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To	:	See MAS Distribution List No. 2
Subject	:	STANAG 4350 LAND (EDITION 1) - CALCULATION OF MINIMUM RESOLVABLE TEMPERATURE DIFFERENCE (MRTD) FOR THERMAL IMAGING SYSTEMS
Reference	:	AC/225-D/1128 / AC/225(Panel VI)D/373(Rev) dated 10 July 1989 (Edition 1)(1st Draft)
Enclosure	:	STANAG 4350 (Edition 1)

1. The enclosed NATO Standardization Agreement which has been ratified by nations as reflected in page iii is promulgated herewith.

2. The reference listed above is to be destroyed in accordance with local document destruction procedures.

3. AAP-4 should be amended to reflect the latest status of the STANAG.

ACTION BY NATIONAL STAFFS

4. National staffs are requested to examine page iii of the STANAG and if they have not already done so, to advise the Defence Support Division, IS, through their national delegation as appropriate of their intention regarding its ratification and implementation.

G.B. FERRARI
Major-General, ITAF
Chairman, MAS

STANAG No. 4350
(Edition 1)

NORTH ATLANTIC TREATY ORGANIZATION
(NATO)

MILITARY AGENCY FOR STANDARDIZATION
(MAS)

STANDARDIZATION AGREEMENT

SUBJECT : CALCULATION OF MINIMUM RESOLVABLE TEMPERATURE DIFFERENCE (MRTD) FOR THERMAL IMAGING SYSTEMS

Promulgated on 18 July 1995

G.B. FERRARI
Major-General, ITAF
Chairman, MAS

RECORD OF AMENDMENTS

No.	Reference/date of amendment	Date entered	Signature

EXPLANATORY NOTES

AGREEMENT

1. This NATO Standardization Agreement (STANAG) is promulgated by the Chairman MAS under the authority vested in him by the NATO Military Committee.

2. No departure may be made from the agreement without consultation with the tasking authority. Nations may propose changes at any time to the tasking authority where they will be processed in the same manner as the original agreement.

3. Ratifying nations have agreed that national orders, manuals and instructions implementing this STANAG will include a reference to the STANAG number for purposes of identification.

DEFINITIONS

4. Ratification is "The declaration by which a nation formally accepts the content of this Standardization Agreement".

5. Implementation is "The fulfilment by a nation of its obligations under this Standardization Agreement".

6. Reservation is "The stated qualification by a nation which describes that part of this Standardization Agreement which it cannot implement or can implement only with limitations".

RATIFICATION, IMPLEMENTATION AND RESERVATIONS

7. Page iii gives the details of ratification and implementation of this agreement. If no details are shown, it signifies that the nation has not yet notified the tasking authority of its intentions. Page iv (and subsequent) gives details of reservations and proprietary rights that have been stated.

ARMY

NATO STANDARDIZATION AGREEMENT
(STANAG)

CALCULATION OF MINIMUM RESOLVABLE TEMPERATURE DIFFERENCE (MRTD) FOR THERMAL IMAGING SYSTEMS

Annex: Description of the calculation procedure
Related Documents : None

AIM

1. The aim of this agreement is to provide a standard procedure for the calculation of MRTD to evaluate and compare thermal imagers and thermal imager concepts.

VALIDITY

2. The calculation method described permits the modelling of properly sampled scanning thermal imager systems using different detector technologies (conventional detector arrays, SPRITE detectors and detector arrays with integrated signal read out).

   It is not valid for undersampled systems or for systems where aliasing effects are not negligible (see Annex, Paragraph 6: Undersampling and Aliasing).

AGREEMENT

3. Participating nations agree that the calculation procedure described in the Annex will apply when evaluating and comparing TI concepts.

IMPLEMENTATION OF THE AGREEMENT

4. This STANAG is implemented when a nation has issued instructions that thermal imager concepts will be modelled in accordance with this STANAG.

DESCRIPTION OF THE CALCULATION PROCEDURE

1. General

In the following pages the calculation procedure for the horizontal MRTD ($MRTD_h$, vertical bars) and vertical MRTD ($MRTD_v$, horizontal vars) is described.

A method for averaging these MRTDs is given in STANAG 4347 on Definition of Nominal Static Range Performance for Thermal Imaging Systems.

