken to ensure that the peak detector responsivity in equation 4 includes only temporal noise sources. This is especially true for staring systems, for which detector responsivity may include spatial noise due to focal plane nonuniformity. Spatial noise is inserted into FLIR92 through the 3-D noise correction functions (section 2.3). Applying a detector responsivity that includes spatial noise will corrupt the model predictions by doubling this type of noise.

2.2 Noise component defaults

For proposed and developmental systems where 3-D noise measurements are likely not available, *FLIR92* defaults the significant noise components to values that depend upon the predicted σ_{tvh}. The default values were derived from the database of system noise measurements made by NVEOD since April, 1990. Because the system noise sources add in quadrature, only the most significant noise components are given non-zero default values. For each system in the database, the 3-D noise measurements were normalized to σ_{tvh} and averaged with other systems of the same class to determine the dominant noise components within that class. In scanning systems, the critical

2. J. M. Lloyd, *Thermal Imaging Systems,* New York: Plenum Press, 1975.

noises are temporal row and fixed row noise; for staring, the critical noise is random spatial noise. Since scanning systems show wide variation in noise levels, defaults for σ_v and σ_{tv} are provided at three noise levels. A single default value for σ_{vh} is provided for staring systems. Table 2 shows the general model defaults for scanning systems and Table 3 shows the same for staring systems. Measurement of 3-D noise is a routine part of NVEOD sensor analyses; the default noise components will be revised as the 3-D noise database grows.

TABLE 2. FLIR92 Default 3-D Noise Components for Scanning Systems

noise term	low noise default	moderate noise default	high noise default
σ_{vh}	0	0	0
σ_{tv}	$0.25\sigma_{tvh}$	$0.75\sigma_{tvh}$	$1.0\sigma_{tvh}$
σ_v	$0.25\sigma_{tvh}$	$0.75\sigma_{tvh}$	$1.0\sigma_{tvh}$
σ_{th}	0	0	0
σ_h	0	0	0

TABLE 3. FLIR92 Default 3-D Noise Components for Staring Systems

noise term	noise default
σ_{vh}	$0.40\sigma_{tvh}$
σ_{tv}	0
σ_v	0
σ_{th}	0
σ_h	0

NVEOD considers the default approach an interim solution to the problem of predicting the critical noise components. Current efforts are investigating methods for predicting σ_v and σ_{vh} using focal plane nonuniformity measurements or specifications.

2.3 Noise correction functions - $k_h(f)$ and $k_v(f)$

The 3-D noise components, from measurements, defaults, or ultimately predictions, are used to generate noise correction functions that modify MRTD and MDTD. The frequency dependent functions[3] for MRTD are given by

$$k_h(f) = \left(1 + \frac{1}{E_t}\left(\frac{\sigma_{vh}^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_v(f)}\left(\frac{\sigma_{th}^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_t E_v(f)}\left(\frac{\sigma_h^2}{\sigma_{tvh}^2}\right)\right)^{1/2} \qquad \text{(EQ 5)}$$

and

$$k_v(f) = \left(1 + \frac{1}{E_t}\left(\frac{\sigma_{vh}^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_h(f)}\left(\frac{\sigma_{th}^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_t E_h(f)}\left(\frac{\sigma_v^2}{\sigma_{tvh}^2}\right)\right)^{1/2} . \qquad \text{(EQ 6)}$$

3. L. Scott, J. D'Agostino, and C. Webb, "Application of 3-D noise to MRTD prediction," *IRIS Passive Sensors Symposium*, February 1992.

The noise correction function for MDTD is given by

$$k_{MDT}(f) = \left(1 + \frac{1}{E_t}\left(\frac{\sigma_{vh}^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_v(f)}\left(\frac{\sigma_{th}^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_v(f)}\left(\frac{\sigma_{th}^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_tE_v(f)}\left(\frac{\sigma_h^2}{\sigma_{tvh}^2}\right) + \frac{1}{E_tE_h(f)}\left(\frac{\sigma_v^2}{\sigma_{tvh}^2}\right)\right)^{1/2} \quad \text{(EQ 7)}$$

E_t, $E_v(f)$, and $E_h(f)$ account for the effects of the eye/brain temporal, vertical spatial, and horizontal spatial integration effects (sections 4.2-4.3). As given, $k_h(f)$ and $k_v(f)$ express 3-D noise in terms of the non-directional noise σ_{tvh}. At each target frequency, the noise functions yield factors that multiply the MRTD or MDTD by the amount of system noise in excess of σ_{tvh}. Note that for MRTD each noise function contains only those noise components "appearing" in that direction, *i. e.*, only noises with a horizontal component contribute to $k_h(f)$ and only noises with a vertical component contribute to $k_v(f)$.

