The system noise may consist of many components and the eye may integrate each component differently:

$$\Delta I = SNR_{th} \frac{k\sqrt{\langle i_1^2\rangle \beta_1 + ... + \langle i_m^2\rangle \beta_m}}{CTF_{sys}} \tag{19-3}$$

or

$$\Delta I = SNR_{th} \frac{k\langle i_1\rangle}{CTF_{sys}} \sqrt{\beta_1 + ... + \frac{\langle i_m^2\rangle}{\langle i_1^2\rangle} \beta_m} \tag{19-4}$$

The Air Force tri-bar target or a four-bar target is approximated by a square wave of infinite extent. If the system is band-limited, then only the fundamental of the square wave has sufficient amplitude to contribute to the response (valid for high frequencies). The fundamental's amplitude is $4/\pi$ times the square wave amplitude. The eye is sensitive to the average value of the first harmonic and the average value of a half-cycle sine wave is $2/\pi$. Therefore, the conversion from a square wave (CTF_{sys}) to a sinusoid (MTF_{sys}) requires a factor of $8/\pi^2$:

$$\Delta I = SNR_{th} \frac{\pi^2}{8} \frac{k\langle i_1\rangle}{MTF_{sys}} \sqrt{\beta_1^2 + ... + \frac{\langle i_m^2\rangle}{\langle i_1^2\rangle} \beta_m^2} \tag{19-5}$$

For thermal imaging systems $k\langle i_1\rangle$ becomes the σ_{TVH}. The square root contains the summary noise factors:

$$MRT = SNR_{th} \frac{\pi^2}{8} \frac{\sigma_{TVH}}{MTF_{sys}} (summary\ noise\ factors) \tag{19-6}$$

The three-dimensional noise model quantifies each $\langle i_i^2\rangle \beta_i^2$ and, therefore, the summary noise factors. The component MTFs are described in Chapters 6 though 11. Noise components are given in Chapter 18: *Sensitivity and Noise*. The eye integration factors, β_i, are presented in this chapter.

Through-out the previous chapters, back-of-the-envelope approximations were made about sensitivity and resolution. Resolution considerations provide the target range as:

$$Range \approx \frac{target\ size}{resolution} \tag{19-7}$$

Using sensitivity limitations, the received signal-to-noise ratio is

$$SNR \approx \frac{\tau^R \Delta I}{system\ noise} \tag{19-8}$$

The MRC and MRT equations combine sensitivity and resolution with the eye's response. Equation 19-7 is the resolution limit of the MRC or MRT equation. Equation 19-8 does not include the eye's filtering capability. It is not a limit of the MRT or MRC equations.

Both the MRC and MRT models are so-called *static* models in that the target is stationary. The target is assumed to be in the center of the field-of-view and no search is required (or at least the observer knows where to look). The observer has an unlimited amount for target discrimination. As with most models, the system is assumed linear and shift invariant with no image enhancement algorithms present.

19.1. THREE-DIMENSIONAL NOISE MODEL

The three-dimensional noise model[3] provides the basic framework for analyzing the various noise sources. The noise is divided into a set of eight components that relate temporal and spatial noise to a three-dimensional coordinate system (Figure 19-1). This approach allows full characterization of all noise sources including random noise, fixed pattern noise, streaks, rain, 1/f noise, and any other artifact that may have been introduced. Analyzing the noise in this manner has the advantage of simplifying the understanding of a complex phenomenon by breaking it down into a manageable set of components. The method simplifies the incorporation of complex noise factors into model formulations.

The T-dimension is the temporal dimension representing the framing sequence. The other two dimensions provide spatial information. However, depending upon the imaging system design, the horizontal dimension may represent time for a scanning system or may represent space for a staring system. For a staring array, m and n indicate detector locations. For parallel scanning systems, m indicates detector locations and n is the digitized analog signal. m is the number of raster lines and n is the digitized analog signal for serial scanning systems.

Table 19-1 groups the noise components into temporal and spatial components. The subscripts describe the noise "direction." σ_{TVH} represents noise calculated from the three-dimensional data set m x n x N. σ_{VH} is the rms noise value after averaging in the T-direction. Its data set contains m x n elements. And so on.

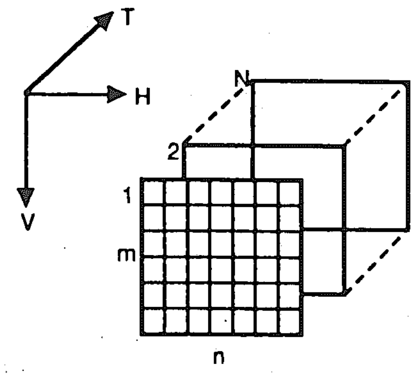

Figure 19-1: Three-dimensional noise model coordinate system illustrating data set N_{TVH}.

