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EXPERIMENTAL MEASUREMENT AND THEORETICAL CALCULATIONS OF MINIMUM RESOLVABLE TEMPERATURE DIFFERENCE OF THERMOGRAPHIC SYSTEMS

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ABSTRACT

First and second generation of infrared (IR) systems are characterized by their variation in the measurement of the Minimum Resolvable Temperature Difference (MRTD). This paper is directed toward the basic measurement of MRTD for both generations of IR systems. Concepts and theory behind the measurment were addressed. The MRTD used for modern systems production and development was introduced. A practical measurement procedure for laboratory imaging scanner type system results and data analysis are also provided. A discussion of the challenges of evaluating new systems such as staring arrays and second generation digital IR systems and the requirements for both horizontal and vertical MRTD measurements are also provided.

KEY WORDS

IR sensors, Minimum Resolvabl Temperature Difference, MRTD, and Thermographic system measurement.

1. INTRODUCTION

In the mid. 1970's CNVEO (Center for Night Vision & Electro-Optics), US Army [1], developed and put into operation a facility called the Image Evaluation Facility (IEF). The purpose of the IEF is to measure MRTD and other parameters necessary to characterize IR sensors. It is usually considered the standard in the free world for these type of measurements. This paper is intended to give an overview of the MRTD measurement. A real measurement is done over a scanner type IR sensor and results with acceptable over all accuracy are obtained.

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2. CONCEPT OF MINIMUM RESOLVABLE TEMPERATURE DIFFERENCE

MRTD is the subjective resolution as a function of a thermal imager (the observer makes a visual assessment of the image on the screen and the method relies on the sensory Physiology and the psychology of the subject). It is a measure of the ability of an observer, looking at the system display to just resolve a four-bar test pattern having a seven to one aspect ratio that has a constant temperature difference (ΔT) between its different bars.

It is probably the most important measure of an IR system's ability to detect and identify a thermal anomaly or target. The MRTD links the thermal resolution to the spatial discrimination of the system. It is a function of both the spatial frequency of the bar pattern and the ambient temperature of the background [1]. It also takes into account the visual acuity of the observer and the quality and settings of the display device. The expression for calculating the predicted MRTD in the scan direction, usually referred to as horizontal MRTD (HMRTD), as given by Raches [2] is:

$$\mathrm{MRTD}(f_x) = \mathrm{SNR}\,\frac{\Pi^2}{\sqrt[4]{14}}\,\frac{\mathrm{NETD}}{\mathrm{MTF_{TOT}}(f_x)}\left[\frac{\Delta y \times v f_x \times Q(f_x)}{\Delta f_n \times F_r \times t_E \times \varepsilon_{ovsc}}\right]^{1/2} \qquad (1)$$

Where:

SNR is the signal-to-noise ratio necessary to recognize the four-bar pattern.
NETD is the noise equivalent temperature difference.
$MTF_{TOT}(f_x)$ is the combined Modulation Transfer Function (MTF) of the opt., eye(H_{EYE}), electronics, display, etc. in the scan direction.
Y is the vertical IFOV in the vertical direction in milliradians [mrad].
V is the detector scan velocity in mrad per second.
f_x is the bar frequency in cycles per mrad.
Δf_n is the electronic noise bandpass.
F_r is the frame rate per second.
ε_{OVSC} is the over scan ratio.
t_E is the eye integration time of approximately 0.16 second.
Q is a noise filtering term given by:

$$Q = \int_0^{\infty} S(f_x)\, H_N^2(f_x)\, H_W^2(f_x)\, H_{EYE}^2(f_x)\, df_x \qquad (2)$$

Where:

$S(f_x)$ is the noise power spectrum out of the detector.
$H_W(f_x)$ is the bar target filter function of bar-width W.
$H_N(f_x)$ is a noise filter function from the detector to the display.

A similar set of formulae in which the sampling effects are averaged out, are the MRTD in the cross scan direction (usually referred to as vertical MRTD (VMRTD)). Fig.1, shows an example of how a typical MRTD curve is plotted [1].

