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Master’s Dissertation 2015

A Feasibility Study for Laser Communications between Micro Satellites and GEO Satellites

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Graduate School of System Design and Management,
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SUMMARY OF MASTER'S DISSERTATION

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Title

A Feasibility Study for Laser Communications Between Micro Satellites and GEO Satellites

Abstract

In recent years, developing micro satellites (50 – 100 kg) has emerged as a new trend in satellite technology because of its advantages such as: short time and low cost for development, low cost for launching. However, the capability of communication between a micro satellite and a ground station is limited in terms of the time duration for communication and data latency. Because of the characteristics of the Low Earth Orbit (LEO), the micro satellite can only communicate with the ground station at most several times per day and the duration of each communication window is only up to 10 minutes. Moreover, there is a gap between each pass during which the data stored in the micro satellite cannot be transferred to the ground station. These problems can be overcome by using a Geostationary Orbit (GEO) satellite as a relay satellite. Several experiments of relay satellite communication have been done in the past. However, in the former experiments or analyses, radio frequency was used as the carrier and the size of the LEO satellite was relatively big. In this study, instead of using radio frequency, laser communications between a micro satellite which is much smaller than the previous ones and a Geostationary Orbit satellite is studied. In this communication model, the micro satellite in Low Earth Orbit (about 600 km altitude) will use laser to communicate with the Geostationary Orbit satellite which is at the altitude of 36,000 km. By using laser as the carrier, the communication speed is improved considerably comparing to the case of using radio frequency. Also, since the LEO satellite will be visible to the GEO satellite for at least 50% of its orbital period [1], the duration and frequency of the communication window are gained in comparison to the case of direct contact to the ground station. The purpose of this research is to study the feasibility of using laser communications between LEO micro satellites and GEO satellites. A simulation model is built to analyse the performance and feasibility of laser communications between LEO micro satellites and GEO satellites.

Key Word (5 words): Laser communications, Micro Satellites, GEO Satellites, Feasibility, Laser Components

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CHAPTER 1. INTRODUCTION

1.1. Communications Architectures of Satellites

In this section, two communications architectures for micro satellites are presented with a discussion of the pros and cons of each. The first option is the case when a micro satellite in Low Earth Orbit (LEO) communicate directly with a ground station while the other one is when the micro satellite will relay all user data through a satellite in Geostationary orbit (GEO) to the ground. In the first option, since the altitude of the micro satellite in LEO orbit is about 500 – 1000 km, the period for one orbit of this micro satellite is about 90 minutes. Because of characteristics of LEO, the micro satellite is able to communicate with the ground station at most several times per day and the duration of each communication session is only up to 10 minutes. Therefore, with 1 Gigabit-per-second (Gbps) data rate, the micro satellite can transfer ~300 Gigabytes (GBytes) to the ground within one day. Another issue of the first communication structure is the data latency when the satellite cannot transmit data to the ground station in every orbit. To improve the communication performance of this architecture, the site diversity method can be used when a network of optical ground stations is deployed. Nevertheless, this may cause considerable increasing of cost to develop and maintain such a network. Moreover, developing a ground station network in different locations over the world is very difficult due to sovereignty issues. One of the advantages of this model is that the pointing requirements of both the micro satellite and its optical system can be loosen since the distance for communication is only several hundred kilometers. Besides, it is possible to access to the ground station while the ability to access to the GEO satellite in its orbit is almost impossible. Therefore, there is a high possibility to improve operation performance of the ground station, thus improve the communication performance.

In contrast to LEO satellites, a GEO satellite is at the altitude of 36,000 km and it moves in the orbit with the same velocity of the Earth's rotation. Therefore, the satellite always keeps the same relative position with a dedicated ground station. Thus, by using a GEO satellite as the relay terminal, the micro satellite can transfer its data to the GEO satellite and then this GEO will transmit the data to the ground station. In other words, whenever the micro satellite can have a Line of Sight (LOS) the GEO satellite, it will be able to transmit the mission data to the ground station via the GEO satellite. In this case, because of very high altitude, the GEO satellite can cover almost half of area of the Earth. If the field of view (FOV) of the optical telescope in the GEO satellite is 20^o, the micro satellite will be able to communicate with the GEO satellite in every of its orbit during one day [2]. Also, one session for communication will occur during almost one half of an orbit of the micro satellite in LEO. It means communication can happen during about 45 minutes per orbit. According to the reference [3], if 5 Gbps laser is used instead of RF waves for communication, the LEO satellite can transmit about 27 Terabytes (TBytes) per day to the GEO satellite and the availability of this link is 100% since cloud blocking does not occur in the space. Then, 2552 Tbytes of the user data can be transmitted from the micro satellite to GEO to the ground station per year. In case the data rate is 1 Gbps as above, the amount of data which can be relayed to the ground is about 5400 GBytes per day. Comparing two transmitted volumes of data which can be transferred in one day, it shows an extremely clear advantage of the relay model to the direct communication one. Even though some benefits can be got from using a GEO satellite as the relay station, it is obvious that the biggest challenge in this type of communication is the stringent pointing requirement because of the narrow beam of laser and extremely long distance between two satellites. Table 1 summarizes the advantages and disadvantages of each communication architecture.

Table 1: A comparison of the relay communication architecture and the direct communication architecture

	Relay communication via GEO relay satellite	Direct communication to ground
Number of communication sessions	~15 (FOV of GEO: 20°)	3 – 4
Communication duration per one orbit	~ 45 minutes	~ 10 minutes
Amount of data with the same data rate	Bigger	Smaller
Data latency	Almost real time communication	Normally, it takes long to wait for the LOS between the satellite and the ground station
Pointing requirement	Stringent	Much loosen comparing to the relay architecture

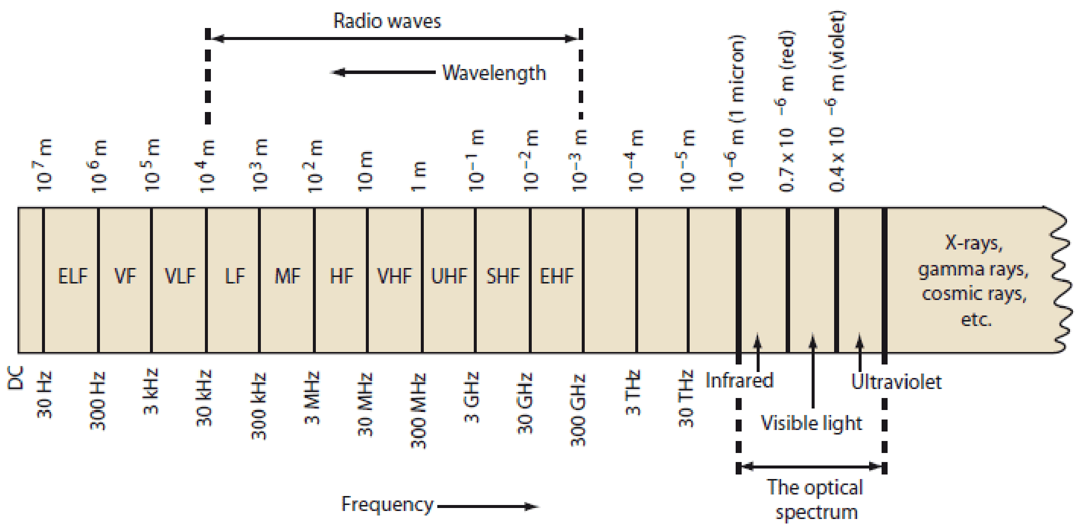
1.2. Comparison of Laser communications and Radio Communication

Traditionally, radio frequencies are used as the carrier for space missions. However, nowadays, there are many radio services that have been developing and that causes the congestion in the bandwidths allocated at microwave frequencies. Besides, required data rate for space applications is increasing quickly. Therefore, free space laser communications becomes a new option for future satellite communications as a promising means of transportation because it offers many advantages in space, including reduced mass, power, and volume of equipment, higher data rates and no frequency regulation such as with RF bands [4]. A review of laser communications shows that the systems of laser satellite communication have one half or less the mass of microwave systems. Moreover, the power is consumed one half or less and the volume occupy one third to one tenth comparing to the RF configuration [5]. In section 1.2.1 and 1.2.2, advantages and disadvantages of laser comparing to radio frequency will be discussed.

1.2.1. Advantages of Laser over Radio Frequency

a) Wide Bandwidth

The optical frequency with the wavelengths of the µm scale includes infrared, visible and ultra violet frequencies. As can be seen in Figure 1.1, radio carrier frequency is much smaller than the optical carrier frequency. While the frequency of microwaves ranges from several to three hundred GHz, optical frequency is about several hundred THz. Since the data is modulated to the carrier to transmit through long distances, the amount of data is directly related to the bandwidth of the modulated carrier. Therefore, using optical communication helps to increase the capacity of data transmission considerably. With the frequency ranges from 10^{12} – 10^{16} Hz, data bandwidth is able to reach up to 2000 THz in case of using optical carrier for communication. The usable frequency bandwidth in RF range is comparatively lower by a factor of 10^5 [6].



1. The electromagnetic frequency spectrum ranges from dc to light. The lower radio frequencies are designated mainly by frequency. The optical ranges are referred to by wavelength.

Figure 1.1: The electromagnetic frequency spectrum

b) Narrow beam size

One of the most advantages of using optical communication in the comparison with the case of using radio waves is the extremely narrow beam of the its signal. A typical laser beam has a diffraction limit divergence of between 0.01 - 0.1 mrad (Killinger, 2002). This extremely narrow beam means that the transmitted power is focused on a very narrow area. Thus the laser link is spatial isolated from its potential interferers. Therefore, the laser beams will be able to work independently that leads to the possibility of frequency reuse in many environments. Moreover, this spatial confinement makes data interception by unintended users difficult.

The maximum narrowness of the laser beam is achieved with diffraction-limited optics, providing a beamwidth of:

$$\theta = 2.24\frac{\lambda}{D} \tag{1}$$

Where:

λ: wavelength of laser transmission

D: diameter of optical aperture of transmitting telescope

From Eq. 1, in the case of laser, for example, with λ = 1 µm with D = 10 cm, the achieved beamwidth is 22.4 µrad. Meanwhile, using X band radio frequency 10 GHz (λ= 3 cm) and with D = 1m, the beamwidth will be 67.2 mrad. This beamwidth is much larger than the case of laser. The extremely different of the ground intercept between the case of laser and the case of radio frequency is shown in Figure 1.2. While in the case of using laser, the diameter of the ground intercept is only 804 m from a synchronous distance (36,000 km), this intercept will be 1880 km for the case of using radio frequency at 10 GHz.