3.0 SAMPLED DATA EFFECTS

FLIR92 does not expand the treatment of sampled data effects beyond that used in FLIR90. The latter model imposed Nyquist frequency limits on the MRTD and had dedicated and optional sampling MTFs for adapting the model to particular system designs. Refinements in FLIR92 have relieved the inflexibility associated with using these features in FLIR90.

3.1 Nyquist-limited MRTDs

MRTD is defined for a periodic target (four 7:1 aspect ratio bars), and the criterion for "calling" MRTD at some frequency is that the four bars must be fully resolved by the observer. In thermal imagers, the four bars of the MRTD target will never be fully reconstructed to the observer at frequencies beyond a system's Nyquist limit, and therefore, the criterion for calling MRTD cannot be met. FLIR92 adheres strictly to this definition by not predicting MRTD at frequencies beyond the Nyquist limit. Model users should recognize that this does not imply that there is no information available to observers at frequencies between a sensor's Nyquist and theoretical limits. Given the aperiodic nature of many targets of interest, imposing Nyquist limits on MRTDs intended for field performance predictions may be overly severe. Yet, because the ability of observers to interpret information for target discrimination at super-Nyquist frequencies has not been quantified, attempting to extrapolate without robust data is unacceptable. In this light, the model's Nyquist-limited MRTDs should be viewed as conservative, in that they will predict, when properly applied, the minimum expected range performance.

3.2 Scene phasing MTF

The MRTD measurement methodology allows the sensor to be moved to achieve optimum phasing between the MRTD target and detectors. If the sensor is held motionless, the MRTD may degrade due to misalignment between target and detector. Because phasing effects have been documented for staring systems,[4] a scene phasing MTF is provided in FLIR92. Its use is optional.

4.0 MRTD Prediction

The general form of the MRTD used in the model is given by

4. C. M. Webb, "Results of laboratory evaluation of staring arrays," *SPIE Aerospace Sensing Symposium*, April 1990.

$$MRTD_z(f) = \left(\frac{\frac{\pi^2}{8} SNR_{TH} \sigma_{tvh} k_z(f)}{MTF_z(f)} \right) [E_t E_h(f) E_v(f)]^{1/2}, \quad \text{(EQ 8)}$$

where the z subscript indicates either the horizontal or vertical direction, and f is the MRTD target spatial frequency in cycles/mrad. SNR_{TH} is the threshold signal to noise ratio required to recognize the MRTD target. σ_{tvh} is the random spatio-temporal noise (section 2.1); $k_z(f)$ is the system noise correction function (section 2.2). $MTF_z(f)$ is the total system MTF. E_t, $E_h(f)$, and $E_v(f)$ represent the temporal, horizontal spatial, and vertical spatial integration of the eye/brain, respectively.

4.1 "Empirical" constants - SNR_{TH} and τ_E

The threshold signal to noise ratio, SNR_{TH}, and the eye integration time, τ_E, derive from visual psychophysics and are most often the model parameters used to "tune" an MRTD prediction to a set of measurements. The importance of establishing standard values is important, particularly when comparing many systems under similar conditions.

In the FLIR90 model, SNR_{TH} was set to 2.5 and τ_E was set to 0.1 seconds; these values are retained in FLIR92. The value chosen for SNR_{TH} is somewhat optimistic when compared to psychophysical data,[5] but is reasonable considering that a proper MRTD measurement requires carefully trained, consistent observers.[6]

Taken from Schnitzler,[7] Table 4 shows the dependence of τ_E on background luminance. The luminances associated with about a 0.1 seconds eye integration time agree well with display luminances NVEOD measured during perception experiments conducted in 1988. In these experiments, under conditions similar to those encountered in MRTD measurements (darkened room and optimal viewing), observers set the display luminance to on average 0.15 foot-lamberts.[8] In higher ambient light level conditions, such as may be encountered with fielded systems, greater display luminances can be expected and thus a faster eye integration time may be appropriate.