2. MRTD formulas:

$$MRTD_h(r) = \frac{\pi^2 \cdot k_T}{4 \cdot \sqrt{14}} \; \frac{r \cdot NETD}{MTF_h(r)} \left[\frac{DAS_v \cdot v_s \cdot \Delta r_{xh} \cdot \Delta r_{yh}}{t_e \cdot F_r \cdot \eta \cdot \Delta f_n}\right]^{1/2}$$

$$MRTD_v(r) = \frac{\pi^2 \cdot k_T}{4 \cdot \sqrt{14}} \; \frac{r \cdot NETD}{MTF_v(r)} \left[\frac{DAS_v \cdot v_s \cdot \Delta r_{xv} \cdot \Delta r_{yv}}{t_e \cdot F_r \cdot \eta \cdot \Delta f_n}\right]^{1/2}$$

where

r	=	spatial frequency [$mrad^{-1}$]	
k_T	=	threshold signal-to-noise ratio (= 2.25)	
DAS_v	=	vertical detector angular subtense [mrad]	
v_s	=	scan velocity [mrad/s]	
t_e	=	eye integration time (0.2 s)	
η	=	detector overscan ratio (ratio of detector subtense to line separation)	
F_r	=	frame rate [Hz]	
NETD	=	Noise Equivalent Temperature Difference [K]	see 3.
Δf_n	=	noise equivalent bandwidth [Hz]	see 3.
Δr_{xh}, Δr_{yh}, Δr_{xv}, Δr_{yv}	=	normalized perceived (noise) bandwidth corresponding to one bar extending in x and y direction	see 4.
MTF_h	=	horizontal MTF	see 5.
MTF_v	=	vertical MTF	see 5.

Note: Throughout the paper the following procedure to select the units indicated in square brackets were used: Established quantities, e.g. D_p^*, were given their customary units, here [$W^{-1} cm\ Hz^{1/2}$]. The remaining units in an equation were then adapted to yield correct numerical results.

3. NETD (Noise Equivalent Temperature Difference)

$$NETD = \frac{4 \cdot F^2 \cdot (\Delta f_n)^{1/2}}{(ab)^{1/2} \cdot n_s^{1/2} \cdot \tau_o \cdot M^*}$$

where

F = F-number: f/D

D = diameter of entrance pupil [mm]

f = focal length [mm]

a,b = vertical and horizontal dimension of detector [cm]

n_s = number of serial detectors

τ_o = optics transmission

M^* = $\pi \cdot W\ D_p^*$ (for W see below) $[Hz^{1/2}cm^{-1}K^{-1}]$

D_p^* = peak detectivity referred to detector cold shield, system F-number and background temperature $[W^{-1}cm\ Hz^{1/2}]$

Δf_n = noise equivalent bandwidth [Hz] (see also footnote):

$$\Delta f_n = \int_0^\infty \frac{S(f)}{S_{max}} \cdot (MTF_N)^2\ df$$

$S(f)$ = spectral power density of noise $[V^2Hz^{-1}]$

S_{max} = power density of noise at frequency of measurement of D_p^* $[V^2Hz^{-1}]$

MTF_N = product of electronic MTFs: $MTF_{el} \cdot MTF_b$; see 5.

$$W = \int_{\lambda 1}^{\lambda 2} \frac{\partial L\ (\lambda, T)}{\partial T} \cdot R_n(\lambda)\ d\lambda$$

$L(\lambda,T)$ = spectral radiance of black body at temperature T $[W\ cm^{-2}sr^{-1}\mu m^{-1}]$

$R_n(\lambda)$ = normalized spectral responsivity of detector

Note: When measuring the NETD, the noise equivalent bandwidth may also depend on the frequency response of the measuring system.

4. Normalized perceived noise bandwidth Δr

For horizontal MRTD:

$$\Delta r_{xh}(r) = \frac{A}{r} \cdot \int_0^\infty \frac{S(g)}{S_{max}} \; MTF_R^{\,2}(g) \cdot MTF_e^{\,2}(g) \cdot \mathrm{sinc}^2\left(\frac{g}{2r}\right) \; dg$$

$$\Delta r_{yh}(r) = \frac{7}{r} \cdot \int_0^\infty MTF_{sc}^{\,2}(g) \cdot \mathrm{sinc}^2\left(\frac{7g}{2r}\right) \; dg$$

For vertical MRTD:

$$\Delta r_{xv}(r) = \frac{7}{r} \int_0^\infty \frac{S(g)}{S_{max}} \; MTF_R^{\,2}(g) \cdot \mathrm{sinc}^2\left(\frac{7g}{2r}\right) \; dg$$

$$\Delta r_{yv}(r) = \frac{A}{r} \int_0^\infty MTF_{sc}^{\,2}(g) \cdot MTF_e^{\,2}(g) \cdot \mathrm{sinc}^2\left(\frac{g}{2r}\right) \; dg$$

where

r	=	spatial frequency of the MRTD test pattern
g	=	integration variable
A	=	normalization constant (= 1.75) to obtain $\Delta r_x(r) = 1$ for medium frequencies
$S(g)$	=	spectral power density of noise; as in 3. (N.B: $f = v_s \cdot r$)
MTF_R	=	device MTF in scanning direction and behind detector: typically $MTF_{el} \cdot MTF_b \cdot MTF_m$; see 5.
MTF_{sc}	=	device MTF perpendicular to the scanning direction and behind the detector: typically $MTF_{b,v} \cdot MTF_m$; see 5

5. MTF Modulation Transfer Function

5.1 System MTF

The System MTF is the product of the MTFs of all the incoherently coupled components including the human observer. Horizontal and vertical MTFs differ since the parameter values of many components are different in different directions (e.g. detector sizes) or since some components act only in one direction (e.g. electronic MTF only in the scanning direction).

