Optical Design for Uncooled 2-D Sensor

M.Murali Mohan*, S.Satyavathi and K.Venkata Ravi
Imaging Infrared Division, Research Centre Imarat, Vignyana Kancha, Hyderabad
*email : mmuralimohan@yahoo.com

ABSTRACT

Sensors based on uncooled focal plane arrays (FPA) have potential defence and civilian applications. The electro optical performance of the uncooled sensor for detection of a target is presented. The specifications for the optics are evolved from this analysis. The detailed design of optics for the uncooled FPA is presented in this paper. From a broader system standpoint, the major issue remaining with staring uncooled LWIR sensor is the need to use fast (~F/1.1) optics. This paper discusses the factors controlling the performance of such FPA.

Keywords: Sensors, uncooled, focal plane arrays, optics design, infrared detection, athermalization

1. INTRODUCTION

Worldwide effort is still continuing to implement very large format arrays at low-cost. Advantages of uncooled bolometers include higher reliability, reduced power consumption, smaller size and reduced weight, as well as multispectral response capability. Just few years ago, achieving noise equivalent temperature difference (NEDT) of 100mK with an uncooled detector was considered a daunting challenge; today, several uncooled sensors that have sensitivity below 20mK have been reported in the literature [1-4]. Uncooled thermal imaging cameras in LWIR region are commercially available in the market for various formats of uncooled FPAs with NETD up to 50mk [5]. Furthermore, pixel sizes have been continuously shrinking while focal plane array (FPA) formats have grown larger. As a result of the rapid progress, the uncooled infrared community places considerable attention on these three attributes – temporal NEDT, pixel size, and array format. Indeed, these parameters have emerged as major criteria by which uncooled systems are compared and judged.

Room temperature IRFPAs have been in development for military applications since the late 1970s. Room temperature LWIR FPAs typically rely upon a thermal detection mode rather than the photovoltaic mode. The key performance-limiting characteristic for thermal detectors is the thermal isolation. Microbolometer use microbridge structures and these structures can achieve thermal isolation that is within a factor of ten of the theoretical radiative limits. It has the potential for significant cost reduction compared to existing IR detector technologies. Uncooled infrared focal planes are fundamentally different from the usual cryogenically cooled, focal plane arrays of photon detectors sensitive to infrared radiation. These two-dimensional (staring) arrays of infrared detectors, which are sensitive to radiation in the 8- to 14-micrometer wavelength region, operate near room temperature and require, at most, thermal stabilization at the operating temperature by means of a single-stage, low-power thermoelectric cooler.

Uncooled focal planes are two-dimensional arrays of infrared detectors that are thermally isolated from their surroundings; the detectors respond to incoming infrared radiation by changing their temperature. The materials used for these detectors are chosen to have some property, such as resistance, pyroelectric polarization, or dielectric constant, which varies sharply with temperature. These detectors, in the form of resistors or capacitors, are read out sequentially. Readout of the signal from each of the thousands of detectors is accomplished through the use of an electronically addressable array of readout cells connected to each individual detector. The detector signals are then multiplexed out of the focal plane for signal processing and display of a visible image of the thermal signature of the scene and targets. Because these thermal detectors are sensitive to the infrared radiation emitted by, a11 objects and living things, no external source of illumination of the target scene is required. This makes them particularly valuable for night operations and also for viewing thermal scenes that are obscured by smoke or dust.

Potential military applications for these uncooled focal planes include weapon sights for individual soldiers, crew-served weapon sights, sensors for missile seekers, and driver's aids for combat support vehicles [6,7]. The relatively low cost for this thermal technology will result in a host of other applications as the costs of the focal plane and complete imaging system decrease. The total life-cycle cost, including not only acquisition cost, but also the cost of training, logistics, maintenance, and consumable supplies (such as batteries), must be evaluated in order to obtain a true measure of the cost of infrared systems.

