Preliminary of Optical Lens Design for Micro-Satellite

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Abstract. The development of micro satellites for the last two decades is emerging rapidly as the need of satellite communication usage is increasing. Earth observation is one of the example of how satellites are on demand. Most observation satellites consist of sensors and imaging system on-board. One of the key element to have a good imaging system is a special optical lens system design. Such lens is designed specifically by calculating every parameter such as refractive, reflective indexes, type of surface, distance and many more. Manufactured lenses sometimes do not match the requirement of an imager system hence the special lens design is needed. This paper will first briefly describe the history of optic, theory related to lens system, then the design and the analysis of lens system for micro-satellites generally and LAPAN A4 particularly.

1. Introduction

The origins of optical technology date back to remote antiquity. Early mirrors were made of polished copper, bronze and later on speculum, a copper alloy rich in tin. At the seventeenth century Willebrord Snell (1591-1626) Professor at Leyden, empirically discovered the long-hidden Law of Refraction in 1621, this was one of the great moments in Optics. By learning precisely how rays of light are redirected on traversing a boundary between two media, Snell in one swoop swung open the door to modern applied Optics. [1]

In the twentieth century, applied Optics had become a phenomenal, more complex design and technology as the advent of the high speed computer was used to design such Optics. The demand of a high speed communication had also taken the Optics technology into another level, and there was also the infrared technology which is highly used in surveillance systems these days. Before a lens can be constructed it must be designed, that is to say, the radii of curvature of the surfaces, the thickness, the air spaces, the diameters of the various components, and the types of glass to be used must all be determined and specified. [2]

Two of the basic elements of Optics which influential are Numerical Aperture (NA) and Reflection. Numerical Aperture is the amount of light from the Field of View which a lens can accept.

\[ NA = n \sin \theta \]  

where \( n \) is the index of refraction of the medium in which the lens is working and \( \theta \) is the half-angle of the maximum cone of light that can enter or exit the lens. [3]

There are three kinds of Reflections, Prism, Cataoptric, and Catadioptric. The type which LAPAN satellite used is Catadioptric. Catadioptric is a combination of Refraction and Reflection using lenses and curved mirrors.

This paper will describe mostly on the Optics design for the micro-satellite for LAPAN A4, which requirement will be similar to the LAPAN A3 imager system.

The next generation of LAPAN satellite would be applying an infrared (IR) micrometer Bolometer, whereas the design would much more complex than the regular lens used for microsatellite, everything...
had been initiated by spectral radiance analysis adjusted by catastrophes sources in Indonesia, mainly wild fire (forest fire) and active volcano [12]. When it comes to the terms of IR micrometer Bolometer. There would be thermal analysis needed.

2. Methodology and Goals
This research was done by studying several literatures and simulation using a lens design software. The goals of this research is so that it will become a reference for further study on Optical Lens Design for satellites, and to find a compatible design for LAPAN A4 imager system.

3. Designing an optical lens
Optical design or lens design is the process used to find the best set of lens construction parameters (e.g., radii of curvature, thicknesses, airspaces, and materials) that optimizes the overall performance (including the manufacturability) of an optical system [4].

There are also some key elements worth to notice in designing a lens, the stray light analysis, and distortion.

3.1. Stray light analysis
Stray light analysis is any unwanted light that reduces performances by striking the image plane of an optical system [4]. In designing an optical lens, there is always the possibility of stray lights, hence there is ray tracing to trace the unwanted lights and baffle is commonly used to fix this such error. Baffle functions as a shield of a light not from the field of view.

![Figure 1](https://example.com/figure1.jpg)

**Figure 1.** Stray light from the sun just outside the lower edge of FOV, shining through the hole in the primary mirror of a Maksutov–Cassegrain telescope whose baffles are undersized [5]

3.1.1. Distortion
Distortion is an aberration in which the magnification varies over the image height. Object points are imaged to perfect points with no blur, but straight lines in the object become curved lines in the image [4].
In its simplest expression, the distortion is a transverse deformation of an image. If a grid is used as an object, its image in a system with distortion will be a grid of curved lines. This is due to the change in the transverse magnification in a system as a function of the distance from the optical axis. When the magnification decreases as the distance from the axis increases, a barrel shaped image occurs. If the magnification increases with the distance, a pincushion image is obtained [6].