MRTDs are used in various ways during the design, development and production of IR systems. Johnson [3] developed a method to relate expected observer field performance for detecting and classifying targets to their predicted or measured MRTD. Predicted MRTDs are used to evaluate system tradeoffs during IR system design and to specify requirements. Measured MRTDs are used to understand and improve modeling of developmental hardware as well as to determine compliance to specification. Both predicted and measured MRTDs are used to analyze expected performance for different applications. Fig.3, shows the tow dimensional MRTD of the High Performance Portable IR System (HIPPS) designed by Cincinnati Electronics Corporation, compared with the HIPPS specification [4]. The system was measured using the General Range setting with an integration time of 7.62 milliseconds and operated within the "M-band" alone. The 2D MRTD at 4.6 cycles/milliradian is 0.060°C.

In the CNVEO, in its Image Evaluation Facility (IEF), They provide range predictions (detection and recognition of tactical targets) for the FLIR (Forward looking IR systems) based on the measured MRTD data. Table 1, includes range predictions with and without the Nyquist limit [4] for HIPPS based on its measured MRTD data. HIPPS recognition ranges for tactical targets are in excess of 4 kilometers under weather conditions that span from hot/humid to cold/dry.

The idea behind all evaluations including MRTD is to gain an understanding of the device being tested so that improvement can be made and performance modeled or predicted. This philosophy requires that highly trained, skilled, motivated and creative engineers, scientists, and technicians to be assigned and provided with a good support, including equipment.

3. EXPERIMENTAL SETUP

The equipment needed for the successful determination of MRTD of a thermal imager are collimator optics, differential blackbodies with bar patterns or targets, AC and DC power supplies, thermocouple with a very sensitive multimeter, optical bench with a scanner head, collimator and differential blackbody mounts, and a display. A typical arrangement is shown in Fig.5. Accuracy, confidence and ease of measurement are directly related to the equipment used. Each of these components will be briefly described. Fig.4, shows a schema of the equipment used in our setup.

3.1. Optics

The optical collimator is the backbone of the thermal imager test laboratory. It is used to present target imagery, at apparent infinity focus, to the sensor under test. Collimators are generally broken down into two main categories, those using reflective and those using refractive main elements. Generally reflective optics are used for narrow FOV, high-resolution systems and where different band sensors are evaluated. Refractive lenses are more practical for wide FOV, low-resolution systems [1]. The collimator MTF should be much greater than the MTF of the sensor system to be evaluated, and the useful collimator exit aperture should be at least one inch larger than the entrance aperture of the sensor under test. The collimator MTF and transmission factor should be measured for the spectral region for which it is going to be used. The available collimator we applied in our test is a Germanium collimating concave lens with a focal length of (f_c=107mm), which is large enough to make the lens cover the sensor's entrance aperture. It has its own handle that insures three degrees of freedom with respect to the optical bench mounted on.

3.2. Differential blackbody

We have designed five differential blackbodies, we did our best to be these targets accurately performed. Each of these targets consists of two planes. The forward plane contains a four-bar test pattern, which has a 7:1 aspect ratio. This means that there are in each blackbody four rectangular bars, whose height is equal to seven times their width and that the three spaces between the bars have the same width as the bars. They are etched out of a highly emissive material that is thick enough to minimize non-uniform temperatures, yet thin enough to be accurately and uniformly etched (rough steel plate with 1.5 mm thickness). The bars are also painted with a black matt paint spray to be their emissivities as close to one as possible. These bars are equally heated by Tungsten wires (500 watt) fixed behind them on a distance of 3 mm. The electric circuit of each target, which contains four resistance wires is connected in series. The electric circuit of the first pattern (with the lowest frequency), should be supplied with a 13 v AC power supply. The rest patterns are designed to be supplied with a DC power supply. These heating wires insures a slow rise of the bar's temperature, which gives us the enough time to take hold the required (critical) temperature readings from the multimeter during the MRTD measurement process on any target frequency. The metal bars of each differential blackbody are fixed on a wood box that insures the full insulation of the bars and the electric circuits. Also the good and accurate fixing of the bars on the wood box insures that the distances between the bars i.e. the pattern frequency is held unchangeable during the test process. The backward plane of the differential blackbody is a metal sheet plate, etched out of the same plate used for the bars in the forward plane, and painted in black to be regarded as a blackbody. It has dimensions enough to cover the backspace of the bars and the spaces in between. It is used to insure a uniform temperature distribution over the black bars (assuming the system is being operated in the "white-hot" mode), formed between the metal bars of the forward differential blackbody. The differential blackbody has its own mount, which has three degrees of freedom, x, y, and z, with respect to the optical bench mounted on.
The set of targets is determined before the test, and the frequency in Cycles/Milliradian of the individual target is calculated using the following equation:

