Defence Science Journal, Vol. 67, No. 2, March 2017, pp. 193-197, DOI : 10.14429/dsj.67.11180

Parasitic Flux Analysis of Cooled Infrared Detectors for Space Applications

Ankur Jain* and Amiya Biswas
Space Applications Centre, ISRO, Ahmedabad - 380 015, India
**E-mail: ankurjain@sac.isro.gov.in*

ABSTRACT

An infrared imager measures radiations emitted by an object in specified spectral bands to determine change in object's characteristics over a period of time. A typical infrared imager consists of focusing optics and a cryogenically cooled two-dimensional infrared detector array mounted on the cold tip of an active micro-cooler vacuum sealed with an optical window, typically known as integrated detector cooler assembly (IDCA). Detection of feeble radiant flux from the intended target in a narrow spectral band requires a highly sensitive low noise sensor array with high well capacity. However, in practical applications the performance of an infrared imager is limited by the parasitic thermal emissions from optical elements and emissions from IDCA components like vacuum window, Dewar walls which are generally kept at ambient temperature. To optimise the performance of imager it becomes imperative to estimate these parasitic fluxes and take corrective actions to minimise their effects. This paper explains an analytical model developed to estimate parasitic fluxes generated from different components of a long wave infrared imager. Validation of the developed model was carried out by simulations in ZEMAX optical design software using ray trace method after analytical computations in MATLAB.

Keywords: Parasitic flux; Long wave infrared; Integrated detector; Imager; Stray light; Ray trace

NOMENCLATURE

ϵ_λ	Spectral emissivity
λ	Wavelength (μm)
T	Temperature (K)
h	Planck's constant (W s^2)
c	Velocity of light in vacuum (cm/s)
k	Boltzmann's constant (W s/K)
d	Cold shield aperture diameter (mm)
h	Cold shield height (mm)
r	Cold shield lateral height (mm)
$f/no.$	Cold shield f-number
A_{pix}	Pixel area (cm^2)

1. INTRODUCTION

To achieve background limited performance infrared (IR) detectors require cooling for their operation. The amount of cooling necessary for operation depends on detector material used, operating spectral band and size of detector array. Highly reliable passive radiation cooling is generally preferred for cooling IR detectors in space based imaging applications. First generation IR imaging systems like Indian Space Research Organisation (ISRO)'s very high resolution radiometer (VHRR) used single element detectors operating in whiskbroom scanning mode. Due to their low thermal load these single element detectors can be easily passively cooled in space and can be easily characterised under lab conditions using vacuum sealed Dewar flasks. However, to image wider areas with improved resolution and radiometric performance, second generation IR imagers use area array detectors where a backside illuminated two-dimensional photodiode array is hybridised to a high performance read out integrated circuit (ROIC), known as focal plane array (FPA)[1]. Due to high power dissipating ROIC and large number of electrical interconnections, it is impractical to cool such FPAs operating in long wave infrared (LWIR) band with passive means. To characterise such large array LWIR FPAs and cool them to desired cryogenic temperature, an integrated detector cooler assembly (IDCA) is essential whereby the FPA sits over the cold tip of an active micro-cooler and the detector cooler assembly is vacuum sealed in a thermally isolated Dewar.

However, in practical applications it was observed that the performance of an IDCA based LWIR imager was limited by thermal emissions from focusing optics and various IDCA components which were generally kept at ambient temperature. Parasitic flux from these components falls directly in detector field of view, impinges on the detector retina and generates a large background pedestal. Actual signal charge generated due to radiation from the target under study rides over this background pedestal and it is difficult to segregate the target signal from the background signal. To optimise the performance of imager it becomes imperative to estimate these parasitic fluxes and take corrective actions to minimise their effects. This paper explains an analytical model developed to estimate parasitic fluxes generated from different components of a LWIR imager. Validation of the developed model was carried out by simulations in ZEMAX optical design software using ray trace method after analytical computations in MATLAB.

