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COMPARISON OF NVL MODEL AND FOUR CONTRACTOR MODELS
FOR MINIMUM RESOLVABLE TEMPERATURE (MRT)

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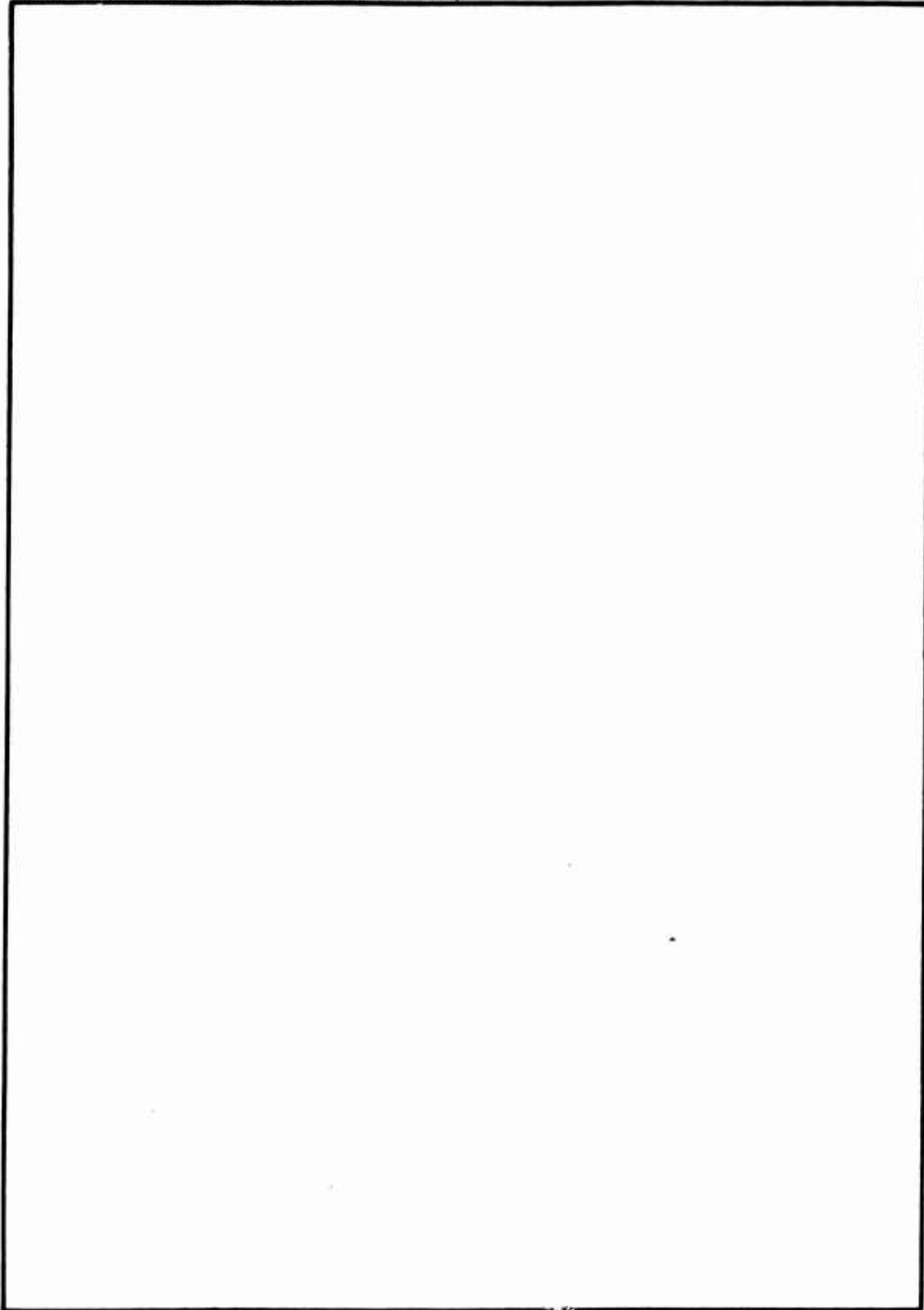
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COMPARISON OF NVL MODEL AND FOUR CONTRACTOR MODELS FOR MINIMUM RESOLVABLE TEMPERATURE (MRT)

I. INTRODUCTION

Minimum resolvable temperature (MRT) has been nominated by the infrared community as the true measure of system performance. It is assumed, and there is partial experimental data to support the contention, that MRT directly relates to field performance, especially recognition performance. Hence, a main effort in any performance prediction capability is to predict MRT, and many infrared houses attempt to do this. This paper compares the MRT models from several sources.

The models considered are those of NVL,¹ Hughes (HAC),² Texas Instruments (TI),³ Honeywell (HRC),⁴ and Sendall.⁵ Each model will be given and the underlying assumptions stated. The models will not be derived. The four contractor models will then be compared to the NVL model. Finally, the NVL model predictions are compared to several system measurements of MRT, and conclusions are thus made on the validity of this approach.

II. NVL MODEL

The form of all equations for MRT is essentially the same. The equations differ only in the choice of subjective constants. In order to show this, the basic MRT equation used by NVL will be used as the standard form for all of the others so that comparison can be facilitated. This MRT equation for vertical bars with 7:1 aspect ratio is:

$$\text{MRT}(f_x) = \frac{\pi^2}{4\sqrt{14}} \left(\frac{S}{N} \right)_D \frac{NE\Delta T}{\text{MTF}(f_x)} \left[\frac{\Delta Y_v f_x Q(f_x)}{\Delta f_n F_R t_E \eta_{ov}} \right]^{1/2},$$

¹ J. Ratches, *et al.*, "Night Vision Laboratory Static Performance Model for Thermal Viewing Systems," U.S. Army Electronics Command Report 7043, April 1975.

² H. Barhydt, "Thermal Imaging Sensor MRT Model," Hughes Aircraft Co. Interdepartmental Correspondence, Dec. 1973.

³ Appendix to "(U) Proposal to Supply a Tank Thermal Sight (TTS) for the M60A1 Tank," prepared for NVL, April 1975 (Confidential).

⁴ J. M. Lloyd, "Thermal Imaging Systems," Plenum Press, New York and London, 1975, Ch. 5.

⁵ R. Sendall and F. Rosell, "E/O Sensor Performance Analysis and Synthesis (TV/IR Comparison Study)," AFAL-TR-72-374, April 1973.

where $(S/N)_D$ is the threshold signal-to-noise ratio necessary to recognize a bar in the four-bar pattern, $MTF(f_x)$ is the device and eyeball MTF at target frequency f_x (cycles/mr), $NE\Delta T$ is the peak-to-rms noise equivalent temperature difference, and:

ΔY = vertical detector angular subtense

η_{ov} = overscan ratio

$\Delta Y/\eta_{ov}$ = raster scan spacing

v = scan velocity in mr/sec

Δf_n = noise equivalent bandwidth

F_R = frame rate per sec

t_E = eye integration time

$$Q = \int_0^\infty S(f) H_D'^2 H_T'^2 H_E'^2 df_x$$

$S(f)$ = normalized noise power spectrum from detector

H_D' = device MTF after detector to display

H_T = target spatial filter function

H_E = eyeball MTF.