$$\text{Target frequency (cyc / mrad)} = \frac{\text{Collimator focal length (in.)}}{\text{Bar size (in.)} \times (2) \times (1000)} \tag{3}$$

The target with highest spatial frequency in the set of targets should be chosen to be the highest spatial frequency that is expected to be resolvable. For most scanning systems it is a little bit lower than the inverse of the sensor IFOV. However for staring systems it is about half that value. The remaining intermediate targets should be selected to provide a suitable representation of the expected MRTD curve including one just below the highest expected resolvable frequency. Usually, six to eight intermediate targets are faire enough. When actually running the test, it is standard

practice for the observer to continue increasing frequency until a target is not resolvable. That frequency is noted on the data sheet as Can Not Resolve (CNR). This helps the system analyzer to properly interpret the actual system performance.
In our measurement curried on a scanner type imaging system having 1.8 mrad spatial resolution, the highest frequency target that should be resolvable by the sensor is about, (1/1.8 mrad =555 cyc/mrad). Whilst we determined the highest frequency target, each of the remaining seven targets, should have half the frequency of the previous one. The realization of the three higher frequency targets was not available, because of the bar's fine width, or the extremely small target resolution distance (twice the bar width). The target having the lower spatial frequency in the test set, has a resolution distance of, T_x=20 [mm] from an observation point at a distance, f_c=107 [mm], this yields to a target angular resolution of, $\theta_d^{1/2}$=187 mrad.

$$\theta_d^{1/2} = (1000 \times T_x)/f_c \qquad (4)$$

The one-half power designation refers to a linear angular measurement, whereas the unity power refers to a two-dimensional measurement. Using the angular resolution of equation. 4, we can define a target spatial frequency as, $f_s = 1/\theta_d^{1/2}$ = 5.35 cyc/mrad (or by using equation.3.). It is $1/2\theta_d^{1/2}$ for staring systems. Applying the 7:1 aspect ratio, the first target should have bars height of 70 mm.
The final fifth test target we reached in our design (having the highest spatial frequency), has a angular resolution of 11.7 mrad, and a size frequency of 85.6 cyc/mrad.

3.3. Sensor mount

The sensor mount is used to properly position the sensor on the optical path of the collimator and to securely lock it down to prevent vibration of the sensor itself from degrading performance. Many sensors have coolers or scanners that cause severe vibration. For laboratory MRTD facility, it would be best if the sensor mount had six degrees of freedom, x, y, z, azimuth, elevation and roll. Azimuth and elevation are important when doing offaxis MRTDs. They are extremely important to minimize phasing effects of the target and detector array in staring sensors. They should have step increment that are five to ten times smaller than the IFOV of the sensor being evaluated. It is important that the MRTD collimator optics, optical bench, and sensor mount be located in an area or room that has very low or no measurable vibrations and that they don't vibrate with respect to each other. The modern solution to this problem is to mount them on stabilized isolation tables. The properly positioning of the scanner head of the sensor under test in the optical path of the collimator is insured by using a stand with elevation mechanism, which gives us the possibility to control its height. The stand can also lock the scanner head down to prevent it from vibrations. The phasing effects of the target bars and sensor detector are minimized by using the phasing adjustment auxiliary mode of the sensor under test (this minimizes distortions observed on vertical edges of objects in the scene, and should be repeated after mounting of each test pattern).