It is universally recognized that image quality of a thermal sensor is a strong function of spatial uniformity, the metrics commonly used to assess range performance of the sensor. Minimum Resolvable Temperature (MRT), the most prevalent test for characterizing overall imaging performance, is best suited for characterizing static performance [8-10]. In the present paper, a brief study to detect a man at 1km using NVTherm is discussed. Based on these results, the required optics to image the target is designed using Zemax and the details of the one such design are provided in the present paper. The ULIS uncooled sensor, sensitive in LWIR (8-12μm) spectral region has been used for performance evaluation. The average NETD at f/1 is less than 100 mK. The FPA's average responsivity is greater than 4 mV/K at f/1.0.

2. PERFORMANCE STUDIES

To evaluate the performance of the uncooled sensor under study, tentative figures for optical parameters have been calculated. The parameters have been evaluated so as to detect a man at 1km. MRTD curve with these parameters has been obtained using NVTherm, a thermal imaging and system modeling software, which uses Johnson criteria for target detection and recognition. The Johnson criterion relates the number of resolution lines across a target critical dimension to the probability that the operator can detect or recognize the target. According to this criterion, a resolution per minimum target dimension of 1.5 line pairs to detect a man of size 1.5mX0.6m is required. The specified resolution is used along with the MRT curve to determine the maximum range at which detection (or recognition) will occur.

The parameters that are used in the system modeling software are as follows:

Sensor Type	: Uncooled, Staring
FPA size	: 320X240
Spectral band	: 8-12 μm (LWIR spectral region)
Pitch	: 45 μm
Field of view	: 8.2^oX6.2^o
F-number	: 1.1
D*	: $2.7X10^9$ cm-$Hz^{1/2}$/W
Integration Time	: 4 msec
Differential Temperature	: 2^oC
Target	: Man of 1.5mX0.6m size (as per standards)
Required resolvable cycles	: 1.5 for 50% detection (as per standards)

4.0 for 50% recognition (as per standards)

8.0 for 50% identification (as per standards)

To calculate the detection and recognition ranges for a man target (1.5×0.6m) with a temperature difference of 2° using the measured MRT curve: From the graph we can see that for an MRT of 2°C, the spatial frequency that can be resolved is 1.5 cycles/mrad. However, from the Johnson criteria, detection requires 1.5 cycle (3 half cycles), and recognition about 4 cycles. Noting that the target has dimensions of 1.5m, each spatial frequency cycle corresponds to a range of 1.5km (where the target subtends one mrad). The maximum range for detection, recognition and identification are therefore calculated and summarized in Table (1).

Table (1): Detection, Recognition and Identification ranges as a function of their Probability of occurrence:

Probability	Det Range	Rec Range	ID Range
	(km)	(km)	(km)
0.1	1.78	0.79	0.46
0.2	1.43	0.54	0.41
0.3	1.26	0.45	0.36
0.4	1.1	0.38	0.31
0.5	0.96	0.32	0.25
0.6	0.85	0.25	0.2
0.7	0.74	0.19	0.15
0.8	0.63	0.13	0.1
0.9	0.52	0.06	0.05

These results do not include any atmospheric losses, however, even for clear-air with a visibility of greater than 4km, transmittance values between 0.72 and 1.0/km are experienced depending on relative humidity and air temperature. We use 1.0/km for this example. In fog with a visibility of 1km transmittance value between 0.1 and 0.2/km occurs. We use 0.2/km for this example. Atmospheric transmittance values that are considered in the present evaluation are in accordance with the STANAG standards [11]. Because the MRT curve is experimental, the easiest way to solve for these additional losses is graphically. There is a linear relationship between detection range and spatial frequency resolution, so we can re-plot the MRT curve with *Rdet* ,*Rrec* and ,*Rid*. The transmittance loss is then plotted on this graph as a function of range starting with the actual temperature difference of 2K. From the intersection of the loss-lines with the MRT graph it can be seen that the detection range in clear-air reduces to 0.98km. In a similar manner the recognition range and identification ranges can be determined under good weather conditions and in foggy conditions Fig (1). Detection, Recognition and Identification ranges under clear weather and foggy weather conditions are listed in Table (2).