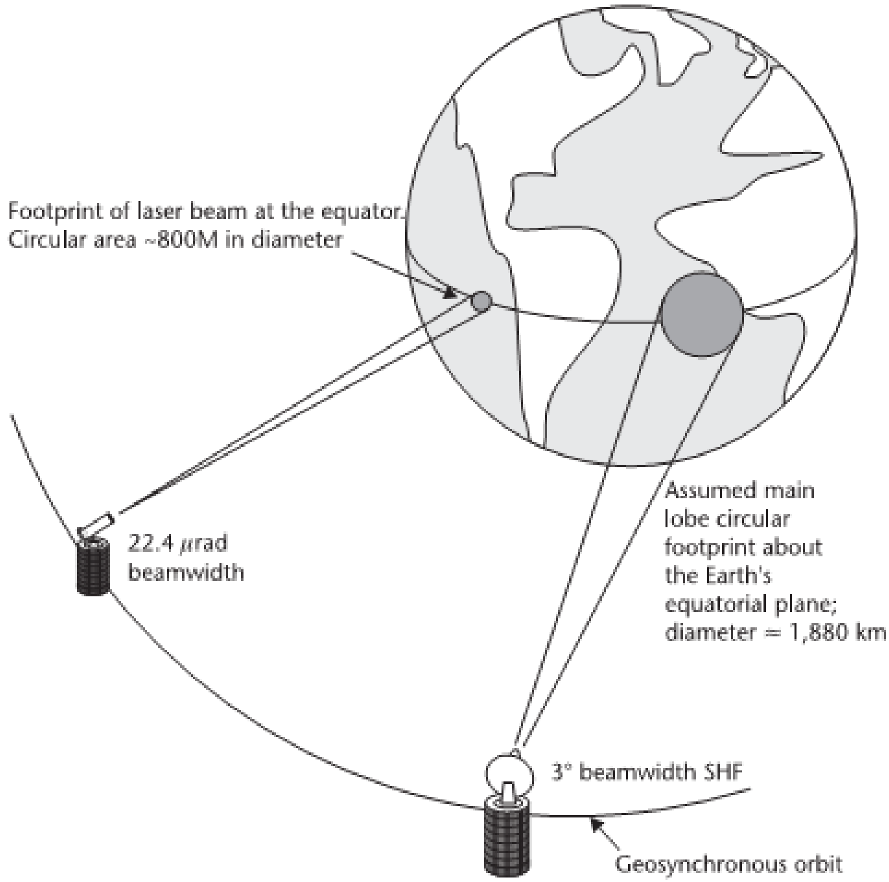


Figure 1.2: Privacy comparison between radio frequency versus laser footprints.

[Courtesy of the U.S. Government] [7]

c) Unlicensed spectrum

Interference from adjacent carriers is a very critical issue in wireless RF communication. Thus, it is necessary to have regulatory authorities to control the frequency regulation to minimize the interference problem. ITU (International Telecommunication Union) is the United Nations specialized agency for information and communication technologies. One of the important tasks of ITU is to manage the international radio-frequency spectrum and satellite orbit resources. To be allocated a slice of the RF spectrum therefore requires a huge fee and several months of bureaucracy [6]. However, nowadays, when more and more RF services have been developing, the time required to get the frequency license from ITU is even longer since it takes lots of time to coordinate among other countries, organizations to share frequency resources. In contrast to radio frequency, until now there is no required procedure for the optical frequencies. Obviously, this is a clear advantage of laser communications comparing to radio communication. Satellite developers do not have to complete a complicated procedure for acquiring the frequency license and the resources will be contributed to solve other issues which are related to the satellite development.

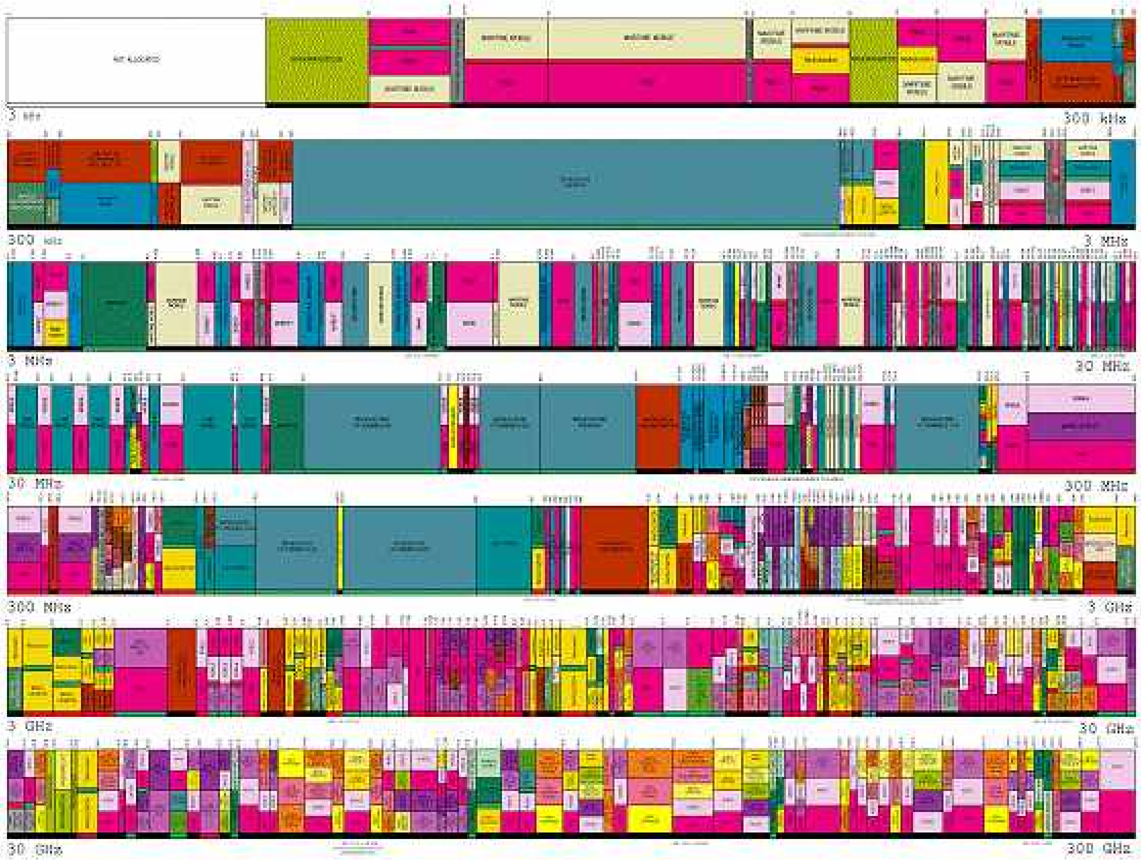


Figure 1.3: United State Frequency allocation

d) Jamming and interference

In radio communication, deliberate jamming and inadvertent jamming (interference) are two serious problems. Radio jamming causes interrupt communications by broadcasting radio transmissions on the particular frequencies used by the targeted devices. In this case, if a transmitter is provided enough power and tuned to the same frequency as the receiving equipment and with the same type of modulation, the signals at the receiver can be overridden. There are some scenarios which radio jamming issue is very critical, especially in military field. That is when intentional communications jamming is aimed at radio signals to disrupt control of a battle. For satellites, the low received signal strength of satellite transmissions can be jammed easily by land based transmitters. GPS satellites, satellite phone and television signals are some targets of jamming. If satellite applications are used for the military's purposes, the security of the satellites' signals can be threatened seriously by jamming caused by unintentional users. Laser satellite communication is characterized by very narrow optical transmit and receive beams with low sidelobes tight to the beams and very high transmit antenna gain. This makes jamming very difficult and provides a high degree of security because any unintended receivers have a low probability of intercept or detection.

e. Size of Antennas

In the reference [8], the author shows examples of link budgets for two RF systems and an optical link of a GEO-LEO distance of 42,000 km as in Table 2. It can be seen obviously that because of the characteristic of laser wave, size of both of the transmitting and receiving antennas in laser communications are much smaller than the ones in RF communication.

Table 2: Examples of link budgets for two RF systems and an optical link at λ=1.55 μm

at a bit rate =2.5 Gbps with a GEO-LEO distance of 42,000 km

	RF Systems		Optical System		
	Ka Band	Milimeter Band			
Transmit power	17.0 dBW 50.0 W	13.0 dBW 20.0 W	Transmit power	40.0 10.0	dBm W
Frequency	32.0 GHz	60.0 GHz	Frequency	193	THz
Wavelength	9.4 mm	5.0 mm	Wavelength	1.55	m
Tx Antenna diameter	2.2 m	1.9 m	Tx antenna diameter	10.2	cm
Tx antenna gain	55.1 dBi	59.3 dBi	Tx antenna gain	109.3	dB
Feeder loss	-3.0 dB	-2.0 dB	Tx loss	-2.0	dB
EIRP	69.1 dBW	70.3 dBW	Strehl ratio	-0.4	dB
Pointing loss	-0.3 dB	-1.0 dB	Pointing loss	-3.0	dB
Polarization loss	-0.5 dB	-0.5 dB	Beam divergence	19.3	rad
Beam divergence	0.25 deg	0.16 deg	Path loss	-290.6	dB
Path loss	-215.0 dB	-220.5 dB	Rx antenna diameter	10.2	cm
Rx antenna diameter	2.2 m	1.9 m	Rx antenna gain	106.3	dB
Rx antenna gain	55.1 dB_i	59.3 dB_i	Rx loss	-2.0	dB
Feeder loss	-2.1 dB	-1.5 dB	Receive power	-42.4	dBm
Receive power	-93.7 dBW	-93.8 dBW	Receive sensitivity	90	photons/bit
System noise	29.6 dBK	29.8 dBK	Required power	-45.4	dBm

G/T	23.4 dB/K	28.0 dB/K	Link margin	**3.0**	dB
Noise density	-199.0 dBW	-198.8 dBW			
C/N**0**	105.3 dBHz	105.0 dBHz			
Required C/N_0	102.0 dBHz	102.0 dBHz			
Link margin	**3.4** dB	**3.0** dB			

1.2.2. Disadvantages of Laser communications

Even though laser shows many of its advantages comparing to radio frequency for communication, there are some disadvantages. One of the most critical problem for laser communications is extremely stringent pointing requirements. Because of very long distance from the micro satellite in LEO and the GEO terminal in GEO and narrow beams of laser, the most challenge mission is to align the two optical systems in the presence of vibration of two spacecraft. This requirement is only able to achieve by a using a dedicated control system which is integrated into two satellites. Another issue of laser communications is about the safety.

Moreover, laser light or other types of optical communication is blocked by clouds. This can decrease the performance of laser communications between satellites and ground stations. In some extremely cases when the cloud is too thick, it is even impossible to communicate. Not only cloud but also the atmosphere is able to cause degradation of laser communications because space to ground optical communications are strongly affected by scintillation effects due to the turbulent atmosphere. Finally, the most critical problem of laser communications comparing to radio communication is the extremely pointing accuracy requirement. Since laser beam is much smaller than radio one, it is really difficult to point a laser beam accurately to the receiver side. Therefore, it is required to focus on developing an advanced control system to control the laser beam in the presence of several sources of vibration. Summary of pros and cons of laser over radio communication is described in Table 3.