TABLE 4. Eye Integration Time vs. Background Luminance

luminance, mL	0.001	0.01	0.1	1	10	100
τ_E, seconds	0.22	0.16	0.11	0.082	0.063	0.068

4.2 Temporal integration - E_t

E_t in equation 7 gives the improvement in signal to noise ratio due to the eye/brain system's ability to temporally integrate video imagery. E_t is given by

$$E_t = \frac{\alpha_t}{F_R \tau_E}, \quad \text{(EQ 9)}$$

5. L. Biberman, editor, *Perception of Displayed Information*, New York: Plenum Press, 1973.
6. C. W. Hoover and C. M. Webb, "What is an MRT and how do I get one?" *SPIE Aerospace Sensing Symposium*, April 1991.
7. A. Schnitzler, "Image-detector model and parameters of the human visual system," *Journal of the Optical Society of America*, Vol. 63, No. 11, pp. 1357-1368, November 1973.
8. J. Howe, et al., "Thermal model improvement through perception testing," *IRIS Passive Sensors Symposium*, March 1989.

where F_R is the system frame rate in Hz. α_t, the temporal sample correlation length, is assumed to be unity. Note that E_t cannot be greater than 1.

4.3 Eye/brain spatial integration

In an electro-optical system, the eye/brain spatially integrates over an image degraded by the system transfer function. Choosing how to model this phenomenon has been a difficult task, since the actual mechanisms employed by the eye/brain are not well understood. The most frequently encountered methods (in electro-optical system models) describe the eye/brain spatial integration using either a matched filter[9] or a synchronous integrator[10] model. From an "end user" point of view, the two methods are indistinguishable in that they yield virtually identical MRTD predictions. When compared to MRTD data, any potential differences, to be expected with severely degraded imagery, will be lost in the inherent error of the MRTD measurement. For these reasons, and because the MRTD equation when formulated with a synchronous integrator is somewhat simpler and more efficiently evaluated, FLIR92 has been written as a synchronous integrator model.

4.3.1 Horizontal - $E_h(f)$

In simplified form, the eye/brain horizontal spatial integration is given by

$$E_h(f) = \frac{\alpha_h}{R_h L_h(f)} \qquad \text{(EQ 10)}$$

where R_h is the horizontal sampling rate (mr^{-1}), $L_h(f)$ is the horizontal spatial integration limit (mr), and α_h is the horizontal sample correlation length. For a scanning system,

$$\frac{\alpha_h}{R_h} = \frac{v_s}{\Delta f_P}, \qquad \text{(EQ 11)}$$

where v_s is the sensor scan velocity (mr/second) and Δf_P (Hz) is the noise bandwidth at the system measuring port (equation 3). For a staring system,

$$\frac{\alpha_h}{R_h} = \frac{\delta_h}{s_h}, \qquad \text{(EQ 12)}$$

where s_h is the number of samples per detector instantaneous field of view and δ_h is the detector instantaneous field of view (mr). Note that for staring systems, the horizontal sample correlation length, α_h, is unity.

4.3.2 Vertical - $E_v(f)$

Again using the simplified form, the eye/brain vertical spatial integration is given by

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9. W. R. Lawson and J. A. Ratches, "The Night Vision Laboratory static performance model based on the matched filter concept," *The Fundamentals of Thermal Imaging Systems*, NRL Report 8311, May 1979.

10. R. L. Sendall and F. A. Rosell, "Static performance model based on the perfect synchronous integrator model," *The Fundamentals of Thermal Imaging Systems*, NRL Report 8311, May 1979.

$$E_v(f) = \frac{\alpha_v}{R_v L_v(f)}, \tag{EQ 13}$$

where R_v is the vertical sampling rate (mr^{-1}), $L_v(f)$ is the vertical spatial integration limit (mr), and α_v is the vertical sample correlation length. For both scanning and staring systems,

$$\frac{\alpha_v}{R_v} = \frac{\delta_v}{s_v}, \tag{EQ 14}$$

where s_v is the number of samples per detector instantaneous field of view and δ_v is the detector instantaneous field of view (mr). As for the horizontal case, α_v is unity.

5.0 MDTD Prediction

In FLIR92, the NVL 1975 thermal systems model[11] MDTD equation is modified to include 3-D noise by replacing $NETD$ with $\sigma_{tvh}k_{MDT}(f)$:

$$MDTD(f) = \left(\frac{SNR_{TH}\sigma_{tvh}k_{MDT}(f)}{q(f)}\right)[E_t\rho_h(f)\rho_v(f)]^{1/2}. \tag{EQ 15}$$

E_t is given by equation 9, and $\rho_h(f)$, $\rho_v(f)$, and $q(f)$ are the same as the ρ_{xA}, ρ_{yA}, and q_A in the 1975 model documentation (page 57). A matched filter model is appropriate for MDTD because of the possibility of sub-pixel size targets, for which the synchronous integrator model has no meaning. The FLIR92 MDTD prediction is not validated.