Table (2) : Range performance with respect to weather condition:

Weather condition	Det Range	Rec Range	ID Range
	(km)	(km)	(km)
Clear weather	0.984	0.375	0.19
Foggy weather	0.91	0.36	0.18

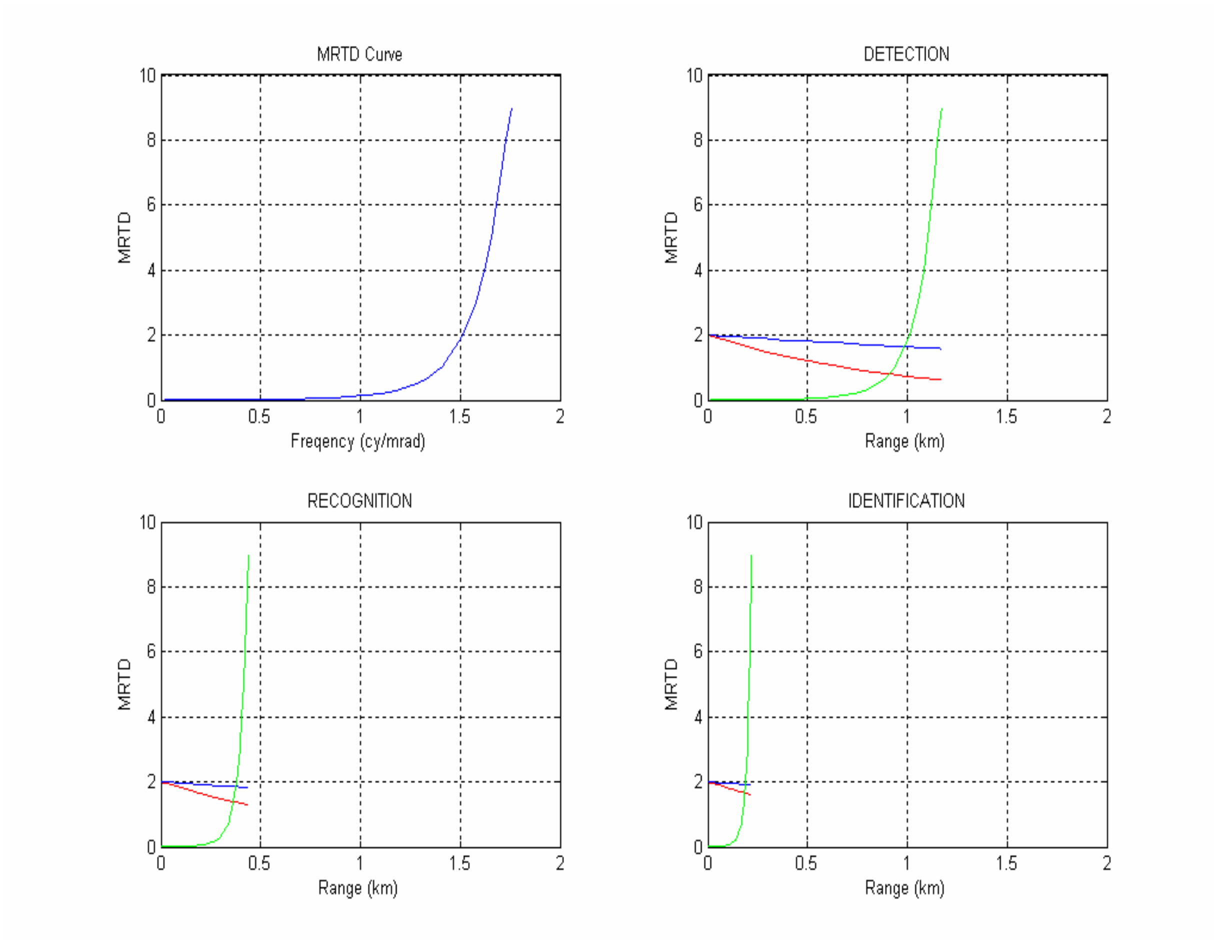

Figure 1: MRT Curves for an Uncooled LWIR Thermal Imaging System

3. DESIGN METHODOLOGY AND LAYOUT

Based on the FPA specifications, and the range performance evaluations, the first order values of the optics are calculated. An uncooled FPA (320 by 240 pixels) is chosen for this design, due to the reasons specified in the above paragraph. The detector has a unit cell of 45X45 μm^2 with image plane dimensions of 14.4 X 10.8 mm and the operating spectral band is 8 to 12 µm.