The system $NE\Delta T$ is given by:

$$NE\Delta T = \frac{4 F^2 \sqrt{\Delta f_n}}{\sqrt{N} \pi A_d^{1/2} \tau_a \tau_o \int_{\Delta\lambda} D_\lambda^* W'_\lambda d\lambda},$$

where

F = optical F number

$A_d^{1/2}$ = square root of detector area

τ_o = optical transmission

τ_a = atmospheric transmission

D_λ^* = specific detectivity in dewar

W'_λ = temperature derivative of blackbody radiation

$$\begin{aligned} \Delta f_n &= \int_0^\infty S(f) H_D'^2 df \\ &= \pi/2 (1/2 \tau_d) \text{ for white noise and RC roll off} \end{aligned}$$

- τ_d = detector dwell time
 N = number of detectors in series.

The signal-to-noise ratio $(S/N)_D$ must be determined from experimental results. NVL experience has found that $(S/N)_D = 2.25$ gives optimum agreement between the measured and predicted results. The other assumptions in this model are:

- area of noise integration is the total bar area = $L \cdot W = 7 W^2$
- eye integration time $t_E = .2$ sec
- sampling effects are ignored
- system MTF includes eyeball.

This model will be compared to laboratory measurements after the other models have been described. In these descriptions, the nomenclature of the NVL model shall be used to prevent the proliferation of symbols for the same quantity.

III. TI MODEL

The TI model is given by:

$$MRT(f_x) = (S/N)_D \left[\sqrt{\frac{T_F}{t_E}} \frac{2\Delta\theta}{\sqrt{7}} Q^{1/2} \right] f_x \frac{NE\Delta T}{MTF(f_x)},$$

and

$$NE\Delta T = \frac{F^2}{\sigma T_o^3 \bar{\tau} D_{\lambda p}^* \Gamma} \sqrt{\frac{1}{2\tau_d \Lambda_d}},$$

where

- σ = Stefan - Boltzmann constant
 T_o = background temperature
 $\bar{\tau}$ = average optical transmission
 $D_{\lambda p}^*$ = peak D_{λ}^*

$$\Gamma = \frac{\pi}{4\sigma T_o^3} \int_0^\infty \frac{\tau_o(\lambda)}{\epsilon_o} \frac{D^*(\lambda)}{D_{\lambda p}^*} W'_\lambda d\lambda$$

$$\begin{aligned}
\tau_o(\lambda), \epsilon_o &= \text{optical and peak optical transmission} \\
T_F &= F_R^{-1} \\
\Delta\theta &= \Delta Y \cdot \Delta X \quad (\text{horizontal detector angular subtense}) \\
Q &= Q/f_x \quad \text{with } H_E = 1.0 \\
MTF(f_x) &= \text{device MTF at target frequency } f_x.
\end{aligned}$$

The assumptions behind this model are:

- no overscan in IR field
- area of noise integration is the total bar area
- $t_E = .2 \text{ sec}$
- $(S/N)_D = 6$
- no sampling effects
- MRT corresponds to 95% of bar recognition
- Q usually calculated with white noise assumption.

With a little algebraic manipulation, this MRT formulation can be put in the same form as the NVL equations. Also, approximations such as

$$\int_0^\infty D_\lambda^* W'_\lambda d\lambda \simeq D_{\lambda p}^* \int_{\Delta\lambda} W'_\lambda d\lambda$$

must be made. Then, the TI equations become:

$$MRT(f_x) = (S/N)_D \frac{\pi}{2\sqrt{14}} \frac{NE\Delta T}{MTF(f_x)} \sqrt{\frac{\Delta Y v f_x Q}{\Delta f_e t_E F_R}},$$

and

$$NE\Delta T = \frac{4F^2 \sqrt{\Delta f_e}}{\pi \tau_o \tau_a A_d^{1/2} \int_{\Delta\lambda} D_\lambda^* W'_\lambda d\lambda},$$

where $\Delta f_e = \frac{1}{2} \tau_d$. If all inputs are identical and if the various methods of carrying out such integrals as Q and $\int D_\lambda^* W'_\lambda d\lambda$ give equal results, then the only difference between models is the constant difference due to $(S/N)_D$, Δf_e , and $\pi/2\sqrt{14}$; using these differences then:

$$\frac{NE\Delta T_{NVL}}{NE\Delta T_{TI}} = \sqrt{\frac{\Delta f_n}{\Delta f_e}} \left[\frac{\int_0^{\Delta\lambda} D_\lambda^* \frac{\tau_o(\lambda)}{\epsilon_o} W'_\lambda d\lambda}{\int_{\Delta\lambda} D_\lambda^* W'_\lambda d\lambda} \right] \approx \sqrt{\frac{\Delta f_n}{\Delta f_e}},$$

and

$$\frac{MRT_{NVL}}{MRT_{TI}} = \frac{\pi^2/4 \sqrt{14} (2.25)}{\pi/2 \sqrt{14} (6)} \sqrt{\frac{Q_N}{Q_{TI}}} \approx .589.$$

IV. HAC MODEL

The pertinent equations for the HAC model are:

$$MRT(f_x) = 5.5 \frac{NE\Delta T}{MTF(f_x)} \left[\frac{\Delta f'_n}{\Delta f_n} \times \frac{\xi}{\rho} \times T_F \right]^{1/2}$$

and

$$N NE\Delta T = \frac{4F^2 \sqrt{\Delta f_n}}{\pi \tau_o \sqrt{NA_d} D_\lambda^* \partial W/\partial T},$$

where

$$\Delta f_n = \pi/2 (\frac{1}{2} \tau_d) \text{ for white noise}$$

$$\partial W/\partial T = \int_{\Delta\lambda} \partial W_\lambda / \partial T d\lambda$$

$$MTF(f_x) = \text{device MTF}$$

$$\Delta f'_n = vQ$$

$$\xi = \text{scan spacing} = \Delta Y / \eta_{ov}$$

$$\rho = \text{bar width}$$

$$5.5 = \pi^2/8 (S/N)_D 1/t_E^{1/2}.$$

HAC analysts employ the NEΔT equation in the MRT expression to give

$$\text{MRT}(f_x) = \frac{5.5}{\text{MTF}(f_x)} \sqrt{\frac{\Delta f'_n}{f_x}} \frac{1}{D_o \rho} \sqrt{\frac{\alpha \beta}{\Delta \theta \eta_{AZ} \eta_{EL} N_d}} \frac{1}{\tau_o \sqrt{\eta_d}} \\ \times \frac{\sqrt{2}}{\pi D_{\lambda}^{**} (\text{AVG} - \text{IDEAL}) \partial W / \partial T} ,$$

where

D_o = lens diameter

α, β = horizontal and vertical fields of view

η_{AZ}, η_{EL} = azimuth and elevation scan efficiencies

N_d = total number of detectors

$\sqrt{\eta_d} = D^*/D_{\lambda}^{**} (\text{AVG} - \text{IDEAL})/2F$

$D_{\lambda}^{**} (\text{AVG} - \text{IDEAL}) = \text{average } D_{\lambda}^* \text{ for } 2\pi \text{ FOV and } 100\% \text{ quantum efficiency.}$

The assumptions are:

- eye integrates over square area of height equal to bar width
- $t_E = .1 \text{ sec}$
- $(S/N)_D = 1.4$
- 33% probability of bar recognition
- sampling effects ignored
- $\Delta f_n = \pi/2 (\frac{1}{2} \tau_d)$.