Received : 28 April 2016, Revised : 22 August 2016
Accepted : 21 December 2016, Online published : 11 March 2017

2. INFRARED IMAGER FLUX MODEL

An infrared imager consists of focusing optics and infrared detector. Focusing optics is a multi element lens assembly which collects and focuses the incident radiation from scene on the detector. Design and selection of focusing optics is generally based on detector parameters like detector format and pixel size, resolution required and imaging platform height from the target. Infrared detector is an IDCA which consists of a focal plane array mounted on the cold finger of an active micro-cooler. Cross sectional view of an IDCA is shown in Fig. 1. It consists of following components:

2.1 Focal Plane Array

The FPA consists of 2-D array of photodiodes hybridised to a Si ROIC. Mercury Cadmium Telluride (HgCdTe) is the pick of materials for infrared detectors due to its excellent band tailorable characteristics. The photodiodes are electrically coupled to ROIC and the charge produced during the integration time is stored in ROIC capacitance. At the end of integration time charge is transferred to a charge voltage conversion amplifier and the output will be an equivalent voltage corresponding to absorbed photons and quantum efficiency of the detector. FPA is attached to the cold finger of the cryo-cooler.

2.2 Optical Filter

A band-limiting optical filter is placed over the FPA to obtain detector response in the desired spectral band. A spectrometer uses an order sorting filter for suppressing signal from all orders other than the desired narrow band whereas a multi-spectral imager uses a strip filter to obtain response in multiple wide spectral bands. This filter is generally attached to cooler cold finger inside the Dewar to minimise parasitic emissions.

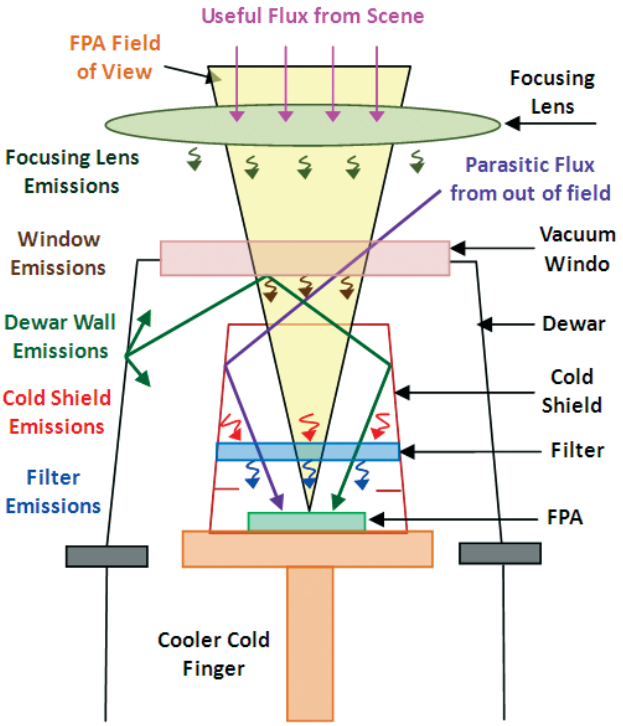

Figure 1. Infrared imager flux model.

2.3 Cold Shield

The cold shield limits the field of view (FOV) of the system and hence shields the detector from unwanted out of field radiations. For quick cool down it is made up of ultra-thin structure and baffles are provided in the cold shield to suppress radiation reflected from mechanical surfaces. The inner surface of the cold shield is 90 per cent absorbing whereas the outer surface is reflecting in nature.

2.4 Dewar and Vacuum Control

The detector works in a temperature range of 50 K -70 K. To ensure this FPA temperature the detector chip is encapsulated in a vacuum sealed Dewar, thereby avoiding any gas or water vapour to condense onto the FPA and the infrared optical filters, which would change its thermal performance and eventually blind the detector. Vacuum inside the Dewar has to be ensured for the specified detector life time, but it is continuously degraded by the outgassing from the component materials. Getter devices are therefore implemented in the Dewar to ensure this vacuum. They have to be activated during the detector life for them to remain active.

2.5 Vacuum Window

A suitable optical window is fixed at the top of the Dewar housing to protect the sensor array and maintain vacuum/inert gas atmosphere inside. This window is anti reflection coated and has excellent transmission in desired spectral band.