Table 3: A comparison of laser communications with RF communication

	Advantages	Disadvantages
Laser communications	High data rates	Stringent pointing requirement
	No regulatory restrictions	The radiation must be within the safety limits
	Narrow beam size	Effect of weather and atmosphere
	Limited of interference	
	Providing a high degree of security	
	Light weight, small size and compactness	
	Low power consumption	
	Low cost for the ground station	

1.3. Micro Satellite and Its Advantages

In 1957, Sputnik, the first satellite was launched by the Soviet Union. This satellite was the world's first artificial satellite with the size of a beach ball (58 cm in diameter), the 83.6 kg satellite moved around the Earth on its elliptical path with its cycle period about 98 minutes. The launch of Sputnik marked the start of the space age and it ushered in new political, military, technological, and scientific developments. Immediately after the Sputnik I launch, the U.S. Defense Department approved funding for another U.S. satellite project. In January 1958, the United States launched successfully Explorer I which carried a small scientific payload to discover the magnetic radiation belts around the Earth, named James Van Allen belts.

In recent years, the use of small satellites for Earth observation has received considerable attention. According to the reference [9], a widely classification of satellites is accepted by many different organizations over the world. In this classification, micro satellite is one of the types of small satellites which has the mass in range of 10 – 100 kg. With such a small size, micro satellites offer some clear advantages in a comparison with traditional ones in the past such as: short time for developing, low cost for development and launching, tailored mission and high operational flexibility. Therefore, developing micro satellites has emerged as a new trend in satellite technology. Now, since the complexity of developing micro satellites is decreased, not only government organizations but also universities and institutions over the world are able to manage satellite projects from initial phases till satellites are launched and operated. Figure 1.4 shows the image of the 50 kg UNIFORM-1 micro satellite. Several Japanese universities, JAXA and institutions are members of the UNIFORM consortium. This satellite was launched successfully in 2014.

Table 4: Classification of satellites. [10]

Class	Cost	Mass
Large satellite	$ > 100 M	> 1000 kg
Small satellite	$50 - 100 M	500 - 1000 kg
Mini-satellite	$ 5 - 20 M	100 - 500 kg
Micro-satellite	$ 2 - 3 M	10 - 100 kg
Nano-satellite	$ < 1 M	< 10 kg

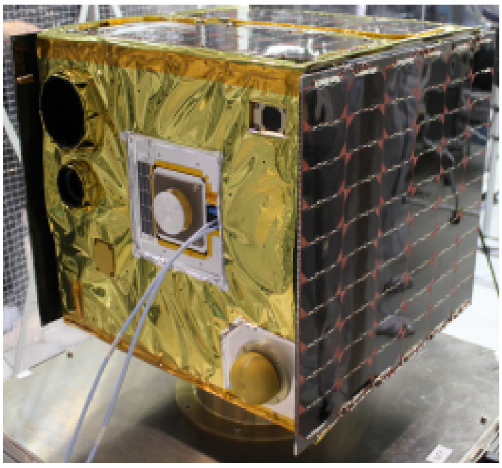


Figure 1.4: The UNIFORM-1 micro satellite (Source: UNIFORM-1 Team)

As can be seen in Table 4, while it costs 2 – 3 million USD to develop one micro satellite, this may take 25 – 30 times more to build a traditional large one. On the other hand, the required time to develop a micro satellite is much shorter in a comparison with the time to develop a large satellite. Normally, a traditional big satellite was developed in about 10 years in the past while it takes only less than 5 years to complete a micro satellite project. Finally, for each kilogram which is put into orbit, it costs $10,000 [10]. Obviously, micro satellites with less than 100 kg mass take huge advantages comparing to large ones because launching cost will reduce significantly.

1.4. Problem Statement and Motivation

Comparing with conventional big satellites in the past, micro satellites offer many advantages of saving time and cost for developing the satellites as it was discussed in the previous section. However, one of weak points of micro satellites is the ability of communication. Generally, the capability of communication between a micro satellite in LEO and a dedicated ground station is limited in terms of the time duration for communication and data latency. Because of the characteristics of the LEO, a micro satellite can only communicate with a ground station at most several times per day and the duration of each communication window is only up to 10 minutes.

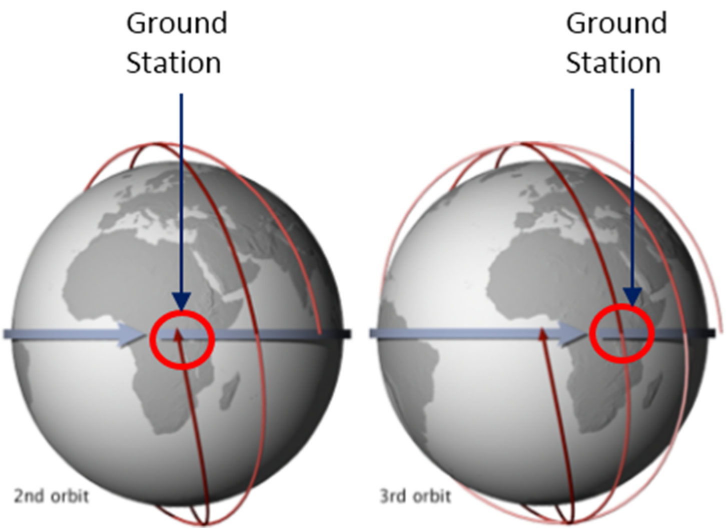


Figure 1.5: The relative position between a satellite in LEO and a ground station

a. 1st orbit the satellite passes through the ground station

b. 2nd orbit the satellite does not pass through the ground station because of the rotation of the Earth

In LEO, the period for one orbit of a micro satellite is about 90 minutes. It means that the micro satellite cycles around the Earth about 15 times per day. However, only several times among them, this micro satellite can have LOS and communicate directly to a specific ground station. In Figure 1.5, the satellite can send data to the ground station since there is a LOS between them in the first orbit. However, in the next orbit there is no LOS between the satellite and the ground station anymore because of the rotation of the Earth on its axis. As a result, communication can not be established. Besides, because of the horizontal line, the duration for each communication session is very limited.

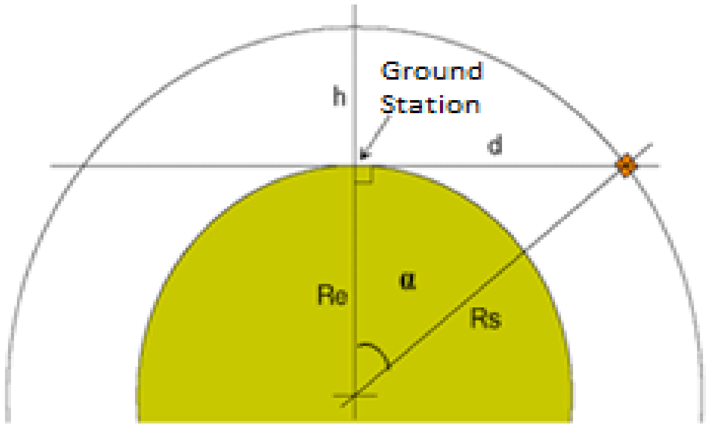


Figure 1.6: The satellite in horizon seen from Ground Station

In Figure 1.6, assuming that a micro satellite operates at the altitude of 700 km, then the angle α is about 25° and the total horizontal angle is about 50°. Nevertheless, due to many reasons, the micro satellite cannot work with the ground station for the whole horizontal seen. In fact, only 80% of theory angle should be considered as the working angle for communication. From this working angle, the time duration for communication between the micro satellite and the ground station can be calculated. It is more or less 9 minutes each pass depending on the distance of orbit to the location of the ground station.

Moreover, there is a gap between each pass during which data is stored in the on-board memory of the micro satellite cannot be transferred to the ground station. As mentioned above, the satellite has to wait for several orbits until it can see the ground station.

The two issues mentioned above limited the capability of micro satellites considerably. Finally, radio frequency in X-band or S-band is often used for communication between micro satellites and ground stations. As discussed above, at present, since many radio services have been developing which causes congestion in radio frequency spectrums, it becomes more and more difficult to get licenses for micro satellites. For a micro satellite, it might take up to 2 years to get a frequency license. In case a micro satellite can be developed in one year and it has to wait for another year to get license, it is a huge waste of time. Therefore, it is needed to find a solution to overcome the mentioned issues so that the capability of communication of micro satellites is improved.

To overcome the problems which are raised above, a Geostationary Orbit satellite can be used as a relay station for the micro satellite. Moreover, different from traditional micro satellites when they use radio waves to communicate with ground stations, laser will be used as the carrier.

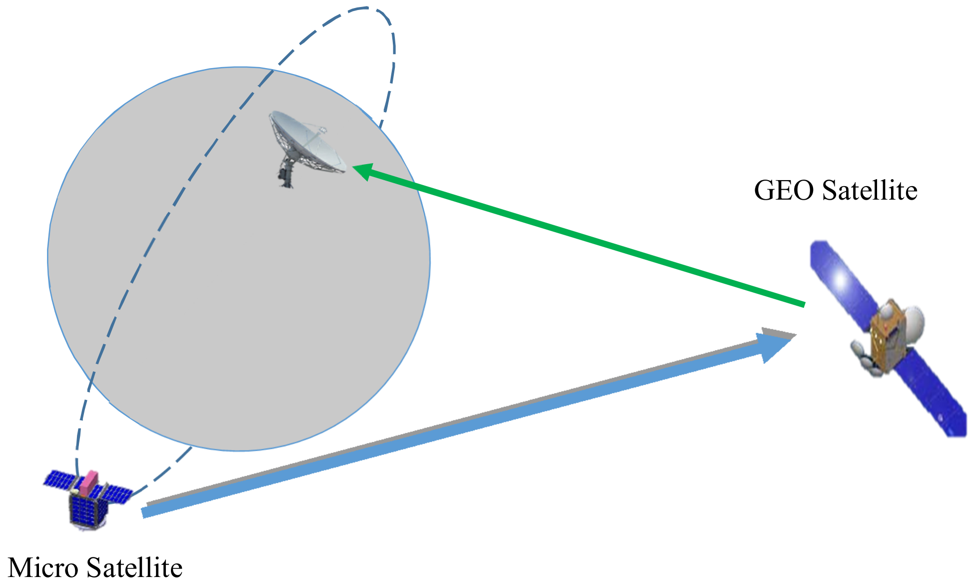


Figure 1.7: The LEO satellite sends data to its ground station by relaying through the GEO satellite

The combination between using a GEO satellite as a relay station and laser as the carrier helps to solve almost of problems of communication which were discussed before. There will be no need to get a license for laser frequency. Communication speed can be improved very much because of the characteristic of laser. Besides, since a GEO satellite can cover about half area of the Earth, this helps to decrease data latency for the communication of a micro satellite because data will be transferred in near real time to ground through the GEO terminal. Finally, in the space between LEO and GEO, there is no cloud and atmosphere. Therefore, laser communications will not be interrupted. As the result, one of the disadvantages of laser is overcome in this model of communication. The goal of this research is designing the communications system between a micro satellite and a GEO satellite. Then, through analyzing the communication link a designed set of parameters will be proposed so that it can be applicable for configuration of micro satellites.