6.0 MRTD Validation

The model validates well against measured MRTDs for scanning and staring thermal imaging systems. The accompanying graphs show representative measurements and predictions for one second generation scanning system and three staring systems. All systems underwent routine measurements at NVEOD in 1990 and 1991. Error bars indicate 95% confidence intervals for the MRTD measurements; all predictions were optimized for comparison to laboratory MRTD.

Figure 1 shows a "well behaved" second generation system. For the horizontal MRTD, the average value of the noise correction function is 1.2; for the vertical MRTD, the average value is 3.6. The difference between measured and predicted horizontal MRTD at the middle frequencies is caused by an optimistic system MTF prediction.

Figures 2 through 4 show predictions and measurements for staring systems. In these systems, σ_{vh} is the dominate 3-D noise component after σ_{tvh}. Both PtSi systems had low 3-D noise; the average value of the noise correction functions were less than 2 for the horizontal and vertical MRTDs. In the HgCdTe system, the average value of the noise correction function is about 4 for the horizontal and vertical MRTDs. As with the scanning system, application of the 3-D noise correction functions results in MRTD predictions that are in good agreement with measurements.

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11. J. Ratches, et al., *Night Vision Laboratory Static Performance Model for Thermal Viewing Systems*, ECOM-7043, April 1975.

