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Optical Design of Thermal Imaging Camera in MWIR Band (3-5µm)

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Abstract:
Thermal imagers are used in many areas of the science and technology, astrophysicist, weather forecasting, military science and other. The aim of this study is to create an optical design of a thermal imager working on the platforms which are lighter (zeppelin, balloon, etc.) or heavier (unmanned aerial vehicles, etc.) than air in the high altitude. An infrared optical system has been also designed for work in the mid-wavelength infrared region (MWIR) 3-4 µm. The relevant design issue is not affected by the rate of change of temperature in terms of various season and atmosphere conditions in operation. The design of the optical camera has selected Ritchey-Cassegrain type and performed by using ZEMAX optical design software. The optical performance analysis of the optical design is also discussed. It was shown that the system should be applied in many civilian and military applications.
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1. Introduction

Remote sensing is one of the main fields of application of space technology, both for terrestrial surveys and for the study of other bodies of the solar system. In the latter case, even if the importance of in-situ measurements is rapidly growing with the development of new technologies, remote-sensing data will always be needed for a thorough under-standing of the scientific issues at wider scales [1-3]. In this respect, the interest in the infrared region of the electromagnetic spectrum has always been very high, due to the wealth of information that an accurate analysis of such spectral region could provide on the general composition of the observed object [1].

High-altitude platforms (HAP) are aircraft positioned above 20 km altitude, in the stratosphere, in order to compose a telecommunications network or perform remote sensing, for civilian or military applications [2]. These aircraft may be airplanes, airships or balloons, manned or unmanned. The stratosphere is the layer of the atmosphere where the temperature starts to increase with altitude. Imme-diately after the tropopause, which has a constant temperature of about -60°C, the stratosphere starts at an altitude of 7 km at the poles and 18 km at the Equator, extending to around 50 km [2].

Optical telescopes can be studied in three main titles, according to the optical elements that they use; refracting, reflecting and catadioptric telescopes. Basically, refractor (also called dioptric) telescopes use a large lens (primary or objective) to bend the light towards a point of focus, and a second lens (secondary or eyepiece) to magnify the image [3]. The reflecting (also called catoptric) telescopes use a different combination of flat and curved mirrors instead of lenses. A large curved primary mirror reflects the light coming from the object to a point of focus. At this point of focus, there is another mirror called secondary which bends the light into the eyepiece, where it is magnified. In order to form an image in the catadioptric type telescopes, lenses and mirrors are combined to use both refraction and the reflection at the same time. This type is generally used for aberration correction of other systems [4,5].

Cassegrain type telescope was produced by the Frenchman Cassegrain in 1672 [3]. Little is known about Cassegrain, even his true name is uncertain; in many books his name is given to be Guillaume,

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Laurent, Nicolas, and Jaques [3]. Cassegrain telescope is a type of reflecting telescope, with a convex hyperbolic secondary mirror placed through the center axis of a centrally perforated concave parabolic primary mirror. This type is known as the Classical Cassegrain, but there are various designs exist which are characterized by the curves used on the mirrors. Classical Cassegrain is modified in the Ritchey-Chretien design, by using hyperbolic primary and secondary to induce some aberrations, which is founded by George Willis Ritchey and Henri Chretien in 1910 [4]. Most of the research-grade astronomical large telescopes are of Ritchey-Chretien type.

The objective of this study was to design a camera system to be used in a High-Altitude Platforms (HAP) which will be launched into at an altitude of 20 km and take images in the MWIR range from the earth surface. In order to find the optimum camera system design, atmospheric conditions at a height of 20 km have been investigated. The temperature, radiation and light attenuation limitations at given altitude, appropriate optical materials have been also determined. However, both the mechanical design of this camera and the radiation effects on these optical materials in this system are not the subject of this study. Therefore, the type of the camera has been chosen as a Ritchey-Cassegrain type of objective, which provides the less optical aberration. The design of optical camera which is a kind of Ritchey-Cassegrain is performed using ZEMAX optical design software. The optical performance analysis of the design is also discussed.

2. Design and Experimental Work

2.1. Design Criterions:

At the very beginning of a system design, the designer must clarify the system requirements from optical aspects to design a good optical system. Optically the design limits include aberrations, modulation transfer function (MTF) at Nyquist frequency should be above 0.5 and close to diffraction limit (free aberration), spot diagrams should be less than single pixel of the detector (less than 35μm) as much as possible, and many other physical parameters [5]. The chosen optical system specifications are listed in Table 1.

Table 1. Optical system specifications.

Pixel Size, w	35 μm
Camera Resolution	320 × 240 pixels
Wavelength	3-5 μm
Altitude, H	20 km
Entrance Pupil Diameter, D	70 mm
Focal Length, f	300 mm
Temperature Range	(-35 ˚C) - (+50˚C)

2.2. Basic Technical Design Parameters:

In this study, 320×240 pixels with 35μm×35μm pixel pitch was determined to be suitable. The camera was designed to take images from 20 km distance from the ground 2.3 m resolution. The system is designed as an optically (passive) athermal optical system was prepared and working in the mid-wave was designed. The basic parameters of the optical system are also shown in Table 1.

2.3. Design Procedure:

The previous basic design parameters meet the target requirements of optical design if at least the design criterions (limits of design) that identified previously are achieved. In the design and optimization phases of the optical system, there are many tasks that the designer must perform and consider [6].