Table 19-1
THREE-DIMENSIONAL NOISE DESCRIPTORS

NOISE COMPONENT	PIXEL VARIATIONS	ROW VARIATIONS	COLUMN VARIATIONS	FRAME VARIATIONS
TEMPORAL	σ_{TVH}	σ_{TV}	σ_{TH}	σ_T
SPATIAL	σ_{VH}	σ_V	σ_H	S

Table 19-2 lists seven noise components and some possible contributors to the components for serial scanning, parallel scanning and staring array imaging systems. For mathematical completeness, the noise model has eight components with the eighth being the global average value, S. Depending upon the system design and operation, any one of these noise components could dominate. The origin of these components is significantly different and the existence and manifestation depend upon the specific design of the imaging system. Not all of the components may be present in every imaging system. Systems sensitive to visible radiation may have different components than those sensitive to infrared energy. Certain noise sources such as microphonics are more difficult to describe since they may appear in variety of forms. "Readout noise" is a catchall phrase for possible staring array artifacts. Depending upon the system design and operation, the same noise source may appear in different noise components. The three-dimensional noise model was developed to describe the noise in thermal imaging systems. The methodology can be applied to all imaging systems.

Assuming the noises are independent, the total system noise is

$$\sigma_{sys} = \sqrt{\sigma^2_{TVH} + \sigma^2_{TH} + \sigma^2_{TV} + \sigma^2_{VH} + \sigma^2_H + \sigma^2_V + \sigma^2_T} \qquad (19\text{-}9)$$

With only random noise, $\sigma_{sys} = \sigma_{TVH}$ and σ_{TVH} is the temporal portion of the NEDT (See Equation 18-52, page 365). Spatial noise is incorporated though σ_{VH}, σ_V, and σ_H. Currently, only σ_{TVH} is predicted and the remaining noise components must be determined from measurements or estimates. The global average, S, is the average intensity level. σ_T is considered negligible compared to σ_{TVH} and therefore is also omitted from the MRT and MDT predictions. Figures 19-2 through 19-4, generated by the ISDEA software[4], illustrate some of these noise sources. Figure 19-4 illustrates how σ_{TV} or σ_V affect the visibility of horizontal bars (as measured by the vertical MRT).

Table 19-2
SEVEN NOISE COMPONENTS OF THE THREE-DIMENSIONAL NOISE MODEL

3-D NOISE COMPONENT	DESCRIPTION	SERIAL SCAN	PARALLEL SCAN	STARING ARRAY
σ_{TVH}	Random 3-D noise	Random and 1/f noise	Random and 1/f noise	Random
σ_{VH}	Spatial noise that does not change from frame-to-frame	-	-	FPN
σ_{TH}	Variations in column averages that change from frame-to-frame (rain)	Microphonics	Microphonics	Readout noise
σ_{TV}	Variations in row averages that change from frame-to-frame (streaking)	1/f noise	Transients (flashing detectors), 1/f noise	Readout noise
σ_{V}	Variations in row averages that are fixed in time (horizontal lines or bands)	Line-to-line interpolation	Detector gain/level variations, line-to-line interpolation	Readout noise, line-to-line interpolation
σ_{H}	Variations in column averages that are fixed in time (vertical lines)	Shading	Shading	Readout noise
σ_{T}	Frame-to-frame intensity variations (flicker)	Frame processing	Frame processing	Frame processing

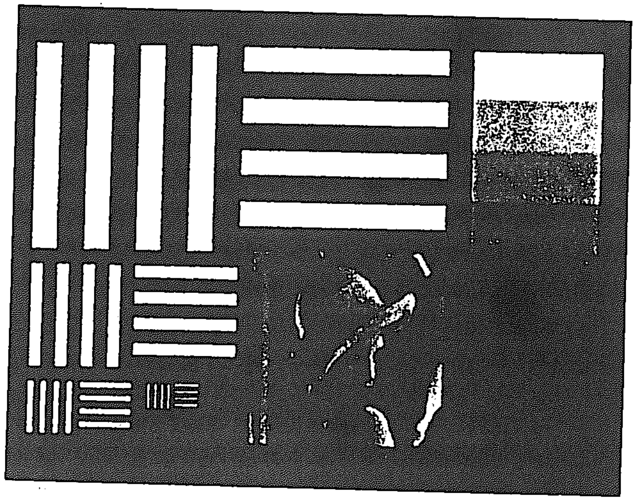

Figure 19-2. Ideal image with $\sigma_{sys} = 0$.