When the HAC NE Δ T equation is reduced to the NVL form, we get

$$\frac{\text{NE}\Delta T_{\text{NVL}}}{\text{NE}\Delta T_{\text{HAC}}} = \sqrt{\frac{\Delta f_n(\text{NVL})}{\Delta f_n(\text{HAC})}} \left[\frac{D_{\lambda}^* \partial W / \partial T}{\int_{\Delta \lambda} D_{\lambda}^* W'_{\lambda} d\lambda} \right] \approx \sqrt{\frac{\Delta f_n(\text{NVL})}{\Delta f_n(\text{HAC})}} .$$

The MRT equation can be reduced to the standard form so that

$$\text{MRT}(f_x) = \frac{\pi^2}{8} \left(\frac{S}{N} \right)_D \sqrt{2} \frac{\text{NE}\Delta T}{\text{MTF}(f_x)} \sqrt{\frac{\Delta Y_v f_x Q}{\Delta f_n F_R t_E \tau_{ov}}} ,$$

and assuming equal NEΔT's,

$$\frac{MRT_{NVL}}{MRT_{HAC}} = \frac{\pi^2/4 \sqrt{14} (S/N)_D 1/\sqrt{t_E}}{\sqrt{2} \pi^2/8 (S/N)_D 1/\sqrt{t_E}} \sqrt{\frac{Q(NVL)}{Q(HAC)}} \simeq .429.$$

V. HRC MODEL

The HRC performance equations are:

$$MRT(f_x) = 3 \frac{NE\Delta T}{\sqrt{\Delta f_n}} \sqrt{\frac{\Delta Y}{\eta_{ov}}} \frac{f_x}{MTF(f_x) \sqrt{t_E} F_R} \sqrt{\frac{\Delta X}{\tau_d}},$$

and

$$NE\Delta T = \frac{4 \sqrt{ab} \sqrt{\Delta f_n}}{\Delta X \Delta Y D^*(\lambda_p) \tau_o \frac{\partial W}{\partial T} D_o^2 \sqrt{N}},$$

where a and b are detector sides in cm. The assumptions are:

- $(S/N)_D = 4.5$
- $t_E = .2 \text{ sec}$
- $Q \simeq f_x$
- only applicable to serial scan systems. As in the other models,

$$\frac{NE\Delta T_{NVL}}{NE\Delta T_{HRC}} = \sqrt{\frac{\Delta f_n(NVL)}{\Delta f_n(HRC)}} \left[\frac{D_{\lambda p}^* \partial W / \partial T}{\int_{\Delta \lambda} D_{\lambda}^* W'_{\lambda} d\lambda} \right] \simeq \sqrt{\frac{\Delta f_n(NVL)}{\Delta f_n(HRC)}}.$$

The MRT expression can be put in the standard form if we replace f_x with Q and $\Delta X/\tau_d$ with v . Then

$$MRT(f_x) = \frac{3 NE\Delta T}{MTF(f_x)} \sqrt{\frac{\Delta Y v f_x Q}{\Delta f_n F_R t_E \eta_{ov}}},$$

so that

$$\frac{MRT_{NVL}}{MRT_{HRC}} = \frac{2.25 \pi^2 / 4 \sqrt{14}}{3} \sqrt{\frac{Q}{f_x}} \simeq .495.$$

VI. SENDALL MODEL

Finally, there is Sendall's model. We do not intend to write out the entire expression for the MRT since it looks so unlike any other model in form. Hence, it would take too much space to define all the new expressions. However, it is identical to the previous models. The derivation starts from the same signal-to-noise expression as the NVL model:

$$(S/N)_D = \frac{\Delta T (8/\pi^2) MTF(f_x) [L \int H_T^2 H_D^2 (f_y) df_y]}{\frac{NE\Delta T}{\sqrt{\Delta f_n}} \sqrt{\frac{v \Delta Y}{\eta_{ov}}} [\int H_T^2 H_D'^2 d^2 f]^{1/2}} \sqrt{t_E F_R},$$

where H_D is the device MTF and L is the bar length. At this point, Sendall's MRT undergoes a radical change in apparent form since the MTF's are all assumed to be gaussian and the integrals are carried out analytically. However, if these assumptions are not made, then the form of the MRT equation becomes

$$MRT(f_x) = (S/N)_D \frac{\pi^2}{4 \sqrt{14}} \frac{NE\Delta T}{MTF(f_x)} \sqrt{\frac{\Delta Y v Q f_x}{\eta_{ov} F_R t_E \Delta f_n}}.$$

The remaining assumptions behind this model are:

- $(S/N)_D = 2.8$
- $t_E = .1 \text{ sec}$
- noise integration over area of bar
- no sampling effects
- white noise assumed.

Assuming equal $NE\Delta T$ and bandwidth calculation, then

$$\frac{\text{MRT}_{\text{NVL}}}{\text{MRT}_{\text{SENDALL}}} = \frac{2.25 / \sqrt{.2}}{2.8 / \sqrt{.1}} = .568.$$

VII. COMPARISON

The comparison among the five models discussed above can be put in a tabular form. Putting all MRT equations in the form

$$\text{MRT} = A \frac{\text{NE}\Delta T}{\text{MTF}} \sqrt{\frac{\Delta Y_v f_x Q}{\Delta f_n F_R}},$$

where

$$A = (S/N)_D \times t_E^{-1/2} \times F.$$

(F is a function of π , bar length, etc), then Table 1 illustrates the differences between the subjective constants in the various models. If $\text{NE}\Delta T$, Q, and $\int D_\lambda^* W'_\lambda d\lambda$ calculations are carried out the same by all modellers, then these subjective differences reflect the total constant differences between the models.

The indication from Table 1 is that the NVL predictions should give optimistic results compared to all the other models by a factor of approximately two. This will be discussed further in relation to the comparison to measured data later. First, we need to analyze the various calculation differences among the various modellers.

Table 1. Subjective Constants in the MRT Models

Model	A	(S/N) _D	t _E
NVL	3.32	2.25	0.2
HAC	7.72	1.4	0.1
HRC	6.70	3.0	0.2
TI	5.63	6.0	0.2
Sendall	5.84	2.8	0.1

Table 2 shows a more detailed comparison of the five models. The first row refers to the philosophical difference among the models as to the area over which the eye is a spatial integrator. The second row describes how the noise-filtering term Q is treated. Note, however, whereas three models treat Q exactly, not all have an eyeball MTF included nor use non-white noise. The third row shows the comparison of the D^* integral for calculations with a real system. The contractor model numbers were obtained from proposals and private communications. The TI vs NVL difference is probably due to an input of D^* vs wavelength difference. The exact form of D_λ^* has not been readily obtainable from TI. Different spectral distributions can obviously cause significant variations in the area under the curve.

