ABSTRACT
Cryogenically cooled IR detectors, which are used in applications such as situational awareness, search & track, missile launch and approach warning, typically use wide angle, single field of view optical systems. We describe a complete IR imaging optical assembly for such applications, which is mounted inside a cold shield and is maintained at a stabilized cryogenic temperature inside the dewar. A typical system houses two to four lenses and a cold filter, and weighs 5 grams or less. Despite this integration and added complexity, the resulting Detector-Dewar-Cooler Assembly (DDCA) has overall dimensions similar to those of equivalent-performing DDCAs without integrated optics. Moreover, Compact designs integrating wide-angle optics and a warm, high-magnification, telescope module for narrow FOV applications are seen as a straightforward extension of our system. We conclude with an in-depth, technical overview describing the design considerations for a typical wide-field imaging system.

Keywords: IR detectors, IR imaging.

1. INTRODUCTION

In the conventional approach to IR imaging, the imaging optics is located outside the detecting DDCA (Detector Dewar Cooler assembly). This is because the imaging optics typically has a relatively high thermal mass. A typical imaging optics arrangement includes a few imaging lenses and/or mirrors, as well as a focus correction system permitting the system to remain in focus at a range of ambient temperatures. Such imaging optics is associated with mechanical assemblies and electronics.

With the conventional approach, an IR imaging system suffers from thermal noise reducing the system performance. On the one hand, uncooled imaging optics, located outside a DDCA, is highly sensitive to temperature changes, because the refractive index of the optics in the IR spectral range is highly dependent on its temperature. A change in the refractive index unavoidably introduces optical aberrations and focus changes, which require focal correction, and which in turn needs the use of focus control and focus adjustment mechanisms. On the other hand, imaging optics (e.g. lenses and mechanical components), as any other object, emit thermal energy in the IR, which presents a noise component in the detected IR signal thus reducing the signal to noise ratio of such systems. Some thermal noise effects associated with temperature changes in the imaging optics might be compensated by utilizing the non-uniformity correction (NUC) procedure for calibration and correction of the readout signal collected from the FPA. However, during the use of the NUC procedure for calibration of the IR imaging system, the system is put in an inoperative state (during which the system is "blind"). It is, therefore, preferable to minimize the number of NUC procedures that are required during the operation of the system.
Introducing cryogenically cooled optics within the dewar, eliminates both the thermal emission from the optics to the detector and the thermal defocusing due to ambient temperature drifts. The cryogenic IR detector with integrated optics provides an IR imaging system configured for relatively far field imaging, for example, imaging with a focus fixed at infinity or at any other fixed distance. Such an imaging system does not need any focus correction and adjustment mechanism. Utilizing cryogenically cooled and temperature stabilized imaging optics practically eliminates the need for focus correction and also reduces significantly the need for periodic non-uniformity corrections (NUC). This increases the system robustness to ambient temperature changes and minimizes the number of NUC procedures that are needed during the operation of the system.

In such a system, two to four imaging lenses are mounted inside the DDCA, with a negligible impact on the size, weight and heat load (thermal mass) of the resulting imaging system. In addition, a cold filter is mounted within the imaging system. Such a cold filter may also be coated on one of the imaging lenses. The resulting integrated optics DDCA is very light. A typical weight increase of such a DDCA is 5 grams or less. This kind of imaging system may be utilized in wide-angle, single field-of-view (FOV) imaging, such as typically used in situational awareness, IR search & track, environmental monitoring, as well as in missile and gun-shot warning systems.

As indicated above, the integrated optics operates at a stabilized low temperature (~80K), thereby eliminating the need to adjust the system focus to compensate for temperature deviations. The cooled optics emits negligible IR radiation thus improving the dynamic range and the noise of the detector. Due to the much smaller size and the smaller number of optical elements, the cost and size of the integrated optics within the dewar can be substantially lower than that of conventional pupil-imaging IR optics of the system level.

2. DESCRIPTION OF A TYPICAL WIDE FOV SYSTEM

Here we describe a typical cryogenically cooled IR optics imaging system. The system described is designed with F/2 optics and a wide field of view (FOV) of 105°x135.5°. Other requirements were to exhibit a relatively uniform illumination on the Focal Plane Array (FPA), and to provide diffraction limited performance with maximum energy (from a point source) focused on a pixel.

Maximum energy on a pixel is a critical parameter for applications such as missile warning systems (MWS).