The field of view requirement is 8° in horizontal and 6° in vertical directions, makes the diagonal field of view requirement is about 10°. This leads to the lens focal length of 100mm. the clear aperture for the system is 90mm and relative aperture is F/1.1.

The designed objective configured with four lens elements to meet the required specifications. The spectral band for design was chosen to match the sensitivity of the detector. Germanium and AMTIR1 were the IR materials used for this design. The optics layout is shown in the Figure 2.

Germanium was selected because its high refractive index and it helps to minimize the aberrations. Its low dispersion in the specified spectral band made it possible to achieve the desired color correction for some extent. The residual color correction is achieved by using AMTIR1 material. In order to make the system to provide an excellent level of performance throughout the entire temperature range, an athermalizaion scheme has been implemented and discussed later in this paper. The dn/dT of AMTIR 1 is about 25% of that of germanium, making it attractive from a thermal defocusing standpoint and AMTIR1 glass gives a better color correction for the wide spectral range [12-14]. The detector window, made of germanium was also included in the design.

The final design for this system provides an excellent level of performance throughout the entire temperature range of -30°C to +60°C.

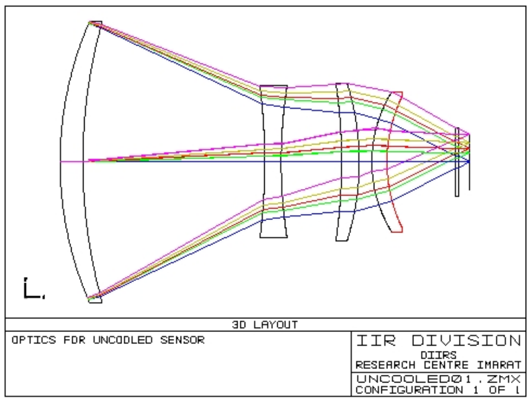

Figure 2

4. OPTICS PERFORMANCE EVALUATION

In this work, the lens design program ZEMAX is used for analyzing and optimizing the system. The designed system is evaluated for an object at infinity at different temperatures for meeting the level of performance throughout the temperature range.

While optimizing, a real ray based merit function is used in the early design phase to reduce the aberrations to low level. Rays are targeted at on-axis, 0.5 field, and 0.75 field and at full field with appropriate weights. The targeted wavelengths are 8, 9, 10, 11, and 12 µm with appropriate weights.

The final optical performance is evaluated in terms of modulation transfer function (MTF), encircled energy, rms spot diameter, and other image quality criteria. The on-axis polychromatic modulation transfer function (MTF) should be near diffraction limited. Figure 3 shows the polychromatic MTF curve of the system with temperature at 20°C and object at infinity. From Figure 3 it is evident that the system is near diffraction limited. Next the spot diagram for all fields and wavelengths should be well with in the pixel size. Figure 4 shows the spot diagrams for different fields and for the targeted wavelengths. It is evident that the image of a point object is well within a pixel for all targeted fields. The other criterion is encircled energy curve, energy percentage plotted as a function of image diameter. As shown in the Figure 5, more than eighty percent of the energy is contained within a diameter of approximately 25 µm, which is a good match to the sensor.

