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Satellite imaging payload design optimization

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ABSTRACT

This paper focuses upon the development of an efficient method for design optimization of an imaging payload of a remote sensing satellite. In this paper, the design of the imaging payload is defined as a multi-objective optimization problem. In the formulation of the problem, the aperture diameter and quality factor are used as a design variable and constraints, respectively, with maximization of signal to noise ratio (*SNR*) and minimization of the spherical aberration values. This paper presents a new method of involving the above two contradictorily objective functions. The approach adapted in this paper achieves the prescribed degree of quality of images and design constraints, whilst minimizing the weight of the payload in comparison with the conventional experimental approaches. The optimization algorithm used to solved the problem based on the genetic algorithms. Results obtained in this study, show that the method introduced in this paper provides an effective way of improving imaging payload in the design of a space system.

1. Introduction

The basic function of an electro-optical imaging system are the optical collection, electro-optical conversion, electronic processing and multiplexing, digital data transmission, image reconstruction, and display of object plane image information created by radiation and reflected electromagnetic energy. The major functions associated with a typical electro-optical image chain are shown in Fig. 1. Radiation from a target image propagates through the atmosphere, and is mapped onto an image plane through collection optics, then sampled, and converted into electronic signals for transmission, data processing and display. The actual configuration and implementation of a given image chain strongly depends on the top-level requirements and resulting flow-down system specifications.

Signal represents the desired physical measurement with the effectiveness of the measurement given by the *SNR* as expressed below:

$$SNR = \frac{S}{N_{Total}} \tag{1}$$

where S is the mean signal value and N_{Total} is the signal standard deviation due to system noise. The composition of system noise and the signal value and how these are calculated are addressed in Section 2. For high accuracy applications of remote sensing satellite, one of the most important requirements is the good image quality of the imaging payload. In the conventional approach to design of a satellite imaging payload, initially, quality factor is selected by a designer using design experiences (see Refs. [5,8,9,11]). This initial solution is then iteratively improved by the designer. This method, however, does not guarantee to achieve the best compromise and may even lead to non-optimal design.

To overcome the above mentioned difficulties associated with the conventional approach, this paper presents an efficient approach for system design optimization of a high resolution imaging payload of a satellite. The quality of satellite images can be expressed by several technical terms such as ground sampling distance (*GSD*), aberration types and *SNR*. In addition, specification of imaging payloads usually involve conflicting objectives related to spherical aberration and *SNR* that can be solved using multi-objective optimization techniques.

The adopted methodology is based on an optimization framework. The reminder of this paper describes the proposed methodology and its implementation to the problem.

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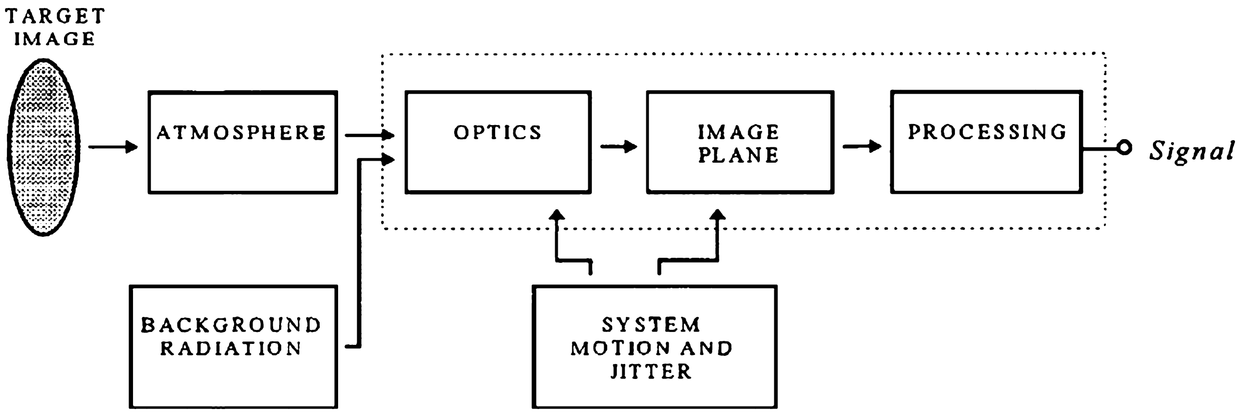

Fig. 1. Electro-optical imaging system [4].