The last two rows in Table 2 refer to the noise bandwidth calculation and an exact MRT calculation. Again, contractor calculations were obtained from proposals and the NVL calculation was normalized to 1.0. The Δf_n calculation is only significant when talking NE Δ T since it cancels in MRT.

Table 2. Relationship Among the Various MRT Models

	Sendall	TI	HRC	HAC	NVL
Integration Area	Bar	Bar	Bar	Square	Bar
Q	White Noise Gaussian MTF	Exact	$Q \rightarrow f_x$	Exact	Exact
Eyeball MRT Probability	No —	No 95%	No 90%	No 33%	Yes Threshold
$\int_{\Delta\lambda} D_\lambda^* W'_\lambda d\lambda$	—	.68	.92	1.0	1.0
Δf_n	—	$\frac{1}{2} \tau_d$	$\pi/2 (\frac{1}{2} \tau_d)$	$\pi/2 (\frac{1}{2} \tau_d)$	Exact
MRT	—	1.03	2.95	3.06	1.0

The difference between NVL and HAC and HRC is due mainly to the subjective-constant differences shown in Table 1. The closeness of the TI and NVL predictions is due to the nullifying effect of the D^* integral. Whereas, the subjective constants differ by two, the NE Δ T calculation cancels much of that difference.

VIII. VALIDATION

The results shown in Table 2 indicate that the NVL predictions should be significantly more optimistic in prediction of system MRT than the other models. This is largely reflected through the subjective constants in Table 1. In order to determine if the NVL constants should be increased, this model was exercised to predict MRT performance for eight widely different systems which have been measured at NVL over the last few years. They are the HAC and TI TOW's (AD), HAC and TI TINTS (AD), HRC CHAPARRAL, HAC DISCOID 525, TI Common Mod FLIR, and NAVY Common Mod FLIR. Figures 1 through 8 show the comparison between measured and predicted results for these eight systems. The X's represent measured data and the solid line represents the predicted data. The dotted line is a prediction based on a measured MTF for each system. This was done to show the effects of the MTF error in prediction. The effect of using predicted vs measured MTF must be determined before a modification in threshold signal-to-noise is made. The difference between predicted and measured MTF is not unique to NVL. Most contractor predictions are better than measured transfer functions.

All systems except the DISCOID 525 show reasonable agreement between prediction and measurement. (There is no measured MTF for the NAVY Common Mod FLIR.) The obvious conclusion to be drawn from these results is that the NVL choice of constants does not give an optimistic prediction by a factor of two. On the contrary, the measured MTF predictions imply that possibly a reduction in the signal-to-noise constant is necessary to agree more closely with the bench data. It should be noted at this point that the MRT measurements made at NVL are not very different than those made at other installations. In fact, MRT measurements appear to be quite close from laboratory to laboratory.

The agreement for the TI systems could be better if the D^* function of wavelength is much different than the one used (as is suspected). It is believed that the spectral D^* is broader than NVL used, hence the $NE\Delta T$ should be lower and the MRT consequently reduced.

Before any further work is done on forcing a closer agreement between predicted and measured data, the error associated with the measurement technique must be quantified. MRT is a subjective measurement; and, as such, one expects some degree of variation between observers. NVL is presently conducting an investigation of this aspect by measuring MRT at various DOD laboratories and possibly some contractor laboratories in order to measure the differences between observers at the respective facilities. Hopefully, we shall be able to then associate error bars with this measurement.

Another problem area connected with the prediction technique is the input uncertainty. Since very accurate and detailed information is needed to make a prediction, uncertainties about such things as detector characteristics can lead to relatively significant errors in the prediction. NVL is trying to attack this problem by obtaining several IR systems which can be disassembled in order to measure the component MTF and noise characteristics. Predictions can then be made on a very accurate input data base.

It is assumed that the input data problem is at least part of the poor agreement for the DISCOID 525 prediction. One of the problems is, however, the large difference in predicted and measured MTF. Although all predicted and measured MTF's are different, the difference is magnified in this case by aperture correction in the DISCOID 525. The agreement between the measured MTF modified MRT (dotted line) is in relatively good agreement with the data.

In conclusion, it has been shown that all MRT models are essentially the same in form with theoretical differences and subjective constant differences. The NVL constants are significantly different from all others; however, laboratory data bears out this choice of constants. Any change indicated would move the agreement with other models even farther apart. Experimental work is being undertaken in order to quantify the measurement errors and input uncertainty before a final analysis is made on the applicability of these models to MRT prediction.