3.1.2. Lens Design Software
There are three most commonly lens design software used these days, Optics Software for Layout and Optimization (OSLO) and TracePro by Lambdares, OpticStudio by Zemax, Code V Optical Design Software by Synopsys. These softwares will mostly help in ray tracing the stray lights and distortion, and optimization.

3.1.3. Basic Optical Design Process
The basic optical design process is as follows:

- A specification document for the optical system is established, and the appropriate type of lens form (e.g., microscope, telescope, camera lens) is selected.
- A starting-point design is chosen from previous projects, historical databases, or patent literature (primarily based on the aperture, field, wavelength, and packaging requirements).
- If an appropriate starting-point design does not exist, designers can choose to start from a first-order solution that identifies focal lengths and object/image/pupil locations and sizes using thin lenses and paraxial rays. The first-order solution can be converted to a third-order thin lens solution where thin lens parameters such as radius of curvature and index of refraction are chosen to minimize third-order aberrations. Thickness is then introduced into the thin lenses to arrive at a thick lens starting point.
- The starting-point design is assessed by tracing real rays at multiple wavelengths through the system to analyze the chromatic and higher-order aberrations. Compliance to performance requirements (e.g., image quality, packaging restrictions, fabrication and assembly tolerances, cost) is evaluated.
- If the performance is not acceptable, optimization is used to improve the design. A set of variables and constraints is defined, and computer software is used to find design solutions as defined by a merit function.
If the solution is still unacceptable, designers must return to a previous step and iterate until
the design meets specifications. This process may require the selection of a different starting-
point design and/or requesting a significant change in one or more of the specifications.

The manufacturability of the design is just as important as the final image quality. Therefore, a
complete design process and performance evaluation includes tolerancing, stray light analysis, and
thermal and other environmental analyses.

Meanwhile the design process for IR micrometer Bolometer is as follows:

- Requirements
  - Athermalization analysis
    - Material Selection
      - 3D-Geometry
        - Thermal Analysis
          - Steady State
          - Transient
          - Orbital Heating Rate

*Figure 3. Design process of thermal analysis*

The work is initiated by determining requirements of the design. Then, it is continued by doing an
analysis of athermalization, either for lens or housing of the sensor. From that process, we've got
the material selection for lens and also for the housing which fulfils the requirements. Based on the prior
result, we create three dimensional (3D) geometry, yet we separate between the housing and the lens
in order to facilitate analysis process. Moreover, this is in accordance with the capacity that we have.
After constructing process finished, the analysis goes through the thermal analysis for each geometry
using commercial software applications, i.e. Finite element and Thermal Desktop 5.0 / Sinda Fluent
5.0. There are three simulation process that we do throughout the analysis, i.e. steady state, transient
analysis, and orbital heating rate using Monte Carlo approach. All three result will be used to analysis
what the appropriate thermal control is for IR Microbolometer optical design, so that the sensor can
operate in severe condition such as space environment. [13]

For applications prone to temperature fluctuations, it is important to develop an athermal optical
system: an optical system that is insensitive to an environment’s thermal change and the resulting
system defocus. Developing an athermal design, which is dependent on the Coefficient of Thermal
Expansion (CTE) of the materials and the change in index with temperature (dn/dT), is especially
critical in the infrared. The dn/dT of most IR materials is orders of magnitude higher than those of
visible glasses, creating large changes in the refractive index. Additionally, while optical systems are
often designed in air, the housing material is also sensitive to thermal change, and should be addressed
when considering an athermalized design. [14]
4. The Optical Lens Design for Micro-satellite

The demand of Earth observation is emerging rapidly these days, everyone wants the technology. For the developing countries with low research and development budget have to considered a way to obtain and actually build the technology, hence the answer is micro-satellites.

One of the possible approaches is taking full advantage of the ongoing technology developments leading to further miniaturization of engineering components, development of micro-technologies for sensors and instruments which allow designing dedicated, well-focused Earth observation missions. At the extreme end of the miniaturization, the integration of micro-electromechanical systems (MEMS) with microelectronics for data processing, signal conditioning, power conditioning, and communications leads to the concept of application specific integrated micro-instruments (ASIM). [7]

The lens design depends on the micro-satellite mission. Earth observation or surveillance mission for example, need a proper resolution, there are three kinds of resolutions: spatial resolution, spectral resolution and temporal resolution. Each resolution shall has Ground Sample Distance (GSD) and the Field of View (FOV) measured precisely. The imaging system payload is basically consists of an Optical Head and Electronic Unit. [6]