1.5. Overall Structure of the Thesis

In this research, firstly, satellite communication architectures are introduced. Then, a comparison between two types of communication using radio frequency and laser will be discussed to see pros and cons of each. Next, a short content about micro satellites and their advantages is mentioned. Then, the problems of traditional communication of micro satellites in LEO orbit is stated in the problem statement section. Based on this discussion, it is strongly motivated to consider an alternative communication model of micro satellites so that the performance of communication will be improved considerably. Final part of chapter 1 will give the overall structure of the thesis. In the second chapter, several prior research and space laser experiments are reviewed. Then, originality of the thesis is shown through this discussion. In the next chapter, the communication link between the micro satellite and the GEO satellite is designed. Also, in order to overcome the link range issue, tracking system which is really important in this type of communication is mentioned. Final part of this chapter shows the common design of the micro satellite as the constraints for the optical system. In chapter 4, simulation for the communication link will be built for verification purposes. By tweaking the parameters of the model, the output which is bit error rate (BER) varies so that it is able to satisfy the requirement of communication. Then, sensitivity analysis will be conducted to see how the input parameters affect to the performance of communication. From the analysis in the previous chapter, chapter 5 will propose a set of parameters which is the best suite for the micro satellite so that laser communications can be implemented on it. After that, the feasibility of using laser communications between the micro satellite and the GEO satellite is assessed by discussing current technology of space laser communications. Finally, the conclusion of the research is given.

CHAPTER 2. LITERATURE REVIEW

2.1. Relay Laser communications from LEO Satellites to Ground through GEO Satellites

Nowadays, laser space communication becomes more and more popular. Comparing to using radio frequency, laser communications has some advantages such as: high data rates, limited of interference and no radio frequency regulation. In Europe, European Space Agency (ESA) was a primary driver in the development of optical communications.

Artemis (Advanced Relay and Technology Mission Satellite) is an advanced telecommunication satellite developed by ESA (European Space Agency) to demonstrate new communication technologies, principally for new mobile communication services and inter-satellite data relay. It was launched on an Ariane 5 rocket on 12 July 2001 from Kourou, French Guiana in South America. However, because of a malfunction of the rocket, ARTEMIS went into a lower orbit than GEO. After several steps of rescue mission, finally by the end of January, 2003, the ARTEMIS satellite reached the final geostationary orbit at about 36 000 km. The unique of this satellite is that it has a data-relay payload which can speed up communication between satellites by using laser as the carrier. After relaying through ARTEMIS, Earth observation data of Low-Earth-Orbit (LEO) satellites is transmitted to appropriate ground stations. The optical payload which is mounted on the geostationary satellite ARTEMIS called OPALE (Optical Payload for Inter-satellite Link Experiment). It is one of two optical terminals of SILEX which is an ESA laser experiment. The other one is PASTEL (PAssager SPOT de Técommunication Laser) which is located on SPOT-4 satellite in LEO orbit. Since April 2003, SPOT-4 could transmit its data via ARTEMIS to CNES in Toulouse using laser communications between two satellites (Figure 2.1). Overview of major parameters of ARTEMIS and its SILEX are summarized in Table 5.

Figure 2.1: LEO-GEO communication between SPOT-4 and ARTEMIS

Table 5: Overview of major ARTEMIS parameters

Spacecraft Characteristics	
Mass at launch, power generation	3100 kg, 2.5 kW
Spacecraft size: height, length, width	4.8 m, 25 m (solar array tip-to-tip), 8 m (antennas deployed)
Design life	10 years
Orbital position	21.5º E (GEO)
SILEX Characteristics	
Mass	150 kg
Telescope diameter	25 cm
Power consumption	130 W
Laser diode power	60 mW
Pointing accuracy	Better than 1 arc second (~ 4.8 μrad)

After the ARTEMIS project, ESA continues working on inter-satellite laser communications to enable high speed data links in space. In 2014, ESA announced the 0.6 Gbps laser transmission of images between the Sentinel-1A satellite in LEO and the Alphasat communications satellite in GEO. The configuration of communication is summarized as in Table 6.

Table 6: Laser communications Terminal (LCT) configuration

LCT	1st Generation	2nd Generation
Link type	LEO-LEO	LEO-GEO
Mission	NFIRE, TerraSAR-X	Sentinel 1 & 2, AlphaSat, ERDS
Lifetime	2-5 years	15 years
Data rate	5.625 Gb/s	1.800 Gb/s
Range	1000 - 5100 km	< 45,000 km
Target BER	1 x 10^{-8}	1 x 10^{-8}
Tx power	0.7 W	2.2-5.0 W
Telescope diameter	125 mm	135 mm
Instrument mass	~33 kg	~53 kg

Lately, another project of ESA, European Data Relay Satellite (EDRS), is going on. This program intends to provide optical links to satellites in LEO in near future.

Europe also cooperates with The United States of America (USA) in enabling high-speed data links in space for inter-satellite communication. In 2007, USA and Germany have succeeded in setting up a laser-optical data link between The Near Field Infrared Experiment (NFIRE) satellite (USA) and TerrSAR-X satellite (Germany). This error free communication was done when the distance of the two satellites is 5,000 km and the transfer rate is 5.5 Gbps. One of the most remarkable demonstrations of laser communications made by National Aeronautics and Space Administration (NASA), USA was the successful transmitting data from lunar orbit to the Earth in 2013. From a distance of 239,000 miles, the laser beam of the onboard Lunar Laser communications Demonstration (LLCD) which was integrated in the Lunar Atmosphere and Dust Environment Explorer satellite (LADEE) was transmitted successfully to the Earth at a rate of 622 Megabit-per-second (Mbps) [11].

In Japan, current trends in space research and development agencies, industries and universities have placed strong emphasis on laser communications for satellites. The Japanese's Optical Inter-orbit Communication Engineering Test Satellite (OICETS) is a Japan Aerospace Exploration Agency (JAXA) technology satellite with the objective to conduct inter-satellite laser communications with ARTEMIS of ESA. After the first demonstration of ARTEMIS and SPOT-4 satellites, in 2005, a first bi-directional optical link with OICETS and ARTEMIS was established successfully. This was the first bi-directional optical link which included both of data and command transmission between two satellites in LEO and GEO. While the forward link's data rate (from ARTEMIS to OICETS) was 2.048 Mbps, the return link could achieve approximately 50 Mbit/s. Comparing to the case of SPOT-4 satellite, the size and mass of OICETS satellite are smaller considerably. While SPOT-4 weighs 2755 kg equipped with 157 kg optical payload (namely PASTEL), the mass of OICETS is only 570 kg. Overview of parameters of OICETS is given in Table 7.

Figure 2.2: Optical transmission scheme of OICETS with ARTEMIS

Table 7: Overview of major spacecraft parameters of OICETS

Spacecraft mass, power	570 kg, > 1200 W @ EOL
Spacecraft size	1.1 m (width) x 2.64 m (height) x 9.4 m (length of solar array x 1.75 m wide)

AOCS (Attitude and Orbit Control Subsystem)	Three-axis stabilized, zero momentum type
Pointing accuracy	Roll / pitch:±0.130º (3σ); yaw:±0.162º (3σ)
Solar array paddle / solar cell	Rigid / high-efficiency silicon
Battery	13Ah, Nickel-Metal Hydride (NiMH) x 2
Antenna	Optical inter-orbit link: center-feed Cassegrain (26 cm) S-band inter-orbit link & USB: Omni-directional
Propulsion	1 N thruster assembly (N_2H_4 monopropellant) x 4 x 2 (redundant)
Design life	1 year

As the coming plan, Japan is going to develop and launch a couple of satellites in 2019; one of them operates as the first Japanese optical relay satellite in GEO and the other one which is an advanced remote sensing satellite operates in LEO and the transferring of its data to the ground will be conducted primarily by an optical link from the LEO satellite through the GEO relay one to the ground station.

2.2. Direct Laser communications from LEO Satellites to Ground Stations

Laser communications was done successfully between not only satellites but also a satellite and a ground station. In 2006, an optical communication experiment was conducted between the OICETS satellite and the ground station of the German Aerospace Center (DLR). In this experiment, a transportable optical ground station (OGS) was used to communicate with the satellite. These successful results pointed out the possibility of constructing space optical communications systems unaffected by weather conditions. Not only continued inter-satellite laser communications experiments with ARTEMIS, OICETS Kirari conducted laser communications experiments with the OGSs of other space agencies including NICT and DLR, to verify the performance of laser inter-orbit equipment in a space environment and to evaluate atmospheric effects. Recently, Space Optical Communications Research Advanced Technology Satellite (SOCRATES) which is a 50 kg class micro satellite of National Institute of Information and Communications Technology (NICT) was developed and launched in 2014. Basic configuration of the SOCRATES micro satellite is summarized in Table 8.

Table 8: Specification parameters of SOCRATES

Spacecraft mass	48 kg
External dimensions of the spacecraft	W 496 x D495 x H485 mm (SAP is folded during launch)
Power generation	~100 W (nominal), 120 W (max), use of SAP deployment mechanism
ACS (Attitude Control Subsystem)	Three axis stabilized attitude control, solar pointing control, earth pointing control
RF communications	S-band

This microsatellite in LEO conducted laser experiment between its equipped Small Optical Transponder (SOTA) and the Optical Ground Station of NICT. The picture of SOTA is shown in Figure 2.3.

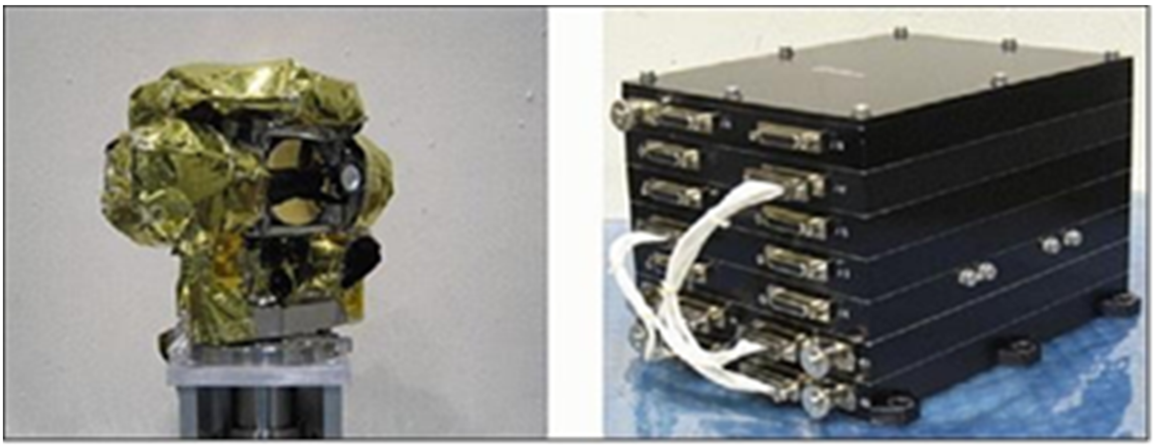


Figure 2.3: Photos of the PFM of SOTA-OPT (left) and SOTA-CONT

2.3. Originality of Thesis

Recently, resources of micro satellites have been improving. Mass of BUS system is also decreased, then, more mass and other resources can be used for optical payloads. Moreover, with the development of technology, size, mass and power of optical modules become smaller and smaller. Till now, it is feasible to implement laser communications in a 50 kg micro satellite like SOCRATES and the link range for this communication is about 1000 km. However, in the LEO-GEO case, the link range is from 36,000 km to 40,000 km. There might be some differences in configuration of optical systems which leads to the differences in mass, size and power between the SOCRATES's case and the LEO-GEO case. That is because of the extremely difference of link ranges in two cases. The purpose of this study is proposing a designed parameters of the optical system so that this system can be used for the micro satellite to communicate with the GEO satellite.