Figure 1 shows a typical optical layout of such cryogenically cooled IR imaging optics. The imaging system is designed to be at optimum performance when cryogenically cooled. The design includes three cold lenses and a cold filter. The cold filter is mounted between lens #3 and the FPA. Such a design was chosen since the filter has very steep cut-on and cut-off slopes and performs best at small angles of incidence (AOI).

The warm window is the DDCA window and has no optical power. Obviously, the optical system is designed to perform at cryogenic temperatures. During the assembly process, the three lenses and the cold filter are mounted in their housing at room temperature. Prior to assembly inside the DDCA, the optical sub-assembly is fully tested and characterized to ensure good performance after assembly inside the DDCA and cooling to the operating cryogenic temperature.

Figure 1: Optical layout of the wide FOV optics described in the text. All elements besides the window to the left are at cryogenic temperature.
Figure 2 shows the optical system MTF at the cryogenic temperature. It can be seen that the optical system is designed to be a diffraction limited system. This is a mandatory requirement for a good optical system. Figure 3 shows the ensquared energy in a pixel of 20x20µm. It can also be seen that the optical system is designed to have maximum possible energy on a pixel.

![Figure 2: Calculated MTF curves for near diffraction limited design. Each curve represents the expected MTF for a certain view angle.](image)

Another design requirement is to have a relative illumination curve that is as flat as possible. A flat relative illumination curve (uniform illumination at the focal plane) provides better dynamic range of the detector, because the offset correction required for a flat relative illumination curve is lower. Figure 4 shows the relative illumination curve of the optical system. It is clear that at a FOV of 65° the relative illumination drops by only 10%.

![Figure 3: Energy content in a pixel (Ensquared energy). Each curve represents the expected pixel energy for a certain view angle.](image)
In order to verify that the optical assembly is manufacturable at reasonable yield, a Monte Carlo tolerance analysis was carried out. The analysis included all lens manufacturing tolerances, the lens housing machining tolerances and the assembly method tolerances. The tolerance sensitivity analysis revealed which lens and housing dimensions are the most sensitive to tolerance variations. Based on this data, design improvements were carried out. The resulting design showed that the optical assembly will perform well within specification and with a good yield after final assembly. Figure 5 shows a cross section of the optics inside the DDCA.

3. ANTI-REFLECTIVE COATING & STRAY LIGHT ANALYSIS

The design of an optical system for a large field of view requires an anti-reflective coating that performs well at small and large angles of incidence. This is a very important parameter as it affects the total system energy transmission. The anti-reflective coating performance also has a major impact on the prevention of ghost images. High transmissibility and low reflectivity are therefore critical for a good system performance. Since some lens surfaces operate at high angles of incidence and other operate at low angles (see Figure 1), two anti-reflective coatings types were developed. One was optimized for the surfaces with relatively low angles of incidence; a second anti-reflective coating type was optimized for surfaces with higher angles of incidence. This approach provided a better system energy throughput and lower system susceptibility to ghost images. In order to achieve even better optical system energy transmissibility, the warm window was designed so as to be curved with no optical power (see Figure 1). It can clearly be seen that the angle of incidence on the first warm window surface is close to zero.
Two key aspects of stray light analysis and design are next addressed. The first addresses the thermal radiation emitted by the dewar housing internal surfaces. The second addresses the ghost image analysis.

DEWAR HOUSING THERMAL EMISSION

The housing internal surfaces are gold coated in order to reduce thermal radiation to a minimum. However, at relatively high ambient operating temperatures the radiation emitted by the housing internal surfaces is quite significant. This energy is then reflected by the warm window and "focused" by the optical system on the FPA. Figure 6 shows this phenomenon qualitatively. In order to calculate the stray light induced current of the FPA pixels, pixel scanning along the FPA diagonal was performed. Figure 7 shows a schematic view of the FPA and the pixel scanning direction from the FPA center to its diagonal end. The pixel dimension is 20µm x 20µm, the FPA has 384x480 pixels. Figure 8 demonstrates the pixel scanning results along the FPA diagonal. It is clear that the pixel current increases dramatically towards the FPA edge.