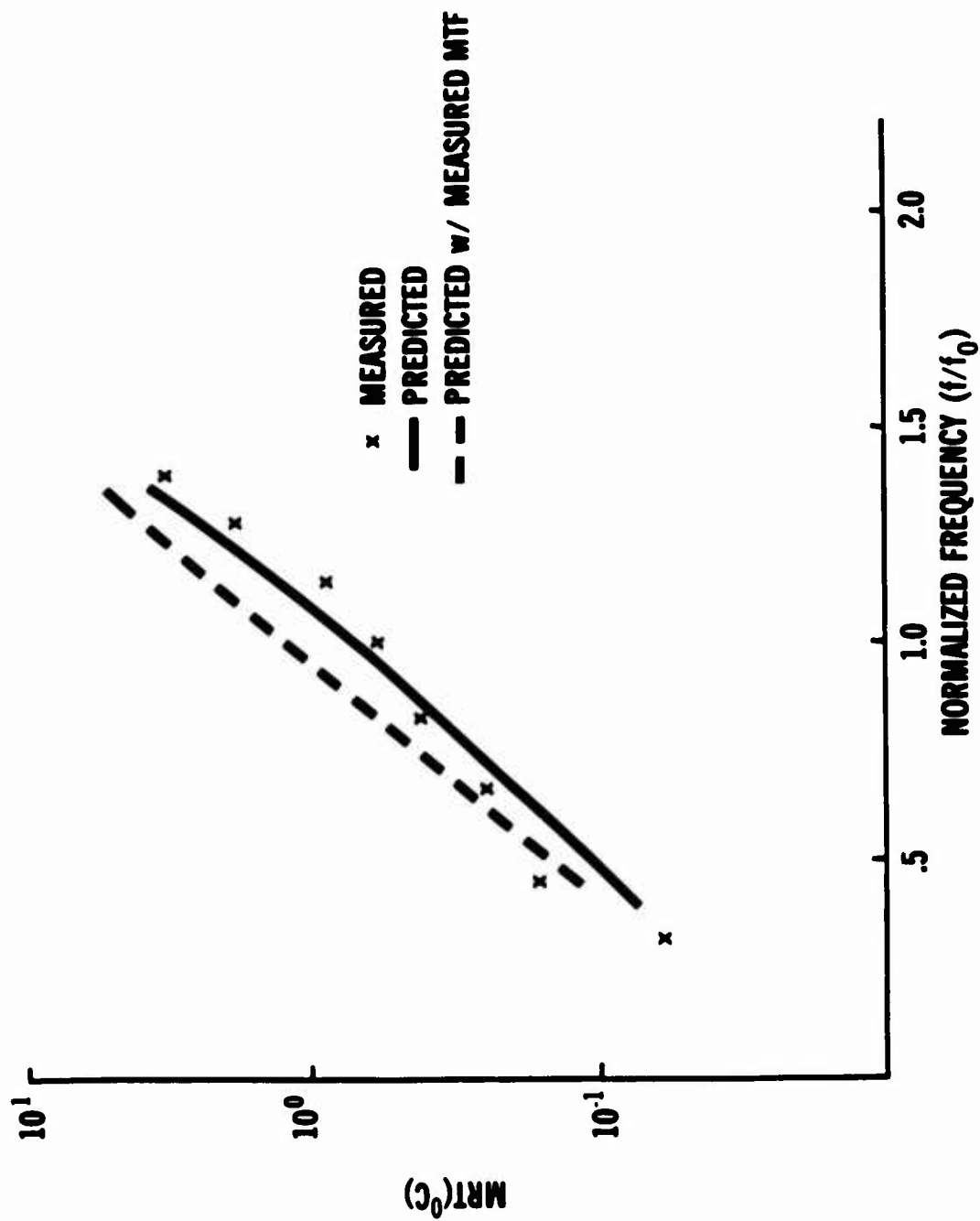


Figure 1. HAC TOW System MRT.

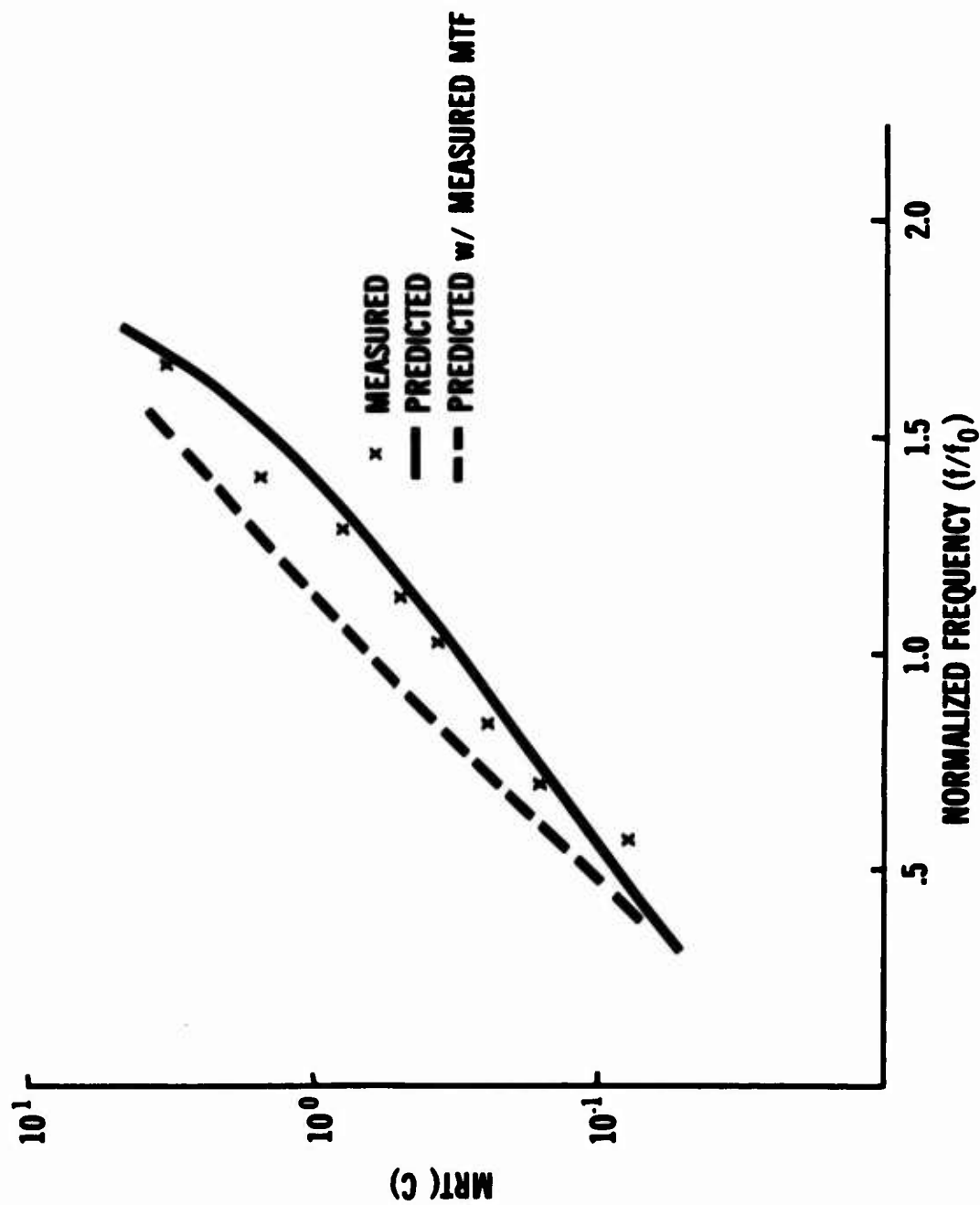


Figure 2. T1 TOW System MRT.