Several experiments and analyses of relay satellite communication have been done successfully so far. However, in these experiments, radio frequency was used as the carrier and the size of the LEO satellite was relatively big. In this research, instead of using radio frequency, laser communications between a micro satellite and a Geostationary Orbit satellite is studied. Moreover, the micro satellite in this case is much smaller than previous big satellites in LEO. This leads to the limitation of resources which can be used for the optical system. In this communication model, the micro satellite in LEO (about 500 – 1000 km) will use laser to communicate with the GEO satellite which is at the altitude of 36,000 km. Because of characteristics of laser, data rate will be improved drastically comparing to the case of using radio frequency as the carrier. Also, comparing to the case when the micro satellite communicate directly to the ground station, the duration and frequency of the communication window are gained considerably since the LEO satellite will be visible to the GEO satellite for about 50% of its orbital period and in almost every orbits. Through this research, a study of the feasibility of using laser communications between LEO micro satellites and GEO satellites is conducted.

CHAPTER 3. SYSTEM DESIGN FOR COMMUNICATIONS BETWEEN MICRO SATELLITES AND GEO SATELLITES

3.1. System Description

In this research, a micro satellite with its mass which is in range from 50 – 100 kg will communicate with a big GEO satellite (several tons) by using laser lights. The micro satellite moves around the Earth at the altitude from 500 – 1000 km (LEO orbit) while the height of the orbit of the GEO terminal is about 36,000 km (GEO orbit). As the result, the maximum distance between the two satellites for communication is about 40,000 km. The communications system is described in Figure 3.1.

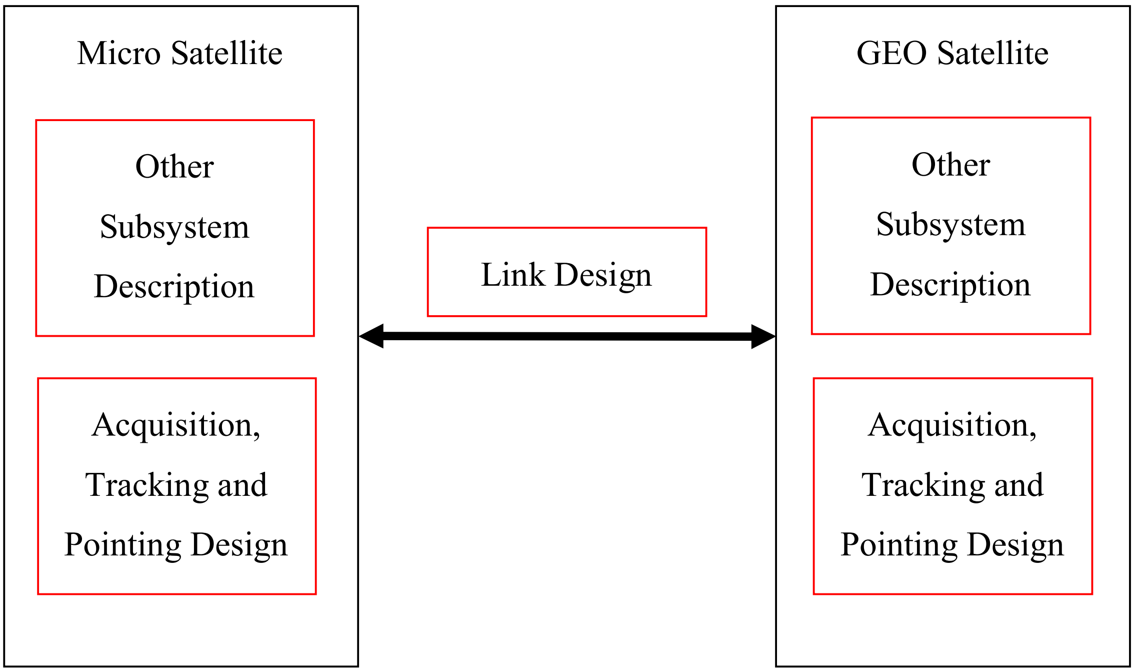


Figure 3.1: Design of the communications system between a micro satellite and a GEO satellite

For any communications system, link design must be considered first to verify the feasibility. In order to do that, in this research, a rough link budget is calculated and verification for the communication link will be done by using the Optisystem software. Besides, basic subsystems of the micro satellite and the GEO satellite are also described. Especially, to overcome the critical problem of pointing accuracy requirement, the attitude controlling subsystem of each satellite is not enough. Each of them needs to have a special and dedicated subsystem, namely Acquisition, Tracking and Pointing (ATP) subsystem. This subsystem will be responsible for controlling the optical system of the satellite very fast and accurately so that the laser communications link can be established and maintained. Physical design of this subsystem will be discussed to express its indispensable role.

3.2. System Requirements and Assumptions

In communication between the micro satellite and the GEO satellite, two crucial requirements for the systems are the Bit Error Rate (BER) requirement and the pointing requirement. In a digital communications system, the system performance measurement or the measure of system accuracy is the BER which is defined as the rate at which errors occur in a transmission system. The definition of bit error rate can be expressed by the formula:

$$BER = \frac{Number\ of\ errors}{Total\ number\ of\ bits\ sent} \tag{2}$$

In this research, after considering several cases in the past, 10^{-6} is determined as the required BER for successful laser communications since this value is typical for micro satellite's communication. One of the most important advantages of laser communications is the capability to achieve very high data rate comparing to microwave communication. Recently, 50 kg micro satellites can observe the Earth's surface with high resolution with a size of several meters on the ground. However, in general, a micro satellite using X-band in frequency range can only achieve data rates from 10 Mbps to several tens of Mbps. To improve the communication speed of radio systems, the research group of Institute of Space and Astronautical Sciences (ISAS), JAXA has cooperated with the University of Tokyo Graduate School of Engineering Department of Electrical Engineering and Information Systems to develop novel technologies to enable high speed on-board transmitters for reception of the transmitted data. The flight model of the X-band high speed transmitter was developed for the micro satellite Hodoyoshi-4. After the launch of this satellite, in December, 2014, the ground station at ISAS received data without error at 348 Mbps successfully. The reference [12] stated that until February of 2015, this communication speed is the fastest one of micro satellites over the world.

Therefore, in this research, to emphasize the advantage of high speed, data rate of laser communications from the micro satellite to the GEO spacecraft is assumed as 300 Mbps which is approximate to the best speed of radio communication for micro satellites currently. The model of communication is asymmetric because there is not much information sent from the GEO satellite to the micro one. The main stream of data will be transmitted from the micro satellite to the GEO satellite while in the opposite direction, only tele-commands are sent to the micro satellite. Thus, the communication speed of the direction from the GEO terminal to the micro satellite is assumed as only 1 Mbps. In general, the altitude of GEO satellites is about 36,000 km and micro satellites fly over the Earth at the altitude of less than 1000 km. As the result, by simple calculation, the maximum distance between two satellites is about 40,000 km. This range of communication is assumed as the requirement for communication in this research. The wavelength of laser is 1.55 µm.

The mass of the optical system which is integrated in the micro satellite is less than 25% of the total weight [13]. Therefore, the diameter of the telescope must be less than 10 cm because this size will be proportional to the total mass of the optical system according to the practical experience of experts, thus, can exceed the limited mass for payloads. In the reference [14], the authors stated that most laser communications links utilizing space based transmitters require average output power levels of laser below 10 W. Therefore, this important data is considered as the constraint of the output power of laser transmitter of the micro satellite in this research. Since the optical system of ARTEMIS could achieve 2.6 µrad pointing accuracy in the past, the pointing accuracy requirement of the optical system in the micro satellite must be at sub-microradian level.

In several successful LEO-GEO laser demonstrations in the past, the conventional LEO satellites which had high quality resources such as pointing accuracy, power generation, mass could satisfy tough requirements of the LEO-GEO link. However, in the case of micro satellites, because of limited resources, the performance of the GEO side must be improved to make the link feasible. Therefore, some assumptions of the configuration of the GEO satellite are considered. In order to assure the gain of the optical antennas can be similar to the experiments in the past, the aperture of the telescope which is integrated in the GEO satellite will vary in range of 35 cm to 45 cm. Temperature of the receiving side is another issue which is needed to consider to prove the link feasibility. High temperature at the receiver side means that lots of thermal noise will be introduced to the optical signal, thus reducing the communication performance. By consulting experts in satellite technology, the temperature of the receiver part which is integrated into the GEO satellite can be cooled down to less than 100 Kelvin (K). This extremely low temperature helps to reduce thermal noise which affects significantly to sensitivity of the avalanche diode (APD). Gain of the photodiode is 100, dark current is 1 nA and responsivity is 0.9 A/W. Finally, the attenuation loss is 0 since there is almost no atmosphere in the space between the micro satellite and the GEO terminal.

The requirements of communication between the micro satellite in LEO and the GEO one is summarized as in Table 9 below:

Table 9: The link requirements of LEO-GEO communication

Parameter	System Requirement and Assumptions
Data Rate	300 Mbps
Link Range	40,000 km
Average Bit Error Rate	Asymmetrical Duplex Link 10^{-6}
Pointing accuracy	Several µrad
Transmitting output power	Less than 10 W
Transmitting aperture	Less than 10 cm
Link Budget	≥ 3 dB (acquisition, tracking, communications)

3.3. Communication Link Design

3.3.1. Link Budget Introduction

Analyzing communication between a transmitter and a receiver by using a link equation is very fundamental and evitable for any communications system. Based on the link equation, the required signal at the receiver side is calculated with respect to gains and losses of the communications system. The result of this equation is the signal margin of the received signals' level to the required signals' one to achieve a specified communication performance. Generally, this performance is based on the bit error rate (BER). In laser communications between the micro satellite and the GEO satellite, the signal delivering is expressed in the equation which is written as below:

$$P_r = P_t\, G_t\, L_t\, L_R\, G_r\, L_r \qquad (3)$$

P_r…the receiving signal power (dB),

P_t… the transmitted optical power at the output of the transmit antenna (dB),

G_t…the effective transmitting antenna gain (dB),

L_t…the efficiency transmitter loss (dB),

L_R…the free space range loss (dB),

G_r…the receiving antenna gain (dB),

L_r…the efficiency loss associated with the receiver (dB), To consider the feasibility of using laser communications between the micro satellite and the GEO satellite, a rough link budget, which is shown in table 7, is calculated based on the reference [8]. This budget shows that with low transmitting laser power (2 W) and small size of the optical telescope (5 cm diameter of the optical antenna), the communication link for LEO-GEO communication can be achieved at a data rate of 1 Gbps with a margin of 5.3 dB. Discussion on several factors of this link budget such as: laser source, optical antennas, losses and receiver is mentioned below.