3.4. Display

The display is that part of the system that interfaces the sensor to the user. The display may be an integral part of the sensor, such as the monocular output of an AN/TAS-4 sight, or may be independent of the system, such as a TV monitor. For systems utilizing a video output to a TV monitor, the test engineer usually evaluate the sensor for two cases. First the performance of the entire system is measured using the display provided with the sensor. The MRTD is intended to provide an end-to-end evaluation of the system as it would be used in the field. The second test should use a standard, high resolution monitor in the place of the system display. The second test provides a measure of sensor performance only. Comparison of the results of these conditions indicates the relative impact of the display on over all system performance. We evaluated the sensor's MRTD for two different cases. First by using the LCD monitor provided with the system, and second by using a high resolution TV monitor Fig.2.

3.5. Thermocouple and a multimeter

The blackbodies temperatures was captured by using a K-type thermocouple (Chromel vs Alomel). During the measurement process, the thermocouple junction or head should be fixed on the defined bar of the target in a complete contact, and its reference junction should be placed in a ice dewar (zero deg. C). The DC current from the thermocouple is measured using the model 34401A multimeter (Hewlett Packard), which has a sensitivity of 0.001 mv. We made the required calibrations on the thermocouple using the same multimeter in the temperature range of [25 ^{0}C- 65 ^{0}C], in order the temperature readings captured from the bars or the backward blackbody (sheet), to be easily changed from millivolts into degrees centigrade. Our MRTD measurement setup is shown in Fig.5.

4. EXPERIMENTAL PROCEDURE

The environment within which the MRTD test is performed is very important. The conditions must remain very stable from day to day. Most importantly, the room temperature must remain constant and as close to 300 Kelvin as possible. This is explained by blackbody radiation law, which states that the spectral radiant flux emitted by blackbody source is a function of the temperature of that source. In short, Plank's law states that an MRTD performed at an ambient temperature of 280°K will produce result higher than those obtained at 300°K. Air currents within the room should also be minimized to eliminate the changes of fluctuating ambient temperature. In addition to the environmental conditions of the laboratory, it is also helpful to perform the MRTD test in darkened room. This allows for maximum pupil dilation of the eye as well as reducing distraction that may be present within the room. The laboratory where we performed the measurements, had a constant ambient temperature of 303°K, the setup was mounted on stabilized isolation tables, and the room was completely darkened.

The sensor under test in our MRTD measurement is a IR Imaging Radiometer which is a LW (long wave) model, sensitive in the spectral band 8-12 μm. It is a scanner type sensor with a (20x15) deg. FOV. It has a single $H_gC_dT_e$ detector with (250x250)μm dimensions. The 1X telescope is mounted on the scanner during the measurements, i.e. the IFOV is still 1.8 [mrad].

The first step in performing MRTD is to securely mount the scanner head of the sensor to be tested and then aligning its optical axis to be parallel to and centered on the collimator mounted on the optical bench, as well as insuring that its entrance pupil is perpendicular to the collimator optical axis. The observer should be dark adapted prior to beginning the test. During testing it is imperative that the observer not be influenced by others. For this reason, the usual procedure is to have the observer isolated from others during the duration of his/her test runs. The display gain and brightness should be optimized prior to the start of the MRTD test to assure that the display setting is not limiting the performance of the sensor. This is usually done by inserting a gray shade pattern into the display input and optimizing the display settings to the maximum gray levels resolvable. Once the display optimum gain and level have been obtained, they should not be altered throughout the test. The target mount on the optical bench, should insure perpendicularly positioning of bars to the collimator optical axis, in its focal plane. This can be calibrated by switching the sensor under test on, putting a hand behind the bars and viewing if the bars are in the required position or not. Adjusting the target position can be done by displacing the target mount in any of the three degrees of freedom it possesses. The next step is fixing the thermocouple sensitive junction on the defined bar from the target mounted on the optical bench, and connecting its terminals to the HP 34401 A, multimeter (it is switched on, and DC mode is selected). The final step of the MRTD setup adjustment is to connect the target electric circuit with the suitable to it power supply.