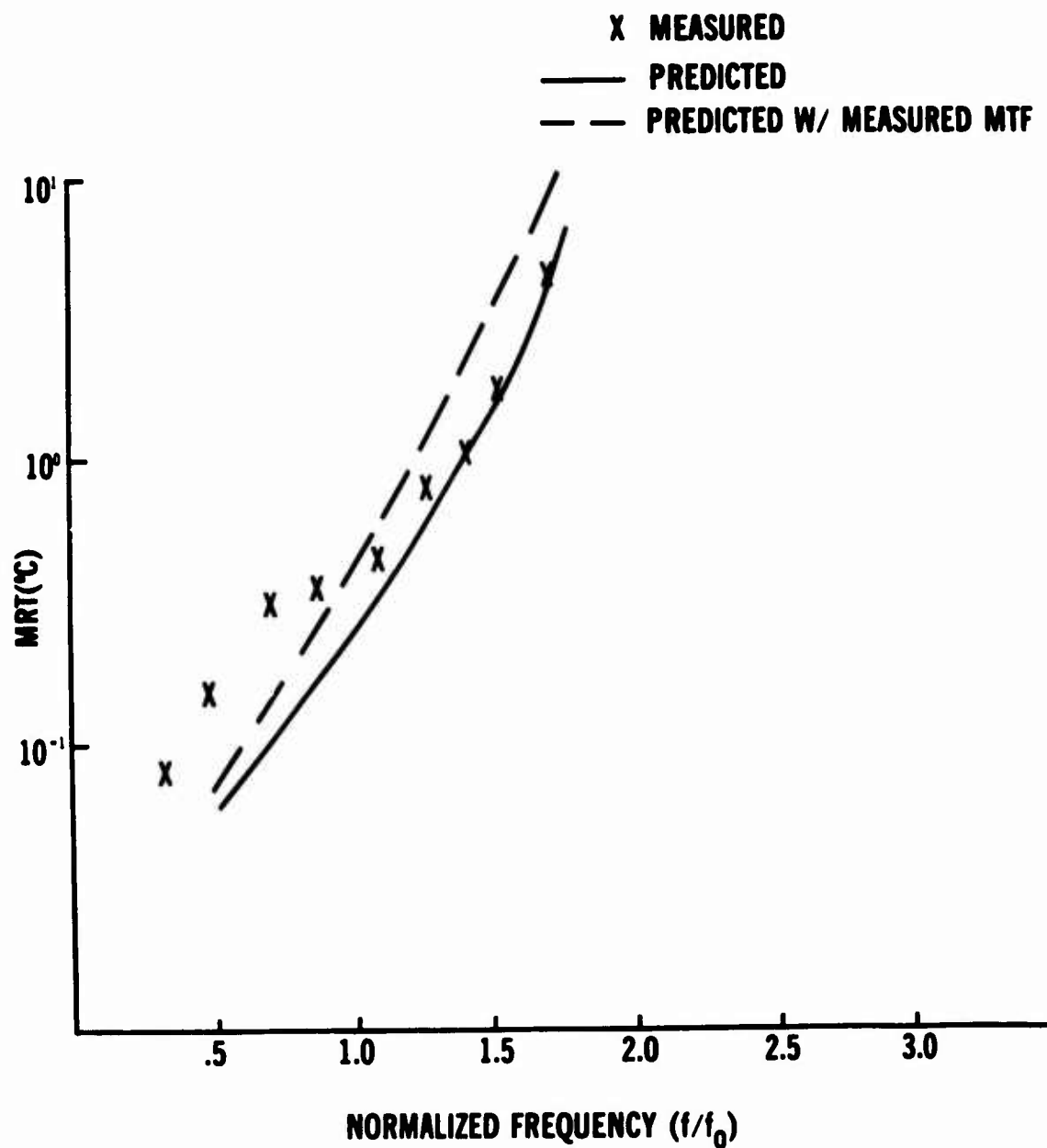


Figure 3. HAC TINTS System MRT.

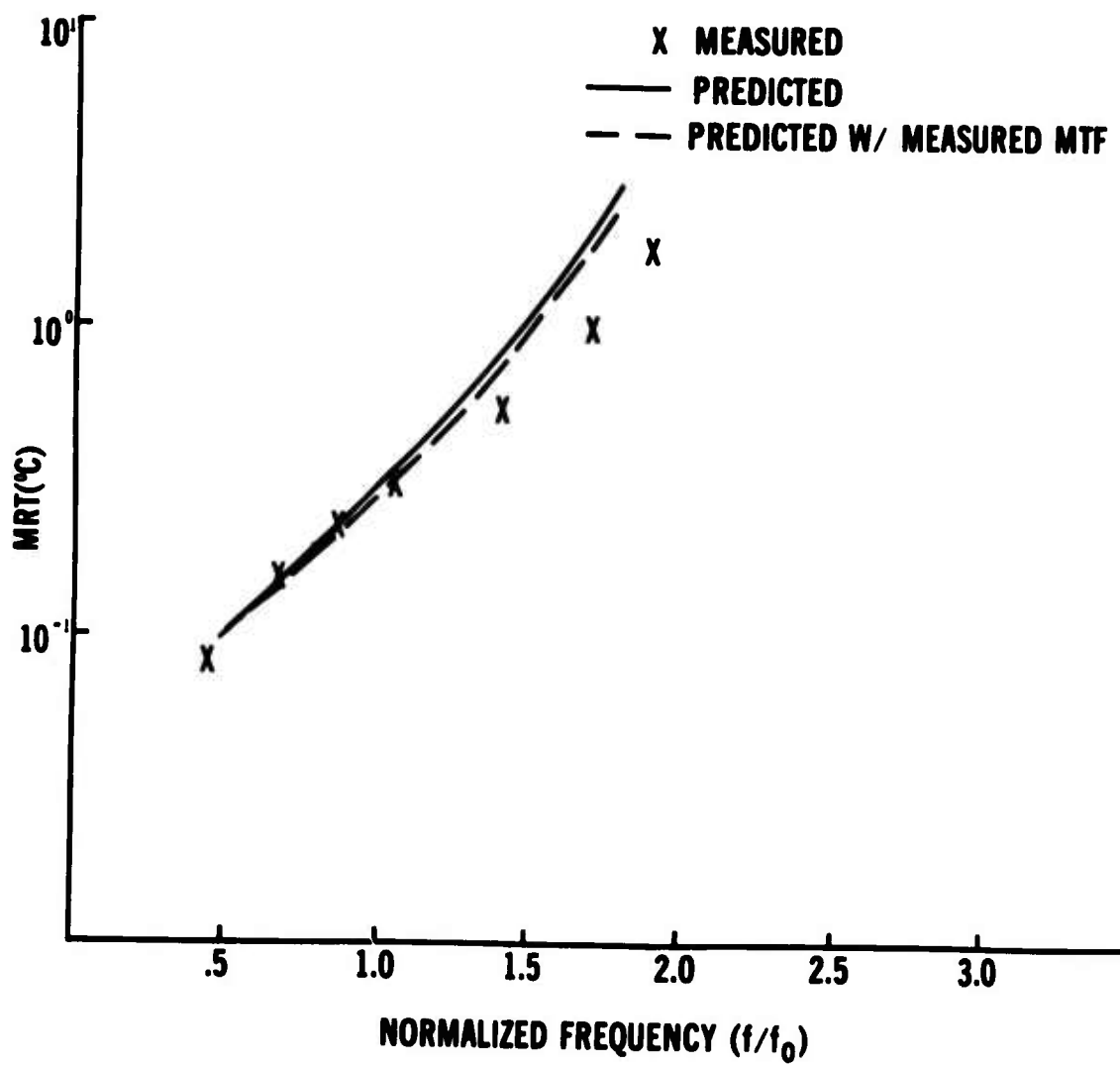


Figure 4. TI PINDTS System MRT.