Table 10: Reference Point Calculation of Link Budget for LEO-GEO communication

Transmit power (dBm)	33
Transmit power (W)	2
Frequency (THz)	1.93
Wavelength (μm)	1.55
LEO Tx antenna diameter (m)	0.05
LEO Tx antenna gain (dB)	103.5
Distance (km)	40,000
Path loss (dB)	-290.2
GEO Rx antenna diameter (m)	0.35
GEO Rx antenna gain	117
Receiver power (dBm)	-44.1
Receiver sensitivity (photon/bit)	90
Data rate (Gbit/second)	1
Required power (dBm)	-49.4
Link Margin (dB)	5.3

3.3.1.1. Laser source

A laser includes an extremely high cavity resonator and an energy amplifier. By pumping the medium to a higher level metastable energy state, amplification is created. There are several types of laser. Normally, the type of material used as the "gain medium" will determine the type of laser. Three types of laser are often used for communications systems are solid-state lasers, gas lasers, and semi-conductor lasers. According to the book "Laser satellite communications" [15], the most viable technology for long-range space communications is the solid-state laser. The most popular solid-state laser is the Neodymium:YAG (yttrium, aluminum, garnet). In this type of laser, the medium is a rod made of a crystalline material (YAG) lightly doped with neodymium. The neodymium ions are pumped to a metastable energy state by optical energy of high intensity tungsten filament lamps or continuously operating ion arc lamps. One advantage of this type of laser is that it can produce extremely high peak output powers. A recently developed version of the Nd:YAG laser achieves the efficiencies necessary for a space borne laser communications system by utilizing arrays of semi-conductor laser diodes to pump the Nd:YAG rod.

3.3.1.2. Optical Antenna

a) Antenna Gain

In RF communications, electromagnetic energy is transmitted by utilizing the propagation. This energy can be transmitted or collected by utilizing antennas. The objective of using these specific equipment is to direct the transmitted energy to the receiver on the transmitting side and focus the transmitted energy on the receiving side or

Similar to RF communications systems, optical antennas are also used to direct the transmitted energy. For optical systems, a design telescope plays a role as an optical antenna for the system. Based on system requirements, the size and geometry of the telescope will be decided. Therefore, in each of satellite, a telescope is integrated to direct the laser beams for tracking and communication. The transmitting gain and receiving gain are calculated as formulas:

$$G = \eta(\frac{\pi D}{\lambda}) \tag{4}$$

where D is the telescope diameter (m) of the transmitter or the receiver, η is the optical efficiency (scalar) of the lens and λ is the optical wavelength (m).

b) Antenna Efficiency

In RF systems, as considering the efficiency of antennas, the most important issue is about the appropriate impedance matching. The impedance of the antennas must be matched with the impedance of the feeder lines so that energy from transmitters can go through both of them smoothly. That means there is no reflected energy in every parts of RF systems. Meanwhile, in optical systems, this impedance matching issue is related to the precision of optical coatings on the surfaces at the optical elements such as mirrors and lenses. Therefore, in laser communications systems, each optical element must be manufactured with a very high quality to improve the efficiency. For example, the surfaces of the mirrors inside the optical system must be extremely flat so that laser beams can be reflected accurately. Or alignment of optical components is also very important in the optical systems.

3.3.1.3. Propagation Loss

Transmission loss reduces to the free space loss is expressed as in Eq. 2 below:

$$L_R = \left(\frac{\lambda}{4\pi d}\right)^2 \tag{5}$$

where d is the distance between the two satellites.

3.3.1.4. Receiver

At the receiver, a semiconductor device which converts energy of light into electrical signals by releasing and accelerating current conducting carriers within the semiconductors. This device called photodiode (PD). Working principals of photodiodes operate based on photoconductivity principals, which is an enhancement of the conductivity of p-n semiconductor junctions due to the absorption of electromagnetic radiation. The diodes are generally reverse biased and capacitive charged [16]. There are two types of photodiodes which are used commonly. They are the PIN photodiode and the avalanche photodiode (APD) because they have good quantum efficiency and semiconductors which they are made of are widely available [17].

An avalanche photodiode is a sensitive semiconductor based photo detector. This electronic device requires a high reverse bias for its operation. Carriers including electrons and holes are excited by absorbed photons are accelerated in the strong internal electric field, so that they can generate secondary carriers. Then, the avalanche process will amplify the photocurrent by a significant factor. Therefore, avalanche photodiodes can be used for very sensitive detectors, which need less electronic signal amplification and are less susceptible to electronic noise.

Generally, if a high detection bandwidth is required, the noise performance of APDs is better than that of ordinary PIN photodiodes. However, if lower detection bandwidth is needed, a PIN photodiode combined with a low-noise narrow-band amplifier can be a better choice. Depending on the device and the reverse voltage applied, the multiplication factor (or gain) of APDs can vary from 50 to 1000. For long wavelengths, APDs based on germanium or indium gallium arsenide (InGaAs) are used. InGaAs APDs are really more expensive than those based on germanium, but exhibit good noise performance and a higher detection bandwidth. Because of this characteristic, the APD type is chosen as the receivers in the communication model of this research.

3.3.1.5. Noise

Optical wavelengths there are basically two types of noise to be considered in the laser communications system: thermal (or Johnson) noise and quantum (or shot) noise [18]. Thermal noise originates within the amplifiers and load resistors internal to the detection system while quantum noise has components both internal and external in origin. Quantum noise internally generated is caused by dark current. The quantum noise produced by external sources is proportional to the total radiation incident on the detector and, therefore, is caused by both the information signal and the background radiation environment in which the system operates. In this research, these two dominant types of noise are considered to affect to the communication link.

3.3.2. Link Budget Trade Off

From Eq. 3, there are several ways to do the trade off analysis so that the communication can be improved:

1) Increasing the transmit power. The simplest way to improve the received signal power is increasing the transmitting power. However, when the transmitting power increases, the total power consumption of the laser system also increases. In the case of big satellites, the power problem can be solved by integrating large areas of solar panels to create more power for laser systems. Nevertheless, small power consumption is one of the constraints of micro satellites. Thus, there is not much freedom in adjusting the transmitting power to improve the communication performance between the micro satellite and the GEO satellite. Furthermore, the increased power consumption causes big changes in the thermal system design of the satellites.

2) Increasing the transmitting aperture. The bigger the aperture of the transmitting antenna is, the narrower the laser beamwidth becomes. Therefore, the gain of the antenna will increase and thus improve the communication link. This effectively reduces the transmit beamwidth and hence improves the power delivery efficiency. However, the aperture of the antenna must be considered carefully since increasing the aperture means that the mass of the optical will increase. Then the mass constraint of the micro satellite might not be satisfied. Another critical point is related to the pointing and tracking issue. Since, the laser beams become smaller when the diameter is bigger, increasing the diameter means the pointing of laser beams is more difficult.

3) Reducing the operating wavelength. Reducing the diffraction loss of the signal by reducing the optical wavelength is another way to improve the link performance. Nevertheless, determination of using which wavelength depends on the current technology of laser and detectors. Also, the transparency of the optical wavelength in the correspondence to the transmission environment will decide the optimal wavelength for the communication.

4) Increasing the receiver aperture area. The total gain of the system can be improved by increasing the aperture of the receiving antenna. Obviously, the bigger mirror extends the ability of receiving the laser signal from the transmitting satellite. Similar to the case of increasing the aperture of the transmitting antenna, this option causes the increasing of mass of the structure. However, in the communication model where the receiver system is integrated in the GEO satellite, the size may not be the critical constraint. One important point is that the size of the receiving antenna can not be increased significantly because the background noise increases when the receiving mirror becomes bigger and that makes the communication impossible.

5) Reduced pointing loss. Reducing the pointing loss improves the overall signal energy and also reduces the point-induced signal power fluctuation.

6) Improving the overall efficiency, including transmit and receive optical loss, and polarization mismatch losses. This generally requires attention to the optical design. Of particular attention is the transmit optics design.

3.4. Satellites Design

Both of the micro satellite and the GEO satellite are constructed of several subsystems. Each subsystem includes specific hardware and software. They play important roles in a satellite so that they help the satellite to operate and achieve its missions. Basically, one satellite consists of 7 main subsystems: On-board Computer (OBC), Communication subsystem (COM), Attitude Determination and Control subsystem (ADCS), Power subsystem (EPS), Thermal Control subsystem, Structure subsystem and Payload subsystem. In Figure 3.2, all of basic subsystems of the micro satellite or the GEO satellite are depicted.