MRTD is implemented by monotonically increasing the temperature of the bars in the forward differential blackbody, while noting the ability of the observer to discern at a minimum temperature the target as four bars. Prior to starting the test, the observer should observe a high frequency test pattern around the center of the sensor input, looking for a place were the resolution is best (this is to insure that the user is testing for the best possible MRTD). The phasing adjustment auxiliary mode of the sensor under test should be checked frequently by the observer, aiming the phasing effects to be minimized. The observer should also adjust the gain and level controls of the system for best performance (usually at high gain for a low noise system).Changing the sensor gain, phasing adjustment, and level for optimum is allowed at each test pattern. The test is executed by selecting the lowest frequency target of the target set. The span temperature of the sensor is set above ambient temperature where the bars are not resolvable. The temperature of the bars is then gradually increased until the threshold of perception $\Delta T_{1\ hor\ (f1)}$ corresponding to the visual separation of the vertical lines in the image is reached (practically $\Delta T_{1\ hor\ (f1)}$ equals to the temperature of the bars read from the multimeter indicator minus the temperature of the backward blackbody at the pointed moment). The temperature difference is increased further until a good image is obtained. The procedure is then repeated in reverse order, i.e., the temperature difference between the pattern lines is reduced by switching off the power supply of the electric circuit that heats the bars, until the periodic structure in the image disappears at $\Delta T_{2\ hor\ (f1)}$. The later is generally lower than $\Delta T_{1\ hor\ (f1)}$. Indeed; it is easier to follow an image that is disappearing because it is initially well localized. In the other case, the attention of the observer is not fixed on any particular point until the image appears. The arithmetical mean of these two temperature differences, gives the MRTD for the first (lower) spatial frequency.

$$HMRTD_{obs1\,(f1)} = (\Delta T_{1\,hor\,(f1)} + \Delta T_{2\,hor\,(f1)}) / 2 \quad (5)$$

The horizontal MRTD for the second observer on the same target is obtained by repeating the same measurement chain done by the first observer. The arithmetical mean of the previous horizontal MRTD's, gives the horizontal HMRTD for the first target.

$$HMRTD_{(f1)} = (HMRTD_{obs1\,(f1)} + HMRTD_{obs2\,(f1)}) / 2 \quad (6)$$

Reversing the target in the perpendicular bar's direction, i.e. the bars orientation is in the horizontal direction, and repeating the same measurement chain done for the horizontal resolution, we obtain the vertical MRTD for the same target. The tow dimensional MRTD for this target is then calculated as:

$$MRTD_{f1} = (HMRTD_{(f1)} + VMRTD_{(f1)}) / 2 \quad (7)$$

We note that the horizontal and vertical MRTD values are not identical due to the sampling geometry of the system under test. We repeat the calculation to get the MRTD value for f2 and so on until the frequency f_n. f_n is the frequency at which the observer cannot resolve the four bars at any ΔT. The frequency is listed as CNR on the data sheet. Practically, we could not reach the f_n frequency, because manufacturing of such metal bars having increasingly small dimensions, in the required accuracy limits, was not available. This means that analysis can be carried only on the lowest spatial frequency target, and the half-cutoff frequency defined as f_o (it is one step higher than the frequency of the fifth target realized in our MRTD measurement).

The MRTD procedure is done usually with minimum of two times for each observer. For experimental systems, three or more observers are used and their values are averaged. In all cases, unbiased observers should be used.

5. DATA ANALYSIS

Once the MRTD is plotted on a semi-log graph of target size frequency, (cyc/mrad vs differential temperature ΔT in deg. C). The lower frequency portion of the curve provides an indication of the system sensitivity. Comparing the HIPPS curve Fig.3, with the system under test curve Fig.2, at the pointed frequency, we note that HIPPS has a clear turn-on temperature, which indicates a theoretically optimized system with good noise limited performance. It would be a good candidate for foul weather scenarios and applications where background sensitivity is required. Another point to look at is the half-cutoff frequency defined as f_o, (the fifth target for the sensor under test and the fourth for HIPPS). Again we can easily note the HIPPS priority, and we can say that the HIPPS possesses better than the tested system performance with smaller and smaller targets. The third area of interest is that of the high cutoff target, which indicates the system resolving power. The curve may increase asymptotically between the last resolvable target and the next available one. It is therefore imperative that the first target that is not resolvable be recorded as CNR.