For a thermal imager which is scanned horizontally

- the horizontal MTF is typically given by

$$MTF_h = MTF_{o,h} \cdot MTF_{d,h} \cdot MTF_i \cdot MTF_{el} \cdot MTF_{b,h} \cdot MTF_{m,h} \cdot MTF_e \cdot MTF_s \cdot MTF_{st,h} \cdot MTF_{D/A}$$

- the vertical MTF is typically given by

$$MTF_v = MTF_{o,v} \cdot MTF_{d,v} \cdot MTF_{b,v} \cdot MTF_{m,v} \cdot MTF_e \cdot MTF_{st,v}$$

where

MTF_o = MTF of the front optics
MTF_d = MTF of the detector
MTF_i = MTF of integrating elements
MTF_{el} = MTF of the electronics
MTF_b = MTF of the contrast enhancement
MTF_m = MTF of the display
MTF_e = MTF of the eye
MTF_s = MTF of the synchronisation error
MTF_{st} = MTF of the stabilisation error
$MTF_{D/A}$ = MTF of the D/A converter

Formulas and specifications are given in the following paragraphs for the calculation of the MTF of frequently used components. These formulas should be used only if no specific MTF data are available.

5.2 MTF of the components

5.2.1 MTF of the front optics MTF_o

a) Diffraction limited optic with circular entrance pupil without obstruction

$$MTF_o(r) = \frac{2}{\pi} \cdot \left\{ \arccos \left[\frac{\lambda r}{D}\right] - \frac{\lambda \cdot r}{D} \sqrt{1 - \left[\frac{\lambda \cdot r}{D}\right]^2} \right\}$$

with r = spatial frequency [$mrad^{-1}$]
D = entrance pupil diameter [mm].
λ = wavelength [μm]

For thermal imagers in the 8-12 μm region of the spectrum, substitute λ = 10 μm.
For thermal imagers in the 3-5.5 μm region of the spectrum, substitute λ = 4.5 μm.
For thermal imagers in the 3-4.2 μm region of the spectrum, substitute λ = 3.8 μm.

b) Diffraction limited optic with central obstruction or with rectangular aperture

see e.g. Lloyd, Thermal Imaging Systems, Fig. 3.23 and 3.22

c) MTF due to aberration

$$MTF_{o,a} = (MTF_o)^q$$

with MTF_o = diffraction limited MTF
q = aberration constant; $q > 1$;

5.2.2 MTF of the detector MTF_d

5.2.2.1 Discrete detectors

a) MTF due to the detector size

For a rectangular detector:

$$MTF_{d,s}(r) = \frac{\sin(\pi \cdot r \cdot DAS)}{\pi \cdot r \cdot DAS}$$

with DAS = detector angular subtense in the horizontal or in the vertical direction respectively [mrad]

b) MTF due to the temporal response of the detector (only in the scanning direction):

$$MTF_{d,t}(r) = \frac{1}{(1 + (r \cdot v_{sc}/f_{gr})^2)^{1/2}}$$

with v_{sc} = scanning speed [mrad/s]
f_{gr} = cut-off frequency of detector [Hz]

c) By taking into account the respective DAS values in both directions the horizontal and vertical detector MTFs are:

$$MTF_{d,h} = MTF_{d,s} \cdot MTF_{d,t}$$
$$MTF_{d,v} = MTF_{d,s}$$

5.2.2.2 SPRITE detectors

a) MTF due to the detector size

$$MTF_{d,s}(r) = \frac{\sin(\pi \cdot r \cdot l/f)}{\pi \cdot r \cdot l/f}$$

with r = spatial frequency [$mrad^{-1}$]
l = read-out zone length or detector width respectivly [μm]
f = optics focal length [mm]

b) MTF due to the diffusion term (only in the scanning direction)

$$MTF_{d,diff}(r) = \frac{1}{1 + (2 \cdot \pi \cdot r \cdot Q_a/f)^2}$$

with Q_a = diffusion length [μm]
f = optics focal length [mm]

c) By taking into account the the respective values in both directions the horizontal and vertical detector MTFs are:

$$MTF_{d,h} = MTF_{d,s} \cdot MTF_{d,diff}$$
$$MTF_{d,v} = MTF_{d,s}$$

5.2.3 MTF of integrating elements MTF_i

For sampled systems with a finite integration time for each sample (only in the scanning direction)

$$MTF_i(r) = \frac{\sin(\pi \cdot r \cdot t_i \cdot v_{sc})}{\pi \cdot r \cdot t_i \cdot v_{sc}}$$

with t_i = integration time for each sample [s]
v_{sc} = scanning speed [mrad/s]

Due to sampling, aliasing may occur (see Paragraph 6.)