Since the DDCA has an axi-symmetric geometry, it is clear that the thermal radiation emitted by the dewar housing will create a "bath tub" energy distribution on the FPA. In order to eliminate this high excess current a radiation shield has been implemented. Figure 9 and Figure 10 show the geometry and location of this radiation shield. The radiation shield completely prevents radiation emitted by the DDCA housing (as per Figures 6 and 8) from reaching the FPA. Therefore, the excess current shown in Figure 8 is completely eliminated. The radiation shield forms a part of the lens housing and is also cooled to cryogenic temperatures.
GHOST ANALYSIS

The second issue that needs to be dealt with is the ghost image analysis. Ghost images may be a significant problem for hot sources in general, and for the sun specifically. The two main parameters affecting ghost images are the anti-reflective coating on the optical elements, and the radii and positions of these elements. As discussed before, a low reflection/high transmission anti-reflective coating provides for better energy transfer as well as for low level ghost images. As mentioned earlier, to achieve the best possible anti-reflective coating performance, two anti-reflective coatings types were developed: one optimized for surfaces with relatively low angles of incidence and the second for surface with higher angles of incidence. In addition, the radii and positions of the optical elements were also optimized for minimum ghost image levels. Ghost image analysis was performed for a wide range of radiation angles. The final design demonstrated that the ghost image levels (for solar radiation) meet the product specification.
Figure 11 shows a simulation of sun radiation at an angle of 50° (reflections off the optical elements are not shown). Figure 12 shows the simulation of sun radiation at an angle of 50° including reflections off the optical elements.

Figure 12: Solar radiation at 50° with internal reflections.

Figure 13: Simulated FPA image of the sun at 50°.

Figure 13 shows the result of the 384x480 FPA image simulation for solar radiation at 50° (logarithmic scale). In order to see the energy level on the FPA accurately, a cross section was performed along the FPA center. Figure 14 shows the curve generated. It can be seen that the peak ghost energies are about 6 orders of magnitude lower than the solar energy.

Figure 14: Cross section (row 192) of the simulated FPA image (Figure 13) of the sun at 50°.

The optical Point Spread Function (PSF) was simulated for various optical designs by Monte-Carlo optics tolerance simulations. The PSF data was calculated for various FOV angles at various assembly tolerances. The PSF data was then convolved with the FPA local response function. The results showed that the system performs well within
specifications. Figure 15 shows the result at FOV of 73° of optics PSF convolved with the FPA local response. Such extreme FOV is beyond the system operating field of view. However, it shows the quality of the results obtained.

4. TESTING BEFORE & AFTER FINAL ASSEMBLY

The lens assembly as shown in Figure 5 is tested prior to assembly inside the DDCA. This testing is done in order to verify that a good quality optical system is assembled in the DDCA. Although the optics design is optimized for cryogenic temperatures, the lens assembly is tested for its expected on-axis performance at room temperature. These tests include spot size, MTF, line of sight (LOS) and back focal length (BFL). The BFL test assists in defining the focus location at cryogenic temperatures. Only lens assemblies that meet the test specification are mounted inside the DDCA. The fully assembled DDCA (with the lens assembly) is then tested for compliance with our specifications. The tests include spot size, MTF/PSF, LOS, field of view (FOV), distortion and relative illumination.

5. SUMMARY

An IR detector with integrated optics provides an IR imaging system configured for relatively wide and far field imaging, for example, imaging with a focus fixed at infinity or at any other fixed distance. Such an imaging system does not need any focus correction or focal length adjustment mechanism. Utilizing cryogenically cooled and stabilized imaging optics practically eliminates the need for focus correction due to ambient temperature drifts and significantly reduces the need for non-uniformity corrections (NUC). Additionally, cooling the imaging optics significantly reduces the thermal radiation emitted from the optics assembly. The resulting integrated optics DDCA is very light, while eliminating the optical module in the system A typical weight increase of such a DDCA is 5 grams or less. Such a cryogenically cooled optical system is temperature stabilized, light weight and very small in size. This kind of imaging system may be utilized in wide-angle, single field-of-view (FOV) imaging, such as typically used in situational awareness, IR search & track, or environmental monitoring, as well as in missile and gun-shot warning systems.
ACKNOWLEDGEMENTS

The authors would like to acknowledge the useful inputs received from Dr. Igor Szafranek, Dr. Itai Shtrichman, Dr. Philip Klipstien, Dr. Tuvy Markovitz and Dr. Lior Shkedy. In addition, we would like to thank Dr. Gilad Francis and Dr. Eyal Berkowicz, David Alfiya, Ilan Vaserman, Alina Koifman and Yonatan Hagbi for their support in this project.

REFERENCES