2.6 Cooler

Due to high thermally generated dark current, Infrared detectors require cryogenic cooling for their operation. Both passive and active approaches are available to cool such detectors, however, the choice of cooler depends on total thermal mass to be cooled. Large array detectors coupled with power dissipating ROICs increases thermal load which in turn increases detector cooling requirements. Such cooling requirements cannot be fulfilled with a passive cooler and it requires development of active cooling technology whereby mechanical coolers are used to cool IRFPAs. Active coolers use closed thermodynamic cycles to achieve lower cold-end temperatures at the cost of electrical input power. The detector focal plane is attached to the cold side of the cooler in a way that allows efficient conductive heat exchange.

Due to temperatures above absolute zero (0 K) all the components of an IR imager emit thermal radiations which after multiple reflections from mechanical surfaces, Dewar walls and window fall in detector field of view and generate unwanted background signals[2]. Flux model of a typical infrared imager is as shown in Fig. 1.

Flux incoming on detector retina have different origins:

(i) Useful flux coming from the scene
(ii) Parasitic flux due to imager components self-emissions
(iii) Parasitic flux from out of field of view.

Flux from the scene is the actual intended flux due to scene temperature reaching the sensor array through the optical system. Parasitic flux from the imager components is the unwanted flux reaching the sensor due to thermal emissions from warm parts of the focusing optics and Dewar. This flux is reflected back into the FPA by multiple reflections within the Dewar. This flux is dependent upon temperature and can be estimated by environmental tests at different temperatures. Parasitic flux from out of aperture is the unwanted flux reaching the sensor due to thermal emissions from objects in detectors out of field region and falling on detector after multiple reflections from internal parts of the Dewar. This flux depends on system configuration.

Parasitic flux from Dewar consists of following major components:

(i) Emissions from vacuum window which is at ambient temperature, falling directly in detector's field of view
(ii) Emissions from Dewar walls operating at ambient temperature, falling on detector after multiple reflections from window, cold shield and filter
(iii) Emissions from cold shield and filter falling directly in detector's field of view.

3. PARASITIC FLUX ANALYTICAL ESTIMATION

As per Planck's Radiation Law[4], spectral radiant emittance of an emitting surface is the function of its temperature, wavelength and spectral emissivity. It is given by Eqn. (1),

$$W_{\lambda,T} = \in_\lambda \times \frac{2\pi hc^2}{\lambda^5} \times \frac{1}{\exp\left(hc/\lambda kT\right)-1}\left[W/cm^2.\mu m\right] \qquad (1)$$

Integrating Eqn. (1) over the wavelength limits gives radiant emittance of the surface into a hemisphere. Thus, the radiant emittance per unit solid angle is given by Eqn. (2),

$$W_T = \int_{\lambda_1}^{\lambda_2} \frac{W_{\lambda,T}}{\pi} d\lambda \left[W/cm^2.sr\right] \qquad (2)$$

The total amount of flux incident on a single pixel is limited by its field of view which is defined by the solid angle subtended by cold shield aperture on the pixel.

Cold shield field of view (FOV), as shown in Fig. 2, is a function of its aperture area and lateral height.

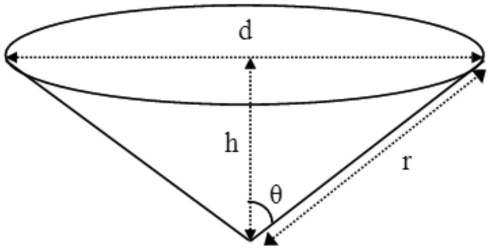

Figure 2. Cold shield FOV.

Cold shield field of view is computed as given in Eqn. (3) and Eqn. (4).

$$Cold\ Shield\ FOV = \frac{Aperture\ Area}{Lateral\ Height} = \frac{\pi\left(d/2\right)^2}{r^2}\left[sr\right] \qquad (3)$$

$$Cold\ Shield\ FOV = \frac{\pi}{4}\left(\frac{d}{r}\right)^2 = \frac{\pi}{4\times\left(f/no.\right)^2}\left[sr\right] \qquad (4)$$

Thus the total flux falling on a detector pixel from an emitting surface is obtained by substituting Eqn. (4) in Eqn. (2).