6. NEWER SYSTEM CHALENGES

The development of advanced staring and scanning second generation thermal imagery has complicated the measurement of MRTD. With the VMRTD of scanning sensors as well as the HMRTD for staring focal plane array FPA systems, the measurement procedure is complicated by the discrete sampling of the detector. Now, in addition to the system noise, the observer must overcome or deal with the problems associated with the phasing of the detectors with respect to the periodic bar pattern. Because of these phasing effects, it is necessary to jog the system under test in steps smaller than the sensor IFOV with respect to the target so as to optimize the phasing relationship. The MRTD curve of sampled systems has an unorthodox shape not necessary similar to that of the characteristic scanned systems. The MRTD results are dependent on the phase relationship between the target and the detector array, and the MRTD of the system may vary as a result of the phasing relationship. Unlike scanning systems whose MRTD curve increases asymptotically as it approaches the cutoff frequency. The HMRTD and VMRTD for staring systems exhibit a peak at or near 0.7 of the Nyquist rate (the inverse of twice the IFOV), which then drops as it approaches the Nyquist [5].

7. CONCLUSIONS

The measurement of MRTD is at best difficult, but if care is taken, good equipment is used, the standard procedures are followed, and observers are well trained, consistent results can be obtained. However, the time has come to find an alternative, less subjective replacement. Because even for a very experienced observers, many things such as time pressures, domestic situations, health, etc. can and do affect performance. That is why several runs by several observers are averaged to get the MRTD. The obvious answer is to substitute a "objective", easy to calibrate, machine to do an automated MRTD and MTF. We hope that this paper will be useful in helping to standardize the measurement of MRTD.

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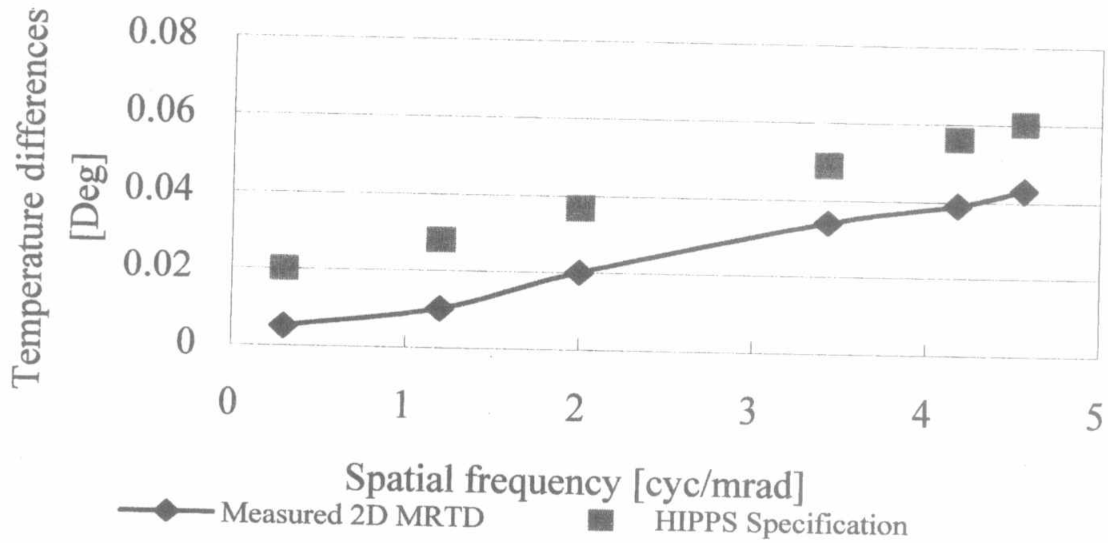

Fig.3.2D MRTD for HIPPS narrow FOV (1.6 x.1.6) deg.