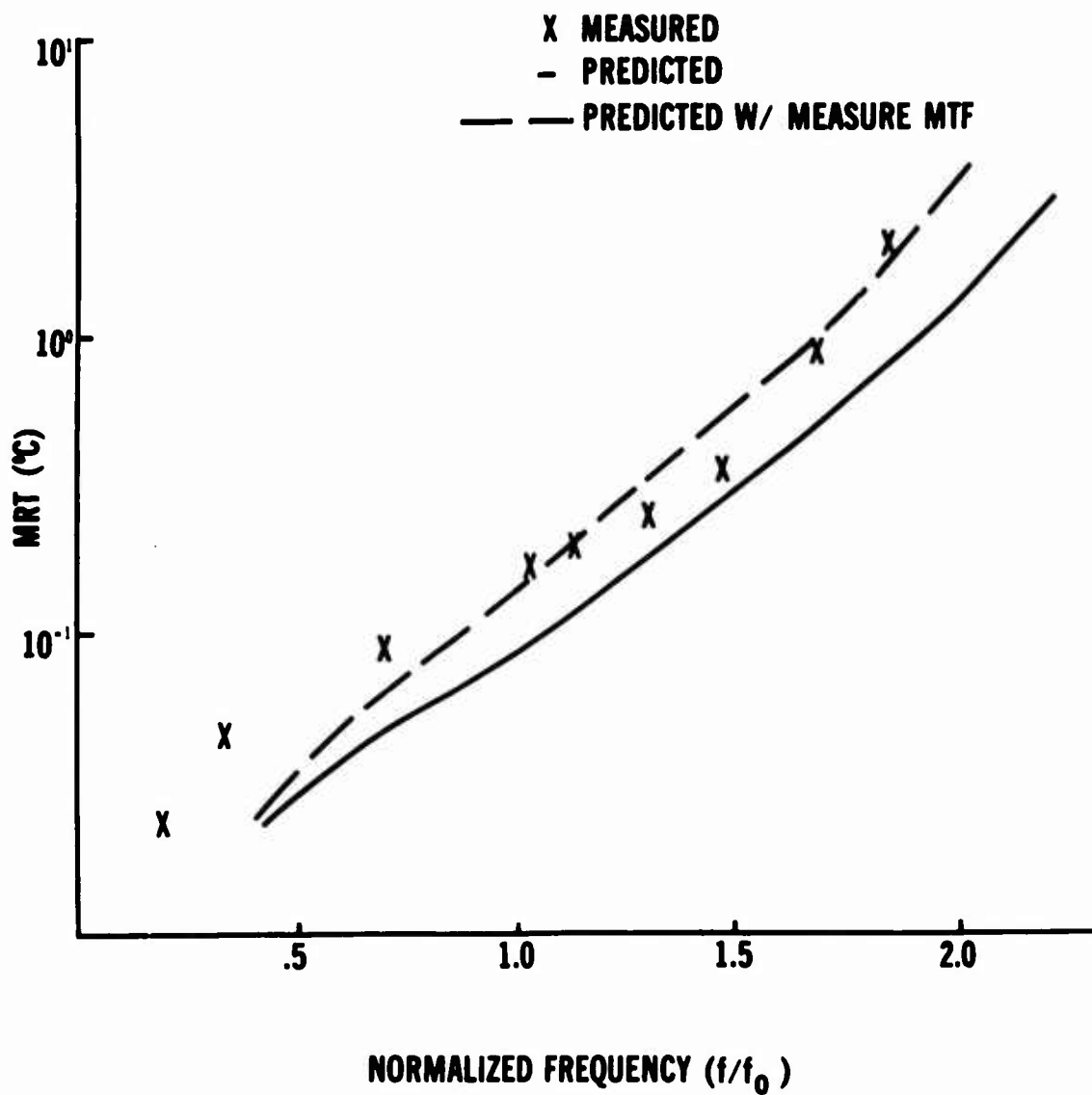


Figure 5. HRC CHAPARRAL System MRT.

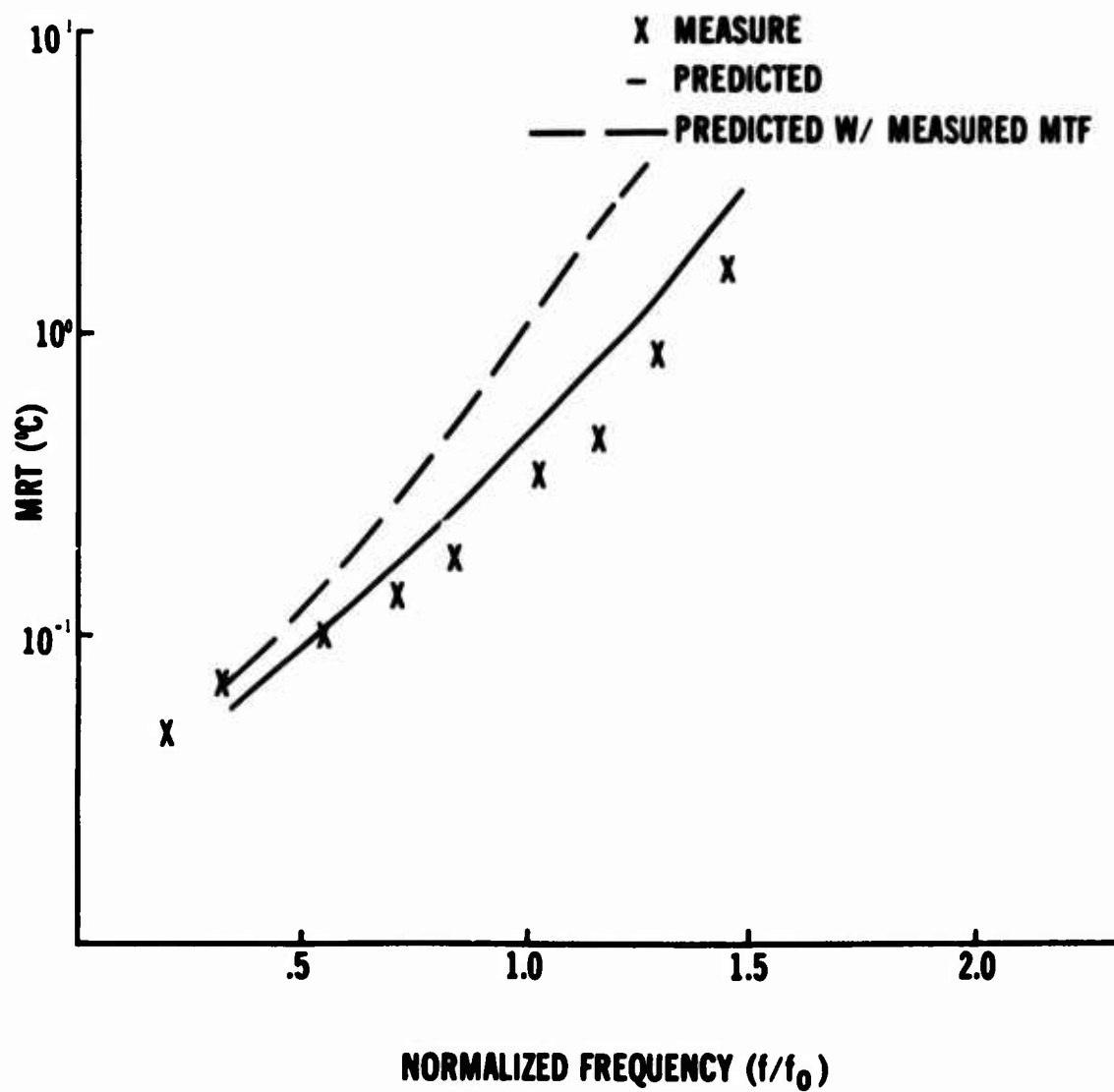


Figure 6. TI Common Mod FLIR System MRT.