Flux on detector pixel due to emitting surface,

$$W_T = \in_\lambda \frac{A_{pix}}{4\times\left(f/no.\right)^2}\int_{\lambda_1}^{\lambda_2}\frac{2hc^2}{\lambda^5}\frac{1}{\exp\left(hc/\lambda kT\right)-1}d\lambda\left[W\right] \qquad (5)$$

Using Eqn. (5) parasitic flux reaching the detector due to thermal emissions from different components of the imager like focusing optics, IDCA vacuum window, Dewar walls, cold shield and filter etc. can be estimated. Since the emissions from Dewar walls do not fall directly into detector's field of view, only the flux reaching after reflection from vacuum window shall be considered and hence window reflectivity shall be taken into account while calculating the flux from Dewar walls emission.

Equation (5) was implemented in MATLAB to calculate the flux emitted by various components of a LWIR imager for determining the irradiance per pixel at the detector at different temperatures. Parameters considered for estimation of dark signal are given in[2] Table 1.

Table 1. Parameters for parasitic flux calculation

Parameter	Value
Spectral band (μm)	7.7 - 11
Detector operating temperature (K)	70
Focusing optics, IDCA window and Dewar walls temperature (K)	253 - 303
Focusing optics, IDCA window and filter emissivity	0.05
Dewar walls and cold shield emissivity	0.9
Window reflectivity	0.02
Cold shield f-number	1.93
Pixel area (cm^2)	9E-6

4. MODEL VALIDATION

Validation of developed analytical model, Eqn. (5), for estimation of parasitic flux reaching the focal plane of an infrared imager is carried out by simulations in ZEMAX optical design software using ray trace method.

ZEMAX operates in two different modes[5], sequential and non-sequential modes. Most imaging systems are well described by optical surfaces which are sequential, which means that rays always trace from the object surface to surface 1, then 2, then 3, etc. in a strict sequence. Each ray 'hits' each surface once and only once in this predetermined sequence. In non-sequential mode the rays trace in the actual physical order they hit various objects or surfaces, and not necessarily in the order the objects are listed in the software user interface. Rays in a non-sequential trace may hit the same object repeatedly, and may entirely miss other objects. Generally, the order in which objects are hit by rays depends upon the object geometry and the angle and position of the input ray. Since in parasitic flux analysis, the rays can hit any surface which it encounters, unlike sequential mode operation, therefore the whole analysis was done in non-sequential mode of ZEMAX[6].

For simulations, a model of complete imager with focusing lens and IDCA was created in ZEMAX. A multi element focusing lens was designed using available detector parameters, given in Table 2.

Table 2. Detector parameters for focusing lens design

Parameter	Value
Spectral band (μm)	7.7 - 11
Detector format	320 x 256
Pixel size (μm)	30
Field (deg)	± 4.7
Spatial frequency (lines/mm)	17

Among IR glass materials Germanium, Zinc Selenide and Zinc Sulphide are the best suited glasses for space applications due to their thermal and mechanical properties[7]. The initial lens design was accomplished using four lenses two of Germanium and two of Zinc Selenide. The design was further optimised for minimum aberrations. To minimise parasitic fluxes and to avoid signal vignetting, lens exit pupil was matched to IDCA cold stop. The optimised lens design with pupil matching is as shown in Fig. 3. MTF at Nyquist frequency of 17 lines/mm of the designed lens is greater than 0.6 across the full field.

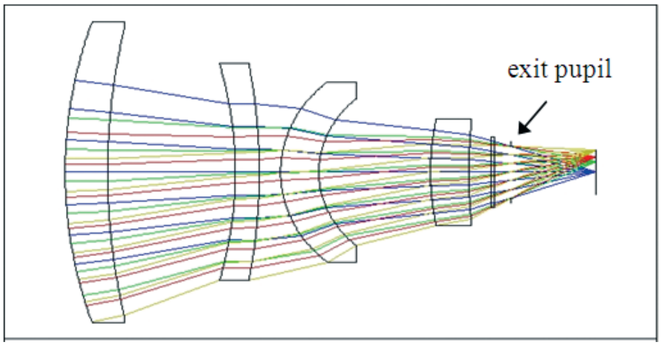

Figure 3. Focusing lens design in ZEMAX.