There is a simple relationship between the dimensions of the detector, the focal length and the orbital altitude define the imaging system's resolution and field of view (FOV). The FOV of an infrared imaging system is one of the most important design para-meters. It is the parameter that describes the angular space in which the system accepts light [7]. Parameters about the field of view were summarized in Table 2.

The FOV can be calculated using trigonometry as mentioned in ref [8],

$$\text{Field of View, FOV} = 2 \cdot \tan^{-1}\left(\frac{D}{2 \cdot f}\right) \qquad (1)$$

Table 2. Final design specifications.

Resolution Cell	2.33 m
IFOV	0.0066°
F-number, f/#	4.28

All calculations in this study were done with ZEMAX software. ZEMAX is a program which can model, analyze, and assist in the design of optical systems. This program uses ray tracing to model refractive, reflective and diffractive optics in a sequential and non-sequential mode [9]. To get the final

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design there are many critical and necessary should be done carefully.

The basic parameters of the system like system aperture, lens unit, FOV, operating wavelength, the information about lenses itself like (surface type, surfaces radius of curvatures, elements thickness, material, etc.) was entered to the software. And that start point was optimized. To achieve the final design, in this procedure, temperature induced changes to n and the system dimensions are placed into a solution matrix, by treating the system as a multiple configuration types and solving for suitable weighted minimum residual "merit function".

Repeated previous steps through ZEMAX optical design program the IR optical system was designed after many optimization cycles. The relevant optical configuration is given in Figure 1.

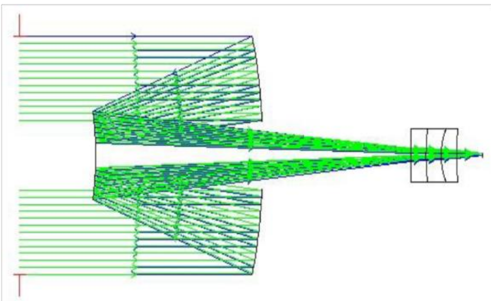

Figure 1. 2D layout of the configuration.

3. Results and Discussion

The results of the optical computations need to be interpreted. There are many ways to measure and evaluate image quality. Simulations include aberrations, modulation transfer function (MTF), spot diagrams and many other physical parameters.

Spot diagram is very useful diagnostic (analysis) tool in ZEMAX. For good imaging, spot RMS radius should be smaller than the airy radius, because 68% of the energy is contained in the airy radius. RMS radius is taken into account while making the optimization [10]. Figure 2 shows spot diagrams for different field of view and temperature.

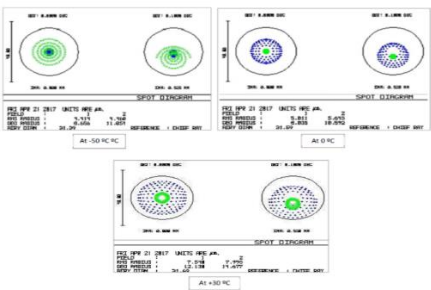

Figure 2. Spot diagrams for different field of view and temperature.

If all three diagrams in Figure 2 are examined, it can be viewed that the airy diameter is approximately 31.4 µm for the working f/number of 4.28. This is a desirable value considering the detector pixel size of 35 µm. It can be said that the design shows diffraction limited performance through -35 to 50ºC.

MTF is one of the most useful means for characterizing the optical performance of an imaging system [6]. The modulation transfer function data tell us how the modulation of the object is transferred from the object to the image as a function of the many varied spatial frequencies in the scene [6].

The MTF curves of the system plotted in Figure 3. Where, a Nyquistic frequency value's contrast ratio is about 0.6 and very close to the diffraction limit, which gives the good image in the temperature range from -35 to +50°C. The system reaches near diffraction limited performance.

As a result of this analysis and simulations, the image quality of this system was defined. It is concluded that the system is very appropriate for 20 km altitude.

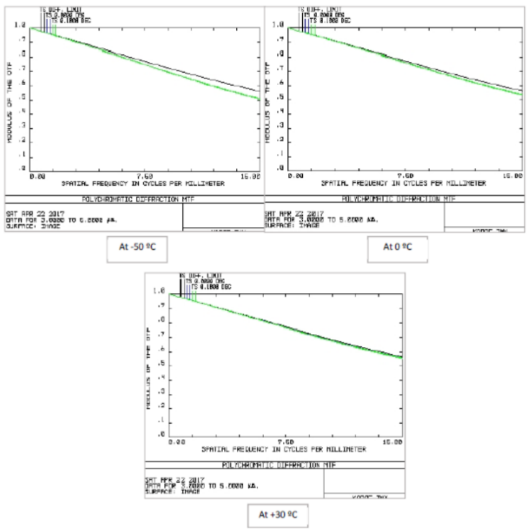

Figure 3. MTF curve diagrams for different field of view and temperature.

4. Conclusion

It was shown theoretically that the optical performance of the designed an optically (passive) athermal optical imaging system is sufficient to operate in the MWIR band. The analysis of the design is in the diffraction limits at the defined temperature range. All analysis shows that the optical system has good athermal performances. As a result, the infrared imager system, which is designed and analyzed that can be easily used in

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various civil and military applications such as marine traffic, ship wastes, and other glare-lit objects.

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