Table 1. Range performance predictions for cold/dry & hot/humid conditions.

Target	Range (km)					
	70% Detection				70% Recognition	
	WFOV		NFOV		NFOV	
	Nyquist	w/oNyq.	Nyquist	w/o Nyq.	Nyquist	w/o Nyq.
M60 Tank (front)	3.0	4.5	12.0	16.7	3.0	4.5
M60 Tank (side)	4.3		17.1		4.3	
Man	0.9	1.4	3.4	5.3	3.4	5.3

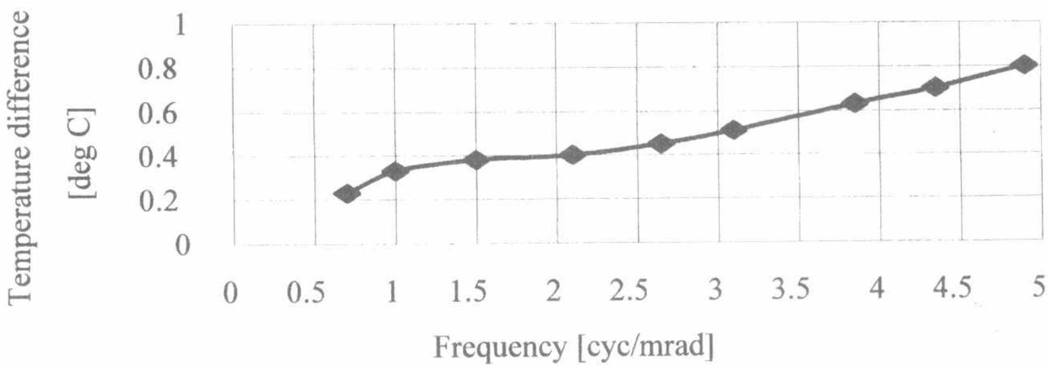

Fig.1. Typical MRTD curve.

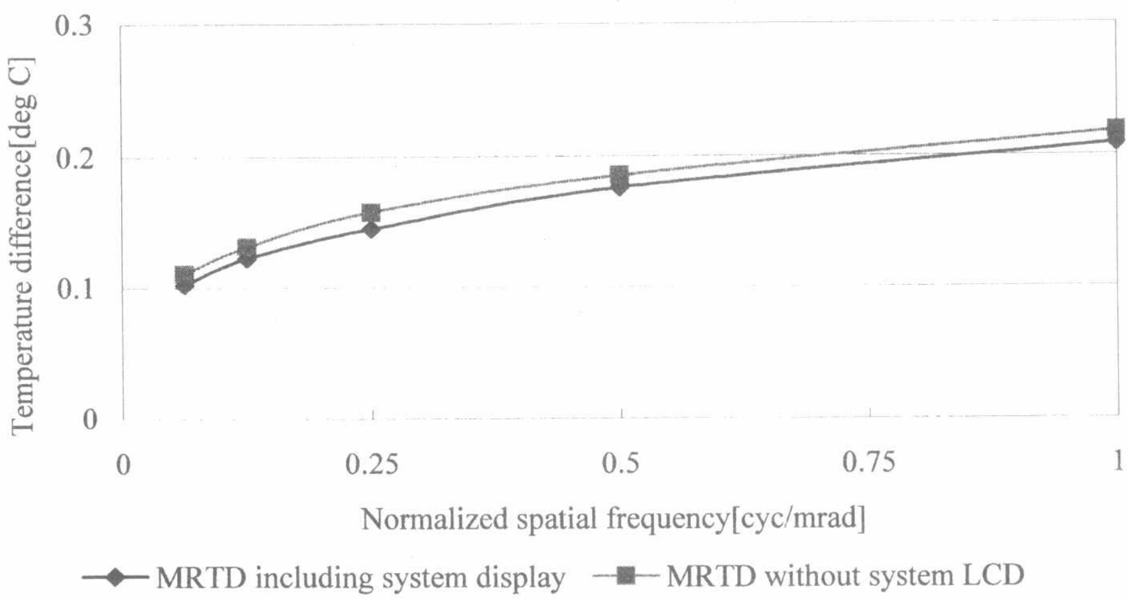

Fig.2. 2D-MRTD for the tested system, (20x15) deg. FOV.