3D model of the full LWIR imager designed in ZEMAX is shown in Fig. 4. For parasitic flux simulations in ZEMAX, each component was modeled as a lambertian source and the flux reaching the detector plane due to individual components is measured using ray trace method at specified temperature range from 253 K to 303 K. 2D view of parasitic flux simulations in ZEMAX is as shown in Fig. 5 and simulated flux due to individual components is as shown in Fig. 6.

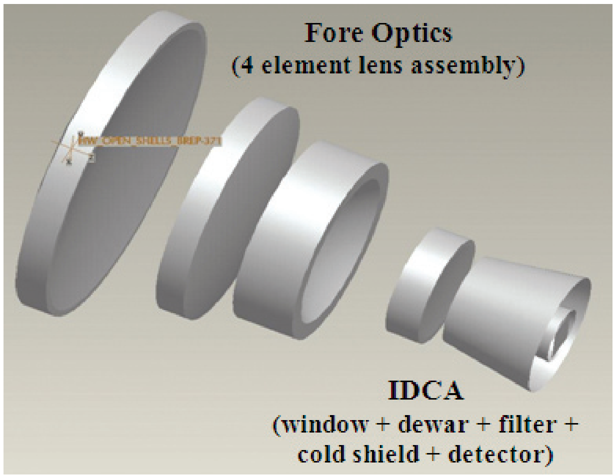

Figure 4. LWIR imager designed in ZEMAX (3D model).

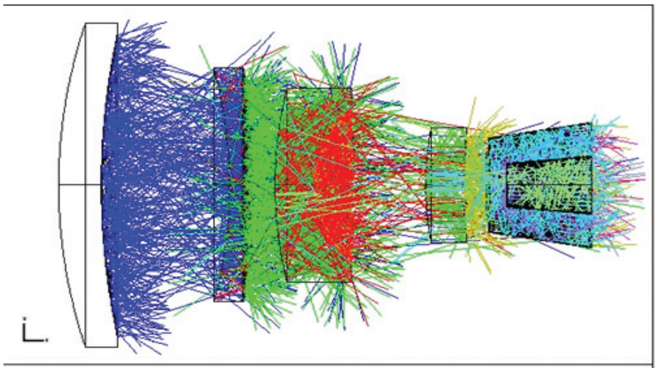

Figure 5. Parasitic flux simulations in ZEMAX (2D view).

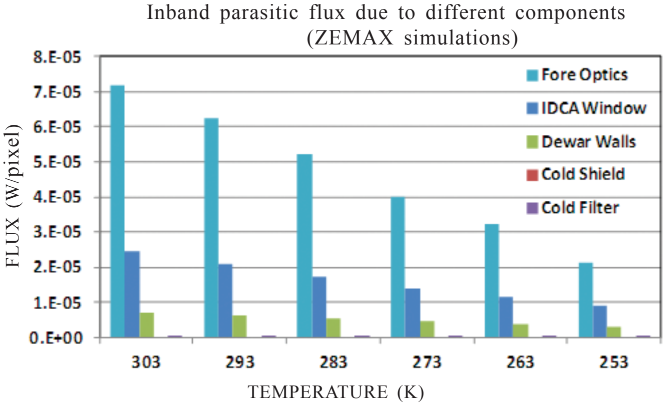

Figure 6. Flux simulations in ZEMAX

The total parasitic flux reaching the detector focal plane is computed by adding the contributions due to individual components. A comparison of total flux computed by both methods, analytical and simulations, is carried out and shown in Fig. 7. It is observed that ZEMAX simulation results are closely matching (within 5 per cent) with MATLAB calculations. Hence, the derived analytical model for parasitic flux estimation of an infrared imager in Eqn. (5) is validated.