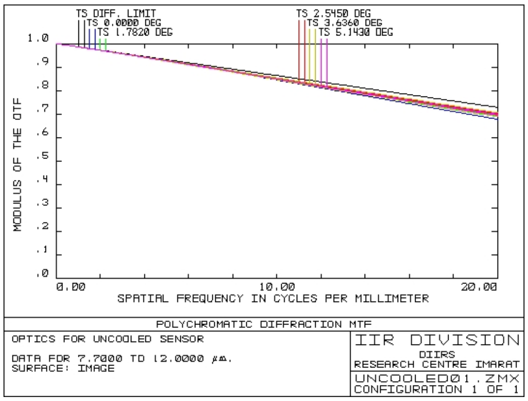

Figure 3

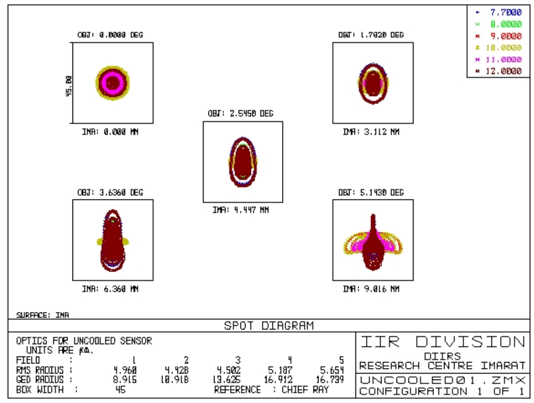

Figure 4

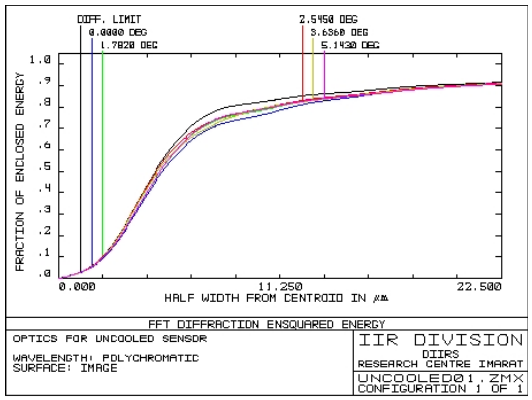

Figure 5

5. ATHERMALIZATION

Focus shift with temperature is a significant problem in the infrared. This is mainly due to the change in refractive index of IR materials. The common IR optical materials have large change in refractive index with temperature. For example, the value of dn/dT for germanium is over 100 times that of common optical glass. This large change in index with temperature makes it difficult to design and fabricate a simple system that works reliably over even a relatively small temperature range [15].

Athermalization is the correction of this effect of focus shift with temperature. There are several mechanical and optical methods, active and passive, available to accomplish athermalization.

Here in this design, in order to compensate for the image shift caused by temperature change, Second element (made of AMTIR1) is moved axially by 0.817 mm for -30°C and 0.623 mm for +60°C either manually or preferably, by electromechanical means. The image quality is maintained same as at the designed temperature of 20 °C. Figure 6, shows the polychromatic modulation transfer function plot for 20 °C. Figure 7, shows the modulation transfer function for -30°C after axially moving the second element by 0.817 mm towards the detector and Figure 8, shows the modulation transfer function for +60°C after axially moving the second element by 0.623 mm away from the detector. The final design for this system provides an excellent level of performance throughout the entire temperature range.