5.2.4 MTF of the electronics MTF_{el}

This MTF applies only in the scanning direction. For a Butterworth low-pass filter of n-th order the MTF is:

$$MTF_{el}(r) = \frac{1}{(1 + (r \cdot v_{sc}/f_{gr})^{2n})^{1/2}}$$

with f_{gr} = cut-off frequency of the filter (-3db point) [Hz]
v_{sc} = scanning speed [mrad/s]
n = order of the filter; n=1: single RC-filter

5.2.5 MTF of the contrast enhancement MTF_b

a) If the contrast enhancement is done by a purely analogue network it works only in the scanning direction. Often it can be described by

$$MTF_b = 1 + \frac{K-1}{2}\left[1 - \cos\left[\frac{\pi \cdot r}{r_b}\right]\right] \quad \text{if } r < 2r_b$$

$$= 1 \quad \text{if } r > 2r_b$$

with K = dimensionless gain factor
r_b = spatial frequency of maximum boost [$mrad^{-1}$]

b) With digital methods a contrast enhancement can be applied in both directions. A digital contrast enhancement can also be described by an MTF, which has to be constructed accordin to the used algorithm.

5.2.6 MTF of a D/A converter $MTF_{D/A}$

$$MTF_{D/A} = \frac{\sin^2(\pi \cdot r \cdot a_s)}{(\pi \cdot r \cdot a_s)^2}$$

with a_s = sample distance of the D/A converter, referred to the object space [mrad]

5.2.7 MTF of the display MTF_m

5.2.7.1 LED-display

If the LED has a rectangular size:

$$MTF_m(r) = \frac{\sin(\pi \cdot r \cdot \alpha_1)}{\pi \cdot r \cdot \alpha_1}$$

with α_1 = horizontal or vertical LED size respectively, relative to the object space [mrad].

5.2.7.2 CRT-display

If the spot profile is Gaussian the MTF is as follows:

$$MTF_m(r) = \exp\left\{ -2(\pi \cdot \sigma_c \cdot r)^2 \right\}$$

with σ_c = standard deviation of the spot intensity distribution, relative to the object space [mrad].

For circular spots, horizontal and vertical MTFs are equal.

5.2.8 MTF of the eye MTF_e

$$MTF_e(r) = \exp\left\{-\frac{\left[\ln(r/r_c)\right]^2}{2\cdot\sigma^2}\right\}$$

with $\sigma^2 = 0.85$

r = spatial frequency in the image (eye) space [mrad]

r_c = spatial frequency of peak eye MTF value:

$$r_c = 0.055\cdot\log L_d + 0.14 \text{ [mrad]}$$

L_d = display luminance [cd m^{-2}]

the normally used value of L_d = 100 cd m^{-2} gives
r_c = 0.25 $mrad^{-1}$

5.2.9 MTF of the synchronisation error of the scanner MTF_s

This MTF acts only in the scanning direction.

$$MTF_s(r) = \exp\left\{ -2\cdot(\pi\cdot\sigma_s\cdot r)^2 \right\}$$

with σ_s = standard deviation of the synchronisation error, referred to object space [mrad].

5.2.10 MTF of the stabilization error MTF_{st}

$$MTF_{st}(r) = \exp\left\{ -2\cdot(\pi\cdot\sigma_{st}\cdot r)^2 \right\}$$

with σ_{st} = standard deviation of the stabilization error in the horizontal resp. vertical direction, referred to object space [mrad].

6. Undersampling and Aliasing

If the thermal imager is undersampling, the System MTF and hence the MRTD are not always defined over the whole frequency range (see Addendum to The Optical Transfer Function Measurement of Imaging Systems, NATO Document Addendum to AISP-1, May 1981).

However, here it is assumed that the calculation procedure for the MRTD still can be applied if aliasing effects, which result from undersampling, are not noticeable on the display.

This can be assumed to be the case when, for the directions in which discrete sampling occurs, the aliased signal (see below) in the useful spatial frequency range (see below)

- is less than 20% of the original System MTF (see below) and
- is less than 0.1

The aliased signal is defined as the device input MTF (including front optics, detector, etc.), folded back at the sampling frequency and multiplied by the reconstruction MTF (electronics, display, etc.).

The upper limit of the useful spatial frequency range is given by the highest spatial frequency which is needed to fulfill the required task.

The original System MTF is the System MTF which would result if no sampling was present.