FIGURE 1. Scanning Second Generation System

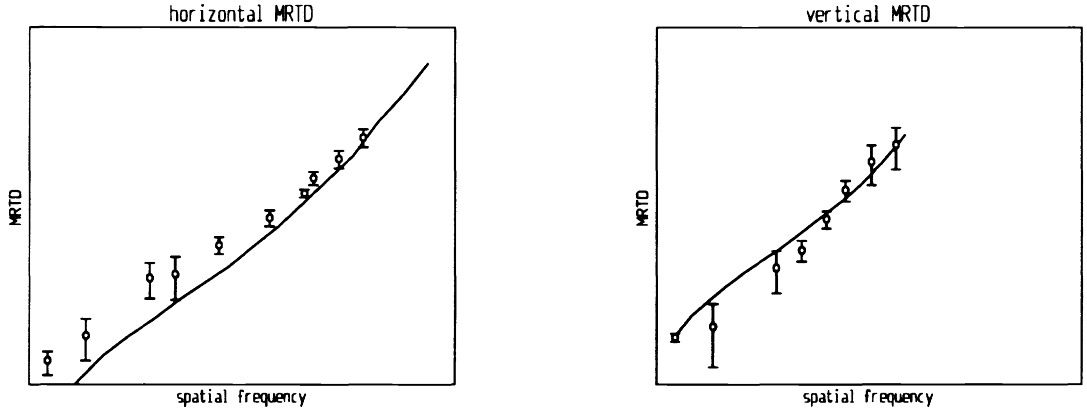


FIGURE 2. PtSi Staring System

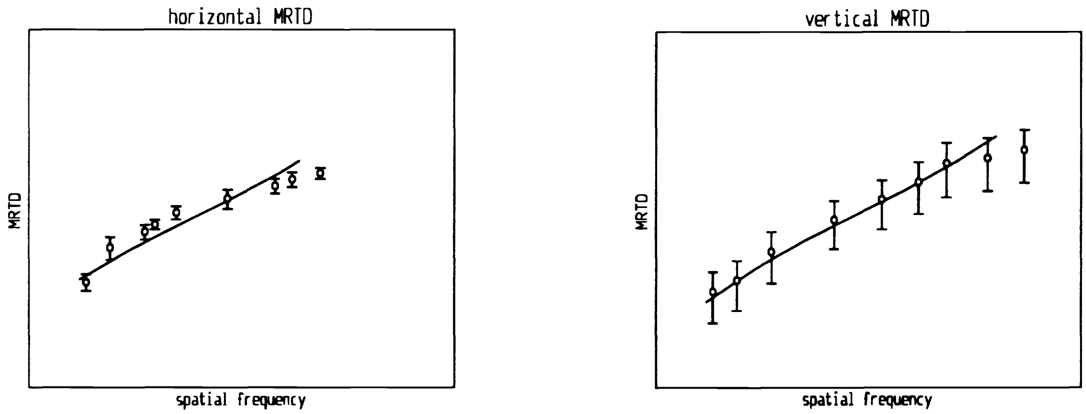


FIGURE 3. HgCdTe Staring System

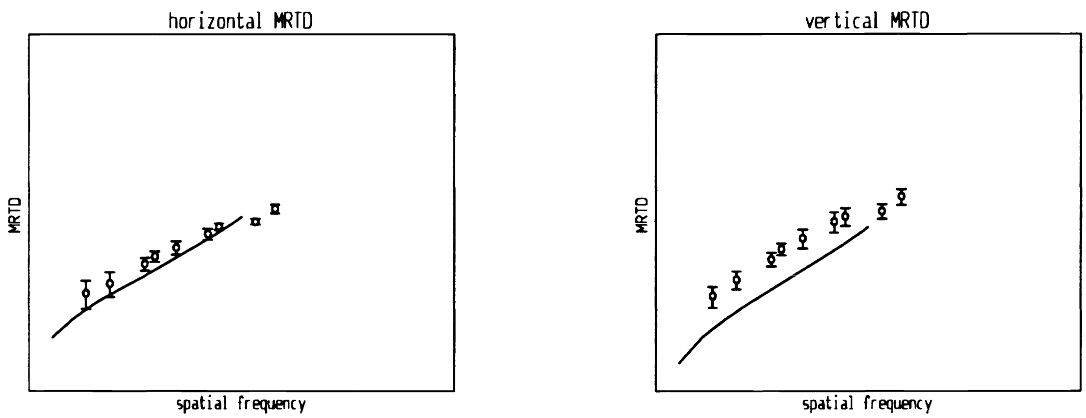
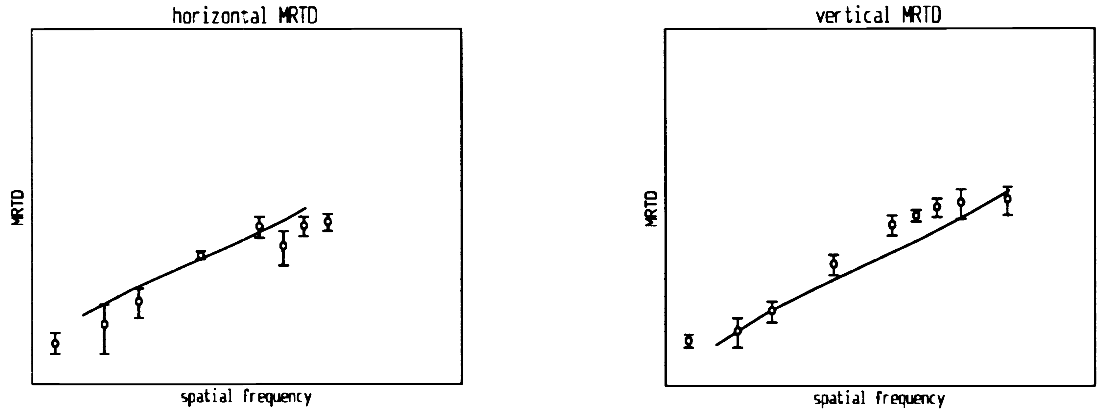


FIGURE 4. PtSi Staring System



7.0 Summary

FLIR92 is a validated thermal imaging systems model suitable for predicting MRTD performance for scanning and staring systems. The model's MDTD predictions are not yet validated. Application of 3-D noise to FLIR92 has enabled the model to accurately predict MRTD for first and second generation scanning systems and for staring systems. The model is currently limited by its inability to predict noise components other than σ_{tvh}. It is highly desirable to be able to predict, using basic system parameters, σ_v and σ_{tv} for scanning systems and σ_{vh} for staring systems. Near term revisions of the model will provide this capability. FLIR92 does not address the subject of signal and noise aliasing. Validation data indicate that modeling aliased spectra may not contribute to the quality of the MRTD prediction. NVEOD will continue to investigate sampled data effects, and in coordination with the modeling community, revise the model as needed. Additionally, the model's MDTD prediction will be validated within the next year.

NVEOD will release FLIR92 in mid-1992, and will fully support the model with documentation, publications, and workshops. Prior to its release, the model will be accredited for use by the U.S. Army Materiel Systems Analysis Activity.