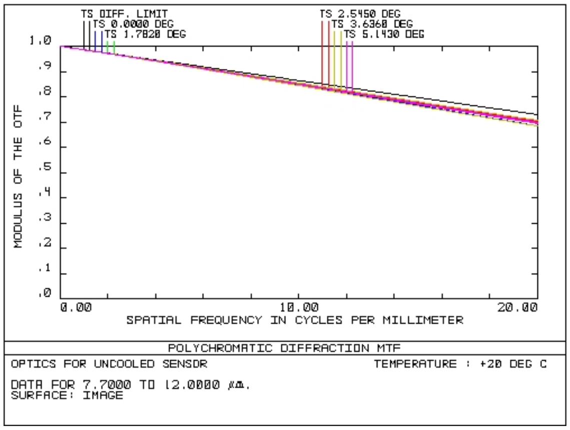

Figure 6

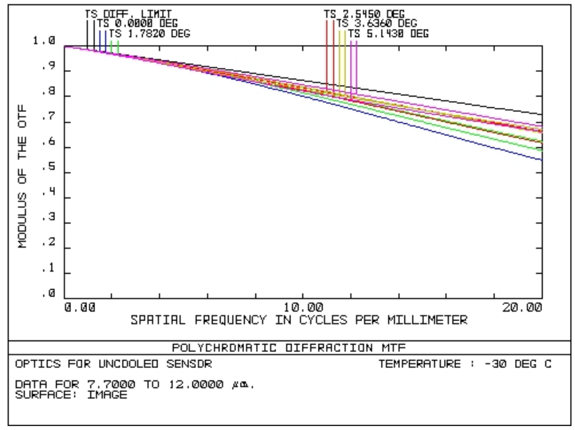

Figure 7

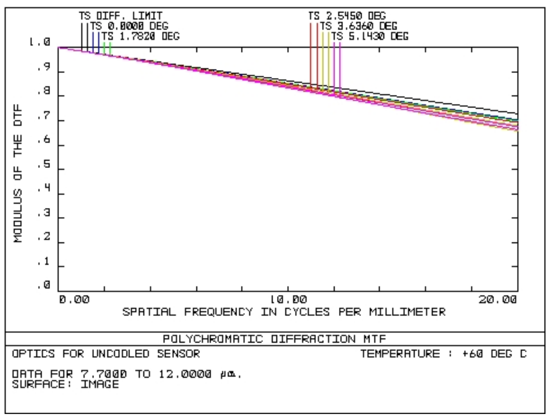

Figure 8

6. CONCLUSIONS

The required specifications to detect a man at about 1 km using 320 X 240 uncooled sensor were generated and based on this the first order values of the optics are calculated. The final optical design along with their performance evaluation curves and polychromatic modulation transfer function plots are presented, showing acceptable performance in all required fields. The final design for this system provides an excellent level of performance throughout the entire temperature range.

REFERENCES

1. Wood, R. A. "Monolithic silicon microbolometer arrays; Uncooled Infrared Imaging Arrays and Systems, Semiconductors and Semimetals", Vol. **47**, P. W. Kruse and D. D. Skatrud, eds.; Academic Press: San Diego, pp. 43–121, (1997).

2. Yoon Soo Park "Current Status of Infrared Detectors and Focal plane arrays." Journal of the Korean Physical Society, Vol. **32**, No. 3, pp. 443-451,(1998).

3. Crastes A., Tissot J.L.et al. "Low cost uncooled IRFPA and molded IR lenses for enhanced driver vision", Proc. SPIE**5252**, (2003).

4. Radford W, Murphy D.M et al. "Microbolometer uncooled infrared camera with 20mk NETD", Proc. SPIE **3379**, 22–35 (1998).

5. "Uncooled thermal imaging systems" , BAE systems, pubs 04-B15 at **http://www.baesystems-iews.com/iris**

6. JANE'S MISSILES AND ROCKETS, 2002, VOLUME/ISSUE: 006/003, SECTION: AIR-TO-SURFACE

7. Joint Direct Attack Munition (JDAM) reports at **http://www.fas.org/man/dod-101/sys/smart/jdam.htm**

8. Kruse, P. W. "Uncooled Thermal Imaging Arrays, Systems and Applications;" SPIE Press: Bellingham, Washington, , p.8 (2001)

9. Murphy, D. et al. "High Sensitivity 25 µm Microbolometer FPAs". Proc. SPIE **4721**, 99–110 (2002).

10. Mottin, E. et al. "Uncooled amorphous silicon technology: high performance achievement and future trends." Proc. SPIE **4721**, 56–63 (2002).

11. STANAG No. 4349, Measurement of the minimum resolvable temperature difference (MRTD) of thermal cameras.

12. SPI Library, http://www.x20.org/library/thermal/infrared.html, 17/02/2000

13. R.E. Fischer and B. Tadic-Galeb, Optical System Design, McGraw Hill

14. William L. Wolfe , "The infrared Handbook", SPIE Optical Engineering Press, 1989

15. Max J. Reidl, "Optical Design Fundamentals for Infrared Systems", SPIE Optical Engineering Press, 1995.