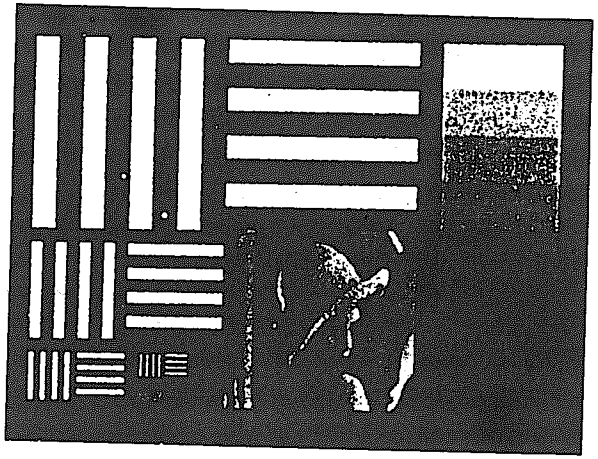

Figure 19-3. Image with noise. Both fixed pattern noise and random noise appear similar in a single frame. Random noise changes from frame-to-frame whereas fixed pattern noise does not. Both scanning systems and staring systems have random noise. Only staring systems have two-dimensional FPN.

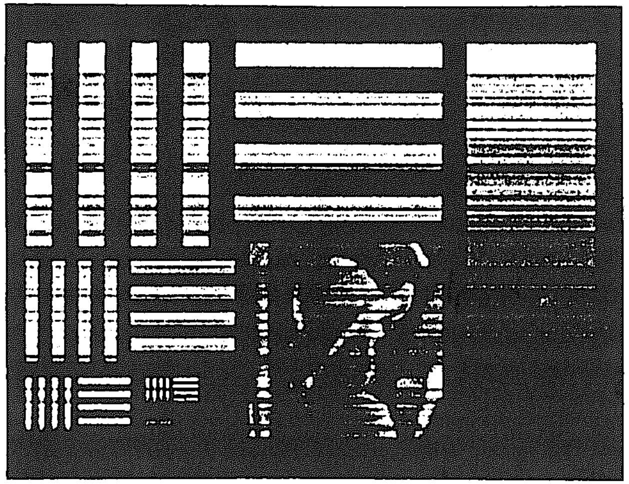

Figure 19-4. Image with dominant horizontal banding (high σ_{TV} or high σ_V). Scanning systems often exhibit this type of noise.

19.2. FLIR92

The 1975 NVL model was developed for predicting[5] the performance of US Army thermal imaging systems. It satisfied the Army's need and it adequately predicts the MRT at mid-range spatial frequencies which corresponds to detecting modest sized targets at modest ranges. The model was essentially one-dimensional and did not incorporate sampling effects and noise sources other than random noise. To overcome these deficiencies, NVESD created FLIR90 that was subsequently updated[6] to FLIR92.

The 1975 NVL model did not adequately predict the laboratory measured MRT values at low or high spatial frequencies. The differences between the measured and the predicted values were attributed to tremendous variability in observers, ill-defined data analysis methodology, and inappropriate modeling of the eye. Test methodology has since been standardized and understanding observer variability is a key component of the data analysis technique[7].

Part of the eye modeling difficulty has been overcome by incorporating a MTF_{eye} of unity (Equation 6-66, page 135) in FLIR92. This eye model does not include the eye inhibitory process but partially accounts for head movement when making measurements. Alternate eye models have been proposed that

include the inhibitory process. Although models with alternate eye MTFs predict the laboratory MRT better than the 1975 NVL model, there are still some differences.

In spite of these discrepancies, the 1975 NVL and FLIR92 models are the main analytic tools for deriving system requirements and predicting performance. They are used for comparative analysis and are reportedly[8] accurate to $\pm$ 20% in range predictions for recognition under favorable target and atmospheric conditions. This is rather remarkable when considering the difficulty in estimating the target area-weighted ΔT and the atmospheric transmittance.

The 1975 NVL model was developed for serial and parallel scan thermal imaging systems that existed in the 1970s. These systems typically had a fixed relationship between the horizontal and vertical resolution of about 2:1. As such it was adequate to specify a horizontal MRT since its relationship with the vertical MRT rarely changed.

Since the 1975 NVL model did not include sampling effects, some users modified the computer code by incorporating a sample-scene phase MTF, digital filter MTFs and post-reconstruction filters. With the advent of staring arrays, the vertical to horizontal resolution changed and the model had to be updated.

In FLIR92, treatment of sampling effects is limited to restricting MRT predictions to sub-Nyquist frequencies. This is not to mean that there is no information above Nyquist frequency. Given the aperiodic nature of targets, imposing Nyquist frequency limits may be too severe for range predictions. However, the ability for observers to interpret information above Nyquist frequency has not been completely quantified and attempting to extrapolate without robust data is inappropriate.

The eye/brain system is probably the most difficult system to model. Two different models exist: the matched filter and the synchronous integrator model. The 1975 NVL model uses the matched filter model where it is assumed that the eye maximizes the SNR. Here, the eye spatial frequency response has the same spatial frequency dependence as the target. This is not a filter in the usual sense since the signal and noise are "filtered" by them. Rather, visual psychophysical data suggest that the eye acts as if it were a filter that can be described mathematically by a filter function. With the synchronous integrator model, the eye integrates over an angular region defined by the target edges and it is used in FLIR92.