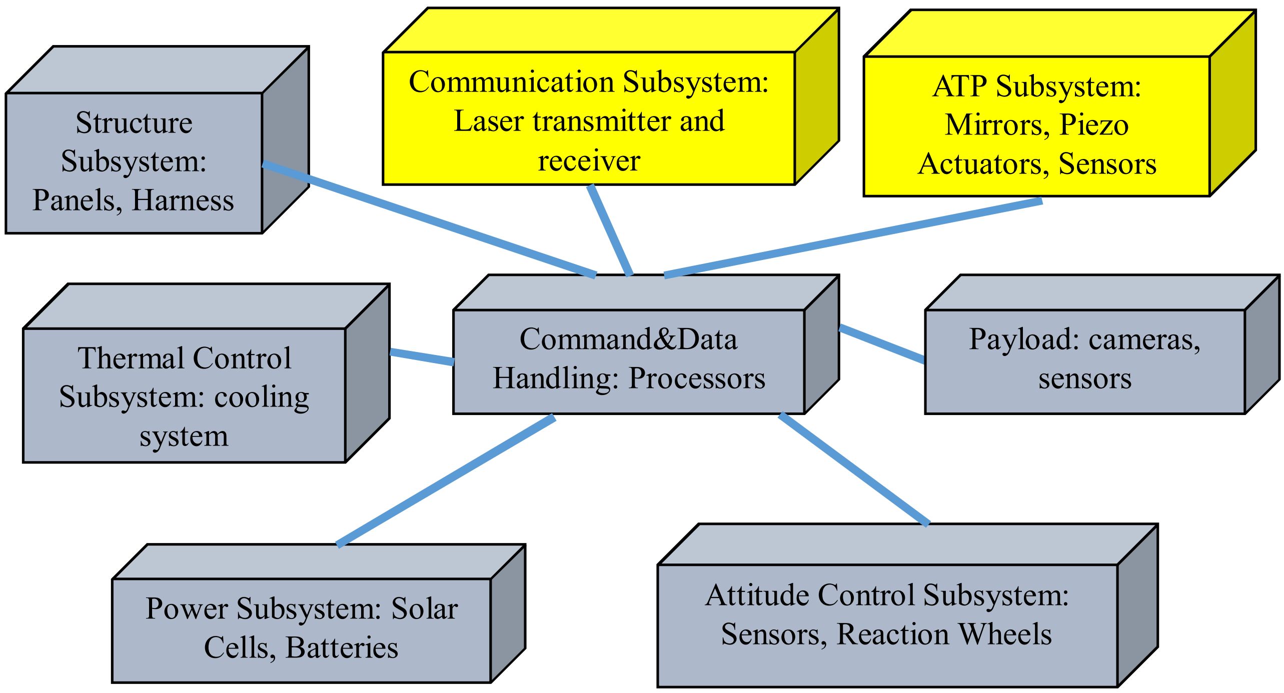


Figure 3.2: Basic subsystems of a Micro Satellite or a GEO satellite

a. Onboard Computer Subsystem

This subsystem is considered as a brain of a satellite. The On Board Computer refers to the computer of the satellite's subsystem where the on board software run. All of activities of a satellite are managed by this onboard computer. Some tasks which is implemented by the OBC subsystem are maintaining timing, receiving and processing commands from the ground, collecting, processing and packing telemetry data which is to be returned to the ground. Besides, this subsystem manages high-level fault protection and safing routines. There are several ways to name this subsystem such as: Command and Data subsystem (CDS). Command and Data Handling subsystem (C&DH), Computer Command subsystem (CCS), and Flight Data Subsystem (FDS). There is one portion of the OBC memory is used to store command sequences and programs which are uplinked from the ground. These commands and programs are normally created by the satellite teams and end users. In the model of laser communications between the micro satellite and the GEO satellite, processors which will be designed as the OBCs must have enough processing capability to calculate the position of the counter satellite and send commands to control the optical system.

b. Attitude knowledge and control subsystem

For almost of satellites, Attitude Determination and Control Subsystem (ADCS) must be required for doing their missions. Sometimes, the satellites have to point to the Sun to get solar energy by using solar cells to absorb the Sun light. Besides, in order to do main missions in LEO which are mostly remote sensing applications, the satellites have to change their attitude so that the side which is integrated with their payloads is directed toward the Earth. Then, the payloads are able to take images, measure atmospheric elements and so on. In the case of GEO satellites, the ADCS subsystem helps the satellite to remain its relative position with the ground constantly. Basically, this subsystem is constructed of sensors and actuators. The sensor devices support the two satellites to determine their positions in a coordinate system. Several types of sensor are Sun sensor, Earth sensor and Star Tracker. In order to control the attitude of the satellites, actuator components are needed. Reaction wheels are the ones to control most accurately. Even though in this research, control of the optical systems is implemented by the ATP subsystems, the role of the ADCS subsystems of both of the satellites is very important because vibration of the two platforms becomes a disturbance for the optical control system. Consequently, these subsystems are required to be designed so that they can minimize the disturbance of both of the two satellites to their optical control system.

c. Structure subsystem

In satellites, structure subsystem provides a place and space to attach components internally and externally. Moreover, due to the severe environmental conditions in space, it is mandatory to protect components of satellites by stabilizing thermal and mechanical conditions so that all of components can operate normally. The structure subsystems establishes the basic geometry of the two satellites, and it provides the attachment points for appendages such as booms, antennas, and scan platforms. It is also support for the circuit boards of equipment, data recorders, computers, gyroscopes, and other components. Without the structure, the satellite will not able to be transported during construction, testing, transportation, and launch. In the two satellites in this research, this subsystem has to deal with how to place the optical systems in the whole structures stably and accurately.

d. Communication subsystem

Communication or telecommunications subsystem is responsible for providing interfaces between satellites and ground stations or between satellites. Depending on requirements of missions, components are chosen for a particular satellite. Basically, distances, planned frequency bands, data rates and available on-board transmitter power are all considered to design communication subsystems. For radio communications system, this subsystem includes radio transceivers and RF antennas. However, in this research, since laser is used for propagating signals, laser transceivers and optical antennas will be used instead. The requirement of this subsystem of the micro satellite is mentioned in Table 9 such as the laser data rate is 300 Mbps, the laser output power is less than 10 W.

e. Power subsystem

Electrical Power Subsystem (EPS) is the crucial subsystem for every satellites. Without power which is provided by this subsystem, satellites are not able to operate and do the mission in space. This subsystem, first, is responsible for generating power from Sun lights. The traditional way of generating power is using solar panels. Many solar cells are attached into the structure surfaces of the micro satellite or the GEO satellite to get the energy from the Sun and convert to electrical energy. This energy then is stored in the battery system of the satellite to provide for satellite operation. The EPS subsystem is also in charge of distributing power to all of components during the operation time of the satellites. In this research, this subsystem must be designed so that it can provide enough power for the micro satellite and its optical system. In the GEO terminal, power requirement might not be the problem because of its strong configuration.

f. Thermal subsystem

Since in space, thermal conditions are more severe and very different from on the ground. All of the components of the satellites are manufactured so that they can work in this harsh condition. However, to assure all of them can work effectively, it is required to keep the temperature of the satellite in a given range. That is the main responsibility of the thermal subsystem. It consists of several mechanisms to keep the temperature of components, panels or spaces of the satellites as designed. In the model of communication between the micro satellite and the GEO satellite, this subsystem is very important in the GEO one because it needs to keep temperature of the receiver in the GEO satellite less than 100 K to gain the communication performance.

g. Payload subsystem

The payload subsystem includes components which will do the main mission for the satellites. For example, for the micro satellite, the main payload can be a camera which can take pictures of the surface of the Earth for monitoring disasters or agriculture. Traditional cameras are the optical types. Recently, Synthetic Aperture Radar (SAR) camera is integrated in LEO satellites to get more information of the ground because this new type of camera can take pictures by using radio waves. In the GEO satellite, the main payload is mainly used for communication purpose. It can be a very complicated RF system to communicate with a big ground station. In this research, the payload subsystems of both of the micro satellite and the GEO satellite are not discussed in detailed

h. Acquisition, Tracking and Pointing subsystem

As mentioned above, the ADCS subsystems of the two satellites are responsible for controlling their attitude so that they can do missions. However, in case of implementing laser communications, because of extremely long distance between the two terminals, using only the ADCS subsystem is not enough to satisfy the stringent pointing requirements. Therefore, a new subsystem, namely Acquisition, Tracking and Pointing must be included to control the optical systems of the two satellites. The main role of this subsystem is to assure the two optical antennas in the two satellites are able to point and track each other fast and accurately. Since this subsystem plays a very important role to make communication happen, a detailed discussion on it is mentioned in the next section.

3.5. Acquisition, Tracking and Pointing System

The most challenge in the communication between a micro satellite and a GEO satellite is to achieve sub-microradian level pointing accuracy in the presence of satellite's vibration. In traditional systems which use RF communication, the beam pointing requirement is loosen when a 1m antenna operating at X band requires a pointing control accuracy of 0.1 – 0.5 degree, and the same antenna operating at Ka band requires a pointing accuracy of a few milliradians. However, in optical communication, it is needed to develop a dedicated pointing control subsystem as a part of the flight laser communications system design so that the two satellites are able to point to each other whenever they have LOS for communication with extremely stringent pointing accuracy. It is called Acquisition, Tracking and Pointing (ATP) mechanism and the correspondent subsystem named ATP subsystem.

3.5.1. Acquisition, Tracking and Pointing Strategy

Before communication between the micro satellite and the GEO satellite can be occurred, the link must be established. Even each satellite can use the orbital information of the other one to determine its position, it is impossible to point the laser communications beams in open loop between two satellites at the beginning [19]. That is because the communication beam is too small to be pointed to the counter satellite in the presence of attitude errors and structural misalignments within the satellites. Moreover, mechanical perturbations in the platform of the satellites make it even harder to point the communication beam in open loop. Therefore, a laser beacon which has wide beam will be implemented in the GEO satellite so that it can help to start the communication link. Then, during the time when the micro satellite is illuminated by this laser beacon, it calculates the position of the GEO satellite. After adding an angle to the calculated result, the narrow laser beam of the micro satellite will be pointed to the predicted position of the GEO terminal.

3.5.2. Acquisition, Tracking and Pointing Functional Description

Because the micro satellite in LEO and the one in GEO do not know about each other's position, it must be required to have pre-pointing and open loop Line Of Sight steering of both satellites.

The wide laser beam of the GEO satellite must be used as the reference for the pointing of the micro satellite to the GEO satellite in the initial phase. The GEO terminal will use this beacon beam over to scan the uncertainty cone systematically to search the LEO one. This event can be done by using the orbital information of the two satellites. The beacon beam will be scanned in a given pattern through the region that the micro satellite is predicted to be appeared. Simultaneously, the micro satellite uses the orbital information to point its optical system to the GEO satellite.

The micro satellite in LEO waits and detects the beacon beam and align the reception LOS with the received beam.

The LEO satellite emits the telecom beams towards the GEO terminal and the GEO one will align the reception LOS with this telecom beam.