![Figure 4](image.png)

**Figure 4.** The Optical Head and Electronic Unit block diagram

The primary purpose of the optical module is to record wide and broadband images of a scene around the satellite. A key requirement of the optical module is therefore to be able to use the field coverage properties to distinguish true element that can be used for star tracking, earth horizon sensing and related tracking functionalities. The optical module must provide all usable telemetric information for the satellite [6]. To obtain that, usually a custom made lens is highly recommended as it will provide the closest specification to imaging system requirement. LAPAN A4 satellite will use catadioptric lens, as we mentioned above, catadioptric is a combination of both refractive and reflective (lenses and mirrors).

Optical systems can be refractive (lenses), reflective (mirrors), or catadioptric (both lenses and mirrors). Because many refractive design forms have analogous reflective forms (e.g., the telephoto and the Cassegrain, the retrofocus and the Schwarzchild, or the Cooke triplet and the reflective triplet), it is useful to understand the advantages and disadvantages of one type over the other. [4]

Some of the advantageous of the reflective systems are no chromatic aberrations hence the mirror can be focused in the visible and used in any wavelength region [2] and better performance over a wider thermal range. [4] Although there are also some of the disadvantageous such as limited FOV and stray lights are harder to manage. One of the advantageous of using a catadioptric system is it can decreased aberrations on lenses.

The method used in designing optics here was the same as to process the optical design in general because it is the common way for all applications. The first process starts with the development of the draft specification that includes first-order properties (Effective Focal Length, Field of View, F / number, spectral band), size and weight restrictions, limitations of material and shape of the surface. Next is to assign one or more starting point. In setting the starting point of the optical engineers rarely developed the early design of the draft itself. Based on the design specifications, engineers specifically used the literature that has been patented or some other database to get the configuration succeeded in meeting the design specifications for their specific applications. One technique that has been used successfully in the developing a starting point for complex systems is to break into the system
functional subsystems of a form that can be recognized. The aim at this stage is not a process to produce a complete draft final, it is more an early form with unique characteristics. As it is still based on the satellite bus until Lapan Lapan-A1-A3, the optical system selected as the starting point was close to the existing optical system specifications on the satellite as lens length of about 30 cm and 10 cm diameter lens. Here the selected model was Maksutov Cassegrain as a starting point as in Figure 5. The Maksutov-Cassegrain is a catadioptric design, which means the use of lenses and mirrors. The system consists of a parabolic primary mirror and a second mirror hyperboloid and lenses are used as lenses to eliminate aberration corrector (aberration) generated from the design that only uses only mirrors

![Figure 5](image-url)

**Figure 5.** Maksutov Cassegrain, an example of a catadioptric system.

From this design we modify it and optimize it to obtain an optical system to get the desired specifications such as the effective focal length (EFL) 1000 mm NA (numerical aperture) of 0.05, 1.27 degrees FOV, as shown in Figure 6.

![Figure 6](image-url)

**Figure 6.** Modified Lens

When the designing work is done, comes another complex task to do, manufacturing. We shall decide which material will be used, whether it is going to use coating or not. High-reflection
(HR) coatings are needed on reflective optics to improve the base metal reflectivity (e.g., an enhanced dielectric coating can boost the reflectance of an aluminum mirror from 90% to over 97%). Dichroics are short- or long-wave-pass filters used for color balancing or color splitting. Cold and hot mirrors are special dichroics that transmit or reflect, respectively, thermal (long-wave) radiation to protect thermally sensitive optics. [8]

Thermal evaporation is the most commonly used coating method. Source material is heated by resistance heating or by electron beam bombardment to either the sublimation or melting point.

Another point of our athermalization design that has become our concern is the housing that holds the lenses in place since its material is affected by thermal change [13].

The Aluminum material does not obtain a high merit comparison of mechanical figure versus thermal stability. Since it has the lowest assembly cost, we finally decide to use it, instead of other materials. Besides, many housing lens use it as the housing material. For this case, Aluminum 2024 T3 has been chosen due to its high strength and excellent fatigue resistance compare to others. [15]

5. Conclusion

Designing an optical lens system for micro-satellite is a complex work to do. We must measure and calculate every aspects. LAPAN might choose to use a catadioptric system because it has advantageous for less expensive and more manageable or flexible control over lenses and mirrors aberrations and errors to fulfill the satellite mission requirement.

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