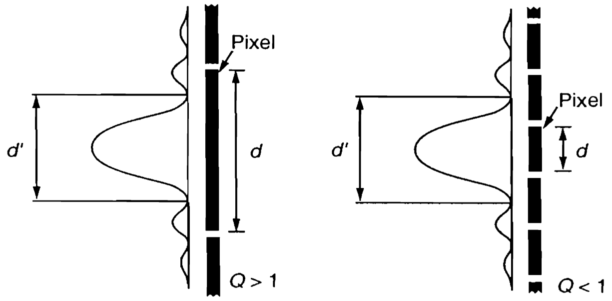

Fig. 2. Effect of varying quality factor [15].

2. Design method of the satellite imaging payload

2.1. Determination of aperture diameter

The aperture is the hole in a camera that allows light to hit film. The amount of light that gets through the aperture determines what a picture will look like. The larger the aperture, the more light can be collected and the high quality images can be obtained. Aperture diameter is determined by [15]:

$$D = 2.44 \times \lambda \times \frac{f}{d} \times Q \tag{2}$$

where Q is quality factor, λ is average wavelength of the radiation, f is focal length and d is pixel size of detector. Quality factor is ratio of pixel size d to diameter of diffraction disk d', which is defined as $Q = d/d'$. Q typically is varied between 0.5 and 2. For $Q < 1$, the resolution is limited by diffraction in the optics and for $Q > 1$, the resolution is limited by pixel size. According to Ref. [15], $Q = 1.1$ is recommended as a design starting point (see Fig. 2).

2.2. Spherical aberration

Because of its compactness, the Cassegrain configuration is frequently used for visible applications. Therefore, it is worthwhile to investigate what two spherical mirrors can do for this configuration. Fig. 3 shows the physical dimensions of the Cassegrain objective in relation to its focal length.

In Fig. 3, f is the effective focal length, a is the spacing between the two mirrors, b is the distance from the secondary mirror to the image plane, called the back focal distance, y is the semi aperture size, and h is the image height. All dimensions identified are considered to be positive. The mirror radii for this arrangement are:

$$R_1 = \frac{2 \times f \times a}{b - f} \quad \text{and} \quad R_2 = \frac{2 \times b \times a}{b + a - f} \tag{3}$$

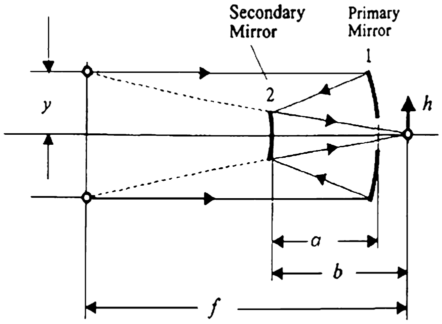

Fig. 3. Basic Cassegrain configuration dimensions.

With the aperture stop at the primary mirror, the general third-order-aberration contribution equations yield the following expressions for the angular blur spots in radians. Thus spherical aberration is presented as below [14]:

$$\beta_{sphere} = \frac{f \times (b - f)^3 + b \times (f - a - b)(f + a - b)^2}{128 \times f \times a^3 \times (F\#)^3} \tag{4}$$

where $F\#$ is the ratio of the focal length f to the aperture diameter D.

2.3. Calculation of the signal to noise ratio

The total amount of received spectral radiance of the target at the orbit altitude H is obtained by the following equation:

$$L_{total}(\lambda) = \frac{\rho_\lambda \times \tau(\lambda) \times E_\lambda}{\pi} + L_p \tag{5}$$

where E_λ is the solar/lunar spectral radiance at orbit altitude from the Earth surface or target, $\tau(\lambda)$ is called atmospheric transmittance in the path (target to sensor), ρ_λ is spectral reflection coefficient of target, and L_p is the sum of the multiple scattered solar and atmospheric emitted radiance into the path.

A Cassegrainian telescope has a central obscuration. Fig. 4 shows aperture diameter and the obscuring diameter x of the telescope. The primary mirror is usually a paraboloid and the secondary mirror is usually a hyperboloid [6].

In order to calculate the signal value, the following relationship can be expressed as follows [4,13]:

$$S = \left(1 - \left(\frac{x}{D}\right)^2\right) \frac{\sqrt{N_{tdi}} \times A_D \times T_{optics} \times t_{int}}{4 \times (F\#)^2} \int_{\lambda_1}^{\lambda_2} R_d(\lambda) \times L_{total}(\lambda) d\lambda \tag{6}$$