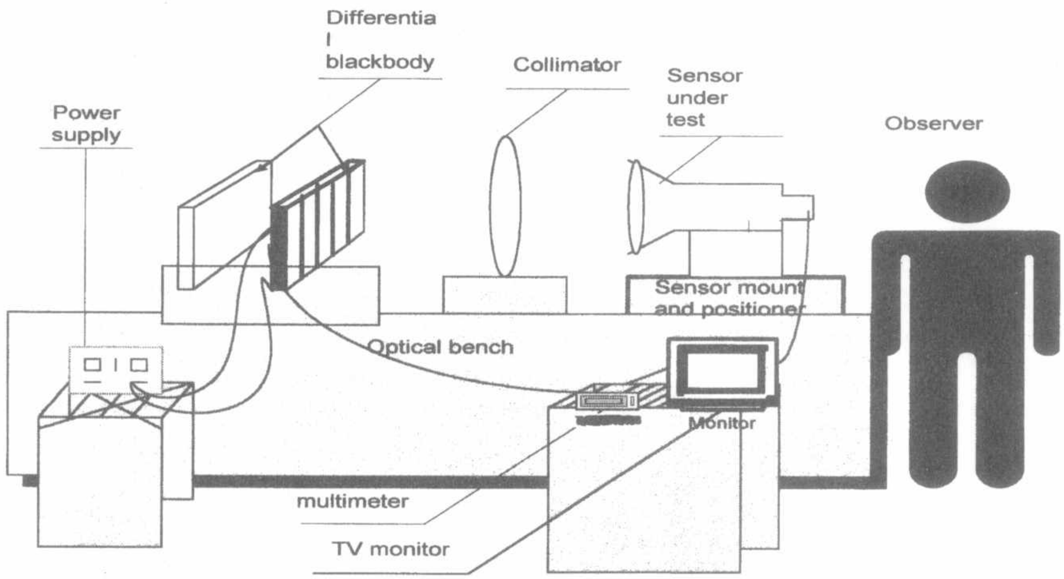

Fig.4. Schematic of the setup

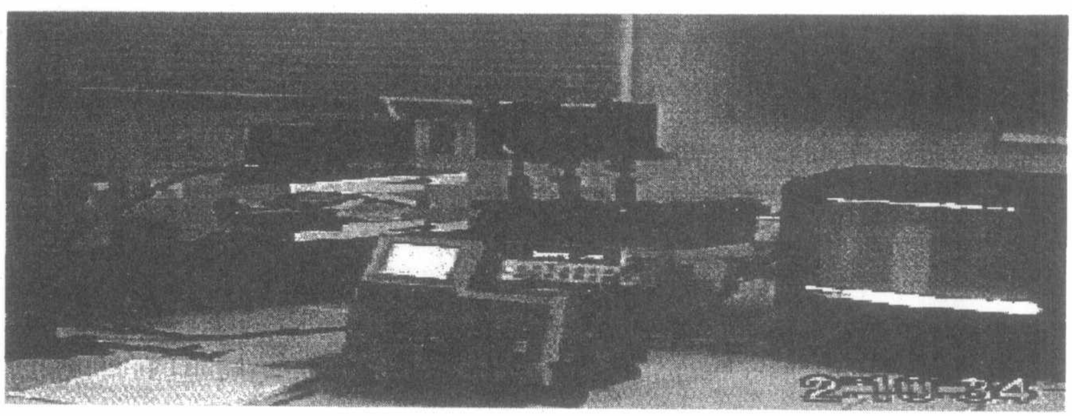

Fig.5. Experimental MRTD measurement setup