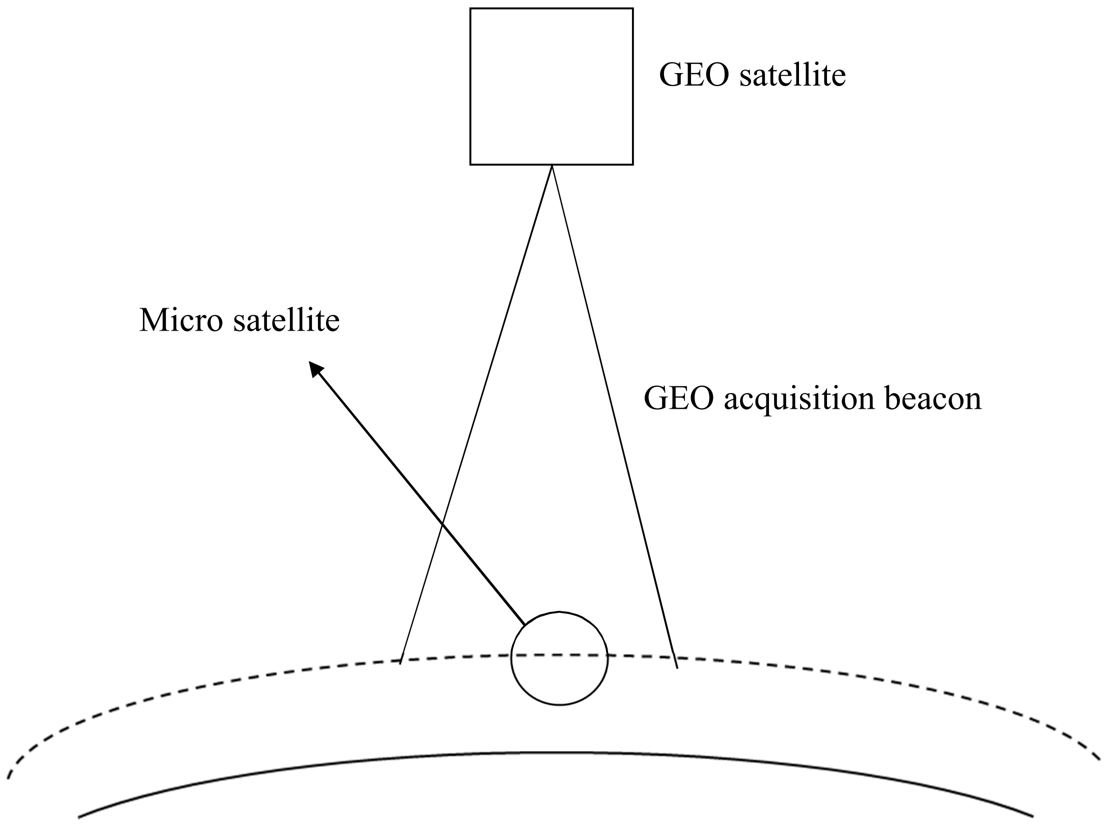


Figure 3.3: The GEO satellite searches the location of the micro satellite by using a wide laser beacon

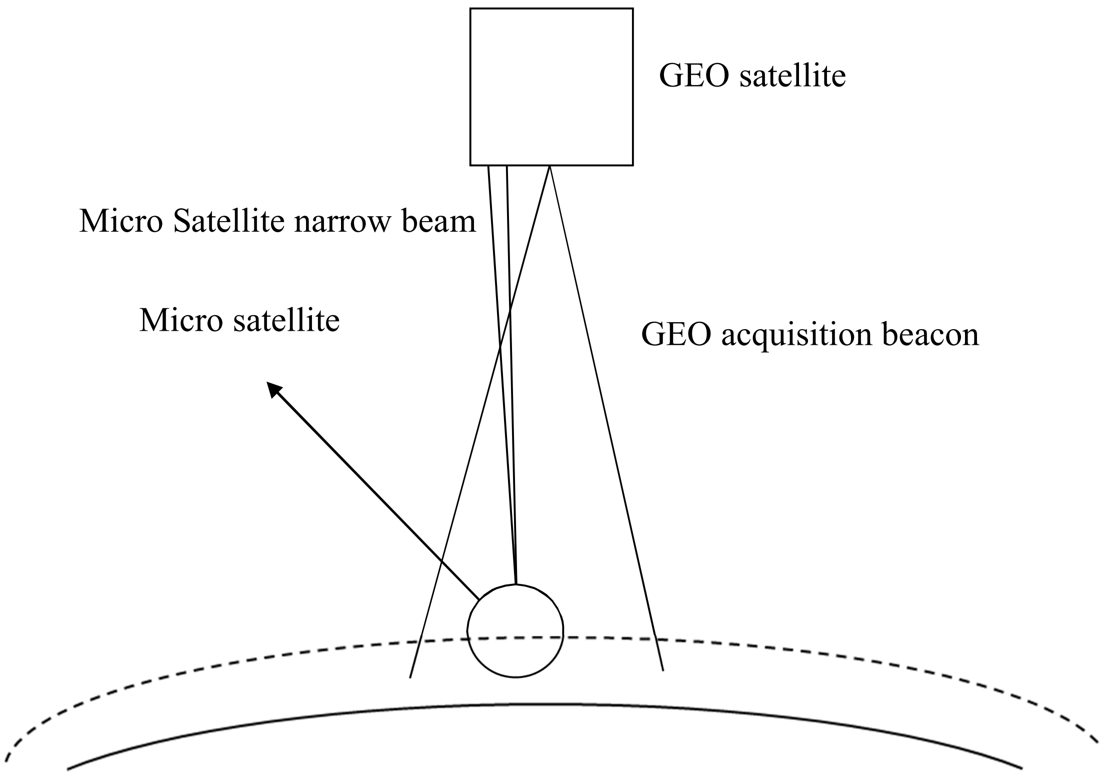


Figure 3.4: The micro satellite tracks the position of the micro satellite and points a telecommunication beam to the GEO satellite

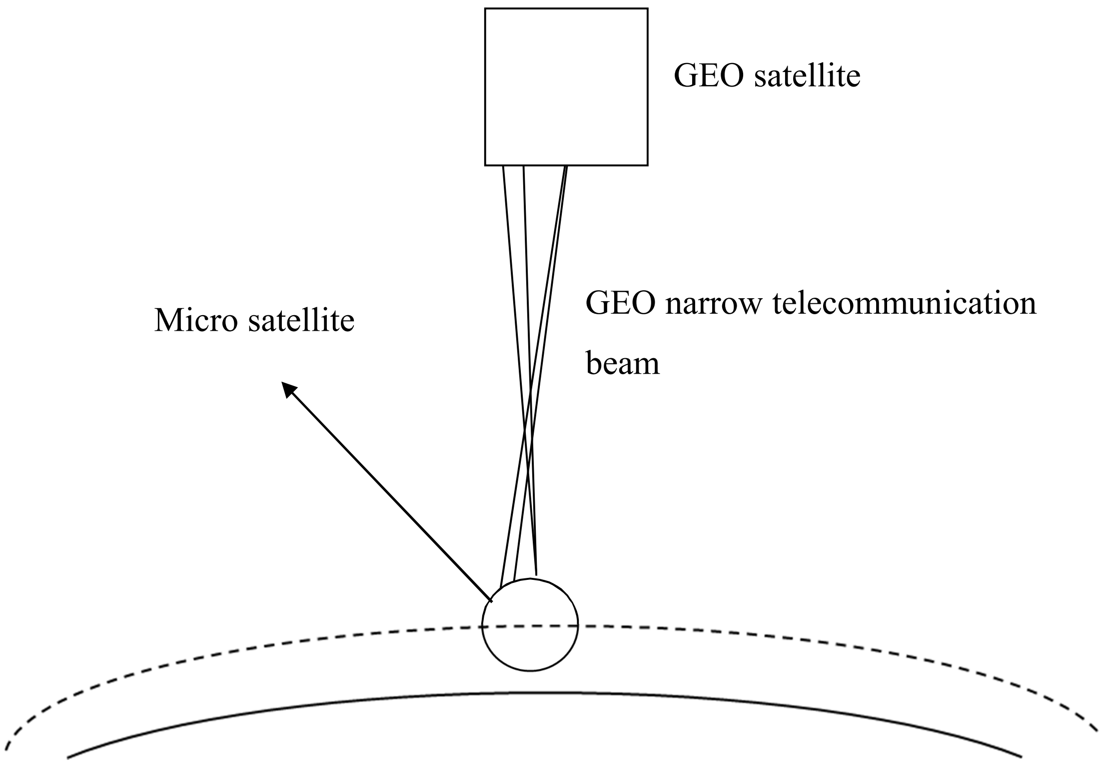


Figure 3.5: The GEO satellite calculates the micro satellite's position and sends back a narrow laser beam to the micro satellite

To minimize the scanning time of the GEO satellite, the precision of the Open loop Line Of Sight steering is very important. Therefore, the uncertainty cone of the scanning must be smaller than the acquisition sensor Field of View (FOV) on LEO.

Another critical point is the acquisition time. The LEO satellite must be illuminated constantly by the transmitted beacon beam of the GEO satellite. This strategy, therefore, puts stringent constraints on the acquisition timing.

The angular velocity of the micro satellite is different from the one of the GEO satellite. That is because it moves around the Earth in LEO while the position of the GEO satellite is in GEO. In theory, the spacecraft in LEO which is nearer the Earth than the one in GEO will have higher angular velocity. This difference of angular velocities causes the change of relative positions of the micro satellite and the GEO satellite. The illustration of relative movement of the two satellites in different orbits is shown in Figure 3.6. Consequently, the final function of the ATP systems must be included, namely Point Ahead Angle (PAA). This function assures that the correspondent angles to the changes of relative positions of the two satellites must be added before laser communications beams are transmitted toward the counter satellites.

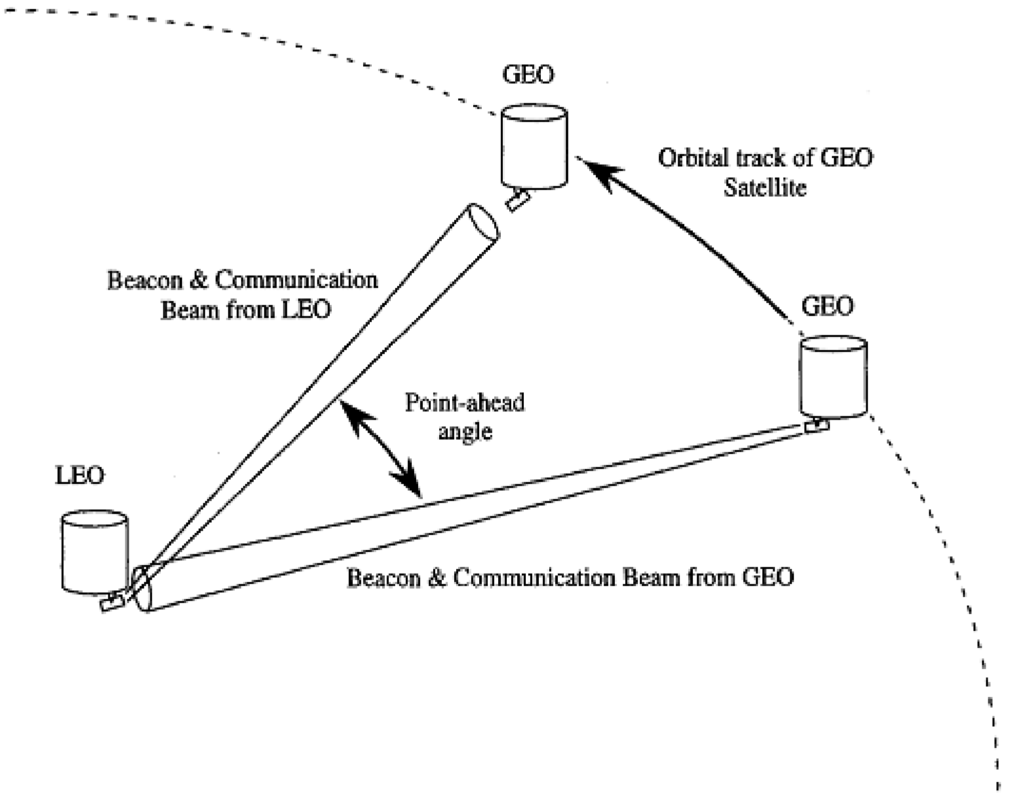


Figure 