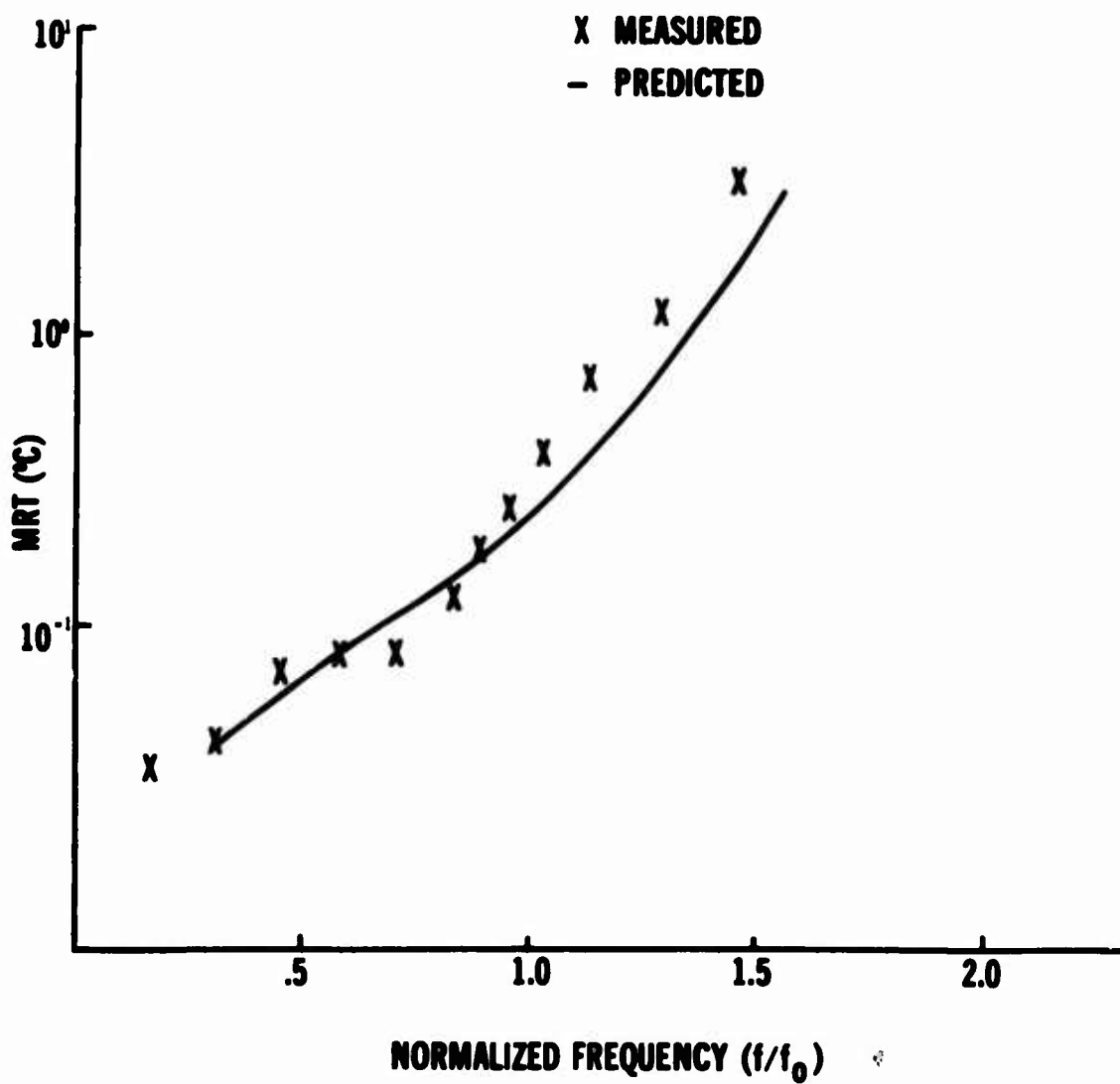


Figure 7. Navy Common Mod FLIR System MRT.

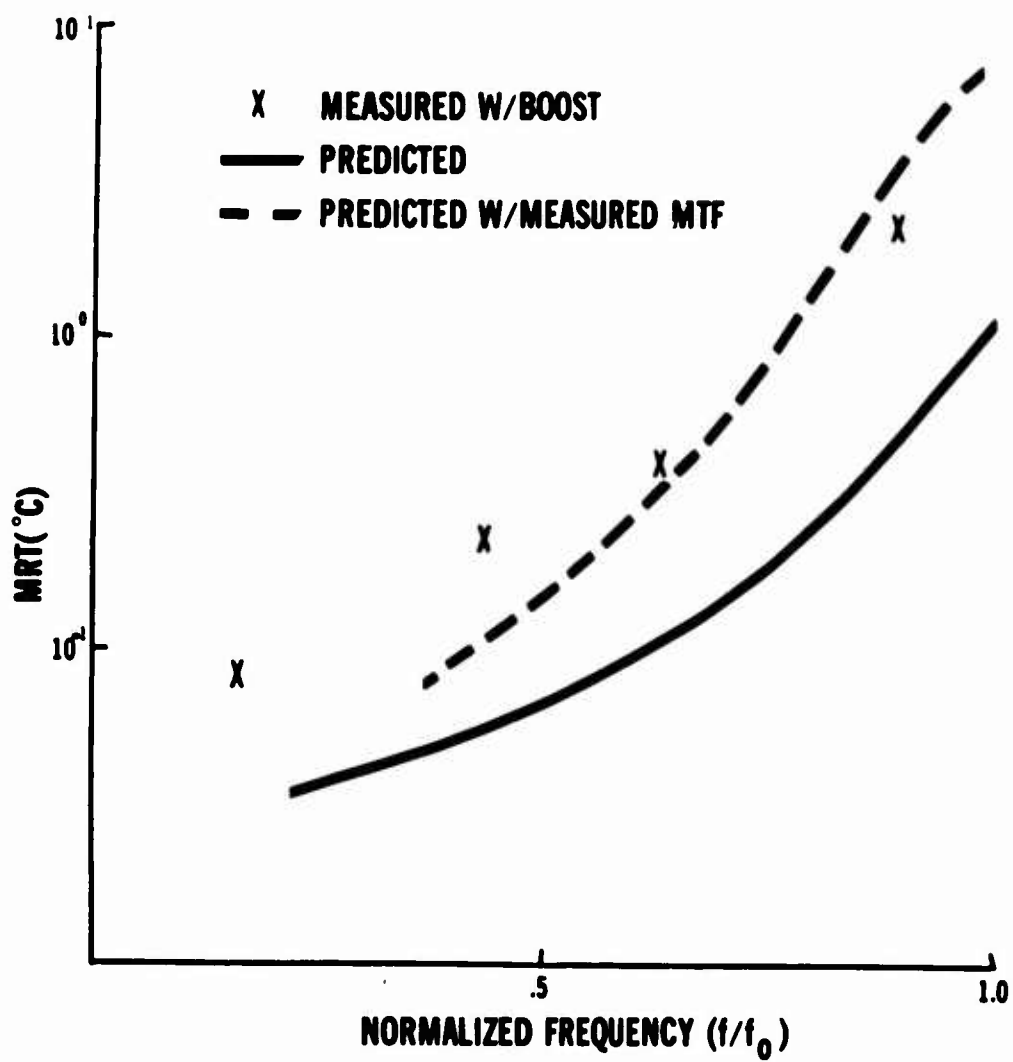


Figure 8. DISCOID 525 System MRT.

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