Simulations and computed results show that thermal emissions from focusing optics and IDCA window, both operating at ambient temperature, are the major parasitic flux contributors. Further, the flux contribution from cold shield and filter is negligible because both of them are attached to cold

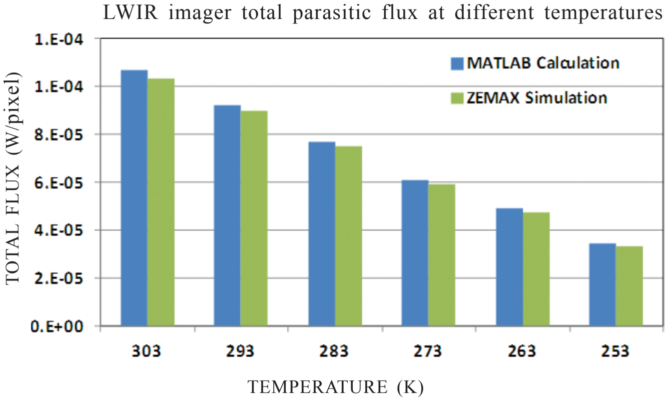

Figure 7. Comparison of total parasitic flux by MATLAB and ZEMAX simulations.

finger and cooled to detector operating temperature. The total parasitic flux reaching the detector reduces drastically (~65 per cent) when the temperature is reduced from 303 K - 253 K.

5. CONCLUSIONS

An infrared imager is very susceptible to thermal emissions from its components. Background signal generated due to parasitic fluxes not only reduces detector dynamic range but also reduces its sensitivity to small signals from low temperature targets. In this paper, a mathematical model is arrived at to compute parasitic flux generated by different components of an LWIR imager. Calculation of incident parasitic flux due to imager components consisting of optics and IDCA components at different temperatures is carried out. Validation of the developed model is carried out by simulating the imager in ZEMAX optical design software. Simulation results are found to be closely matching with calculated results. Further validation of the developed model can be carried out through experimentation. Based on results obtained, it is concluded that in order to improve the sensitivity of a space borne infrared imager, thermal emissions of surfaces falling directly in detector field of view shall be minimised by reducing the surface temperature. Other methods of reducing the thermal emissions like use of low emissivity tapes, thermal paints etc. shall also be explored.

REFERENCES

1. Oster, D.; Singer, M.; Koifman, A. & Markovitz, T. Infra-red imager. U.S. Provisional Patent Application No. 61/249,320.
2. LWIR IDCA, Technical datasheet.
3. Jain, Ankur & Banerjee, Arup *et. al.* Estimation and measurement of background signal of an infrared detector dewar cooler assembly for space applications. *In* Proceedings of 22nd National and 11th International ISHMT-ASME Heat and Mass Transfer Conference December 28-31, 2013.
4. Hudson, J.R. & Richard, D. Infrared system engineering, Wiley-Interscience, 1969. Chap. 2, pp. 35.
5. ZEMAX optical design software, user manual, May 2012.
6. Dan, Hill. How to perform stray light analysis in non-sequential ZEMAX, 2005, ZEMAX Knowledge Base.
7. Savage, J.A.; Webber, P.J. & Pitt, A.N. Infrared optical glasses for applications in 8-12 μm thermal imaging systems. 1997, **16**(11), 2938.
   doi: 10.1364/ao.16.002938

ACKNOWLEDGMENTS

Authors would like to thank Ms Neethu Sasikumar, MTech student from IIST, Thiruvananthapuram for her contributions in the work presented. Authors would also like to record their gratitude to Mr Tapan Misra, Director SAC, Dr K.S. Dasgupta Director, IIST, Mr R.M. Parmar, Deputy Director SEDA, Mr S.S. Sarkar, Group Director EOSG and Mr Arup Banerjee, Head SFSD for their guidance and encouragement towards this work. Help rendered by all the colleagues is acknowledged with thanks.

CONTRIBUTORS

Mr Ankur Jain joined Space Applications Centre, ISRO in 2006. Currently he is working on design and development of Infrared detectors for space applications. He developed the parasitic flux model of infrared imager and carried out the required simulations for model validation.

Dr Amiya Biswas received his MSc optics and optoelectronics from University of Calcutta in 1995 and PhD in optical engineering from Loughborough University in 2007. He joined Indian Space Research Organisation as a Scientist in 1997. His research interests include optical design, analysis and simulations. The optical design of the imager and validation of the analytical model presented in this paper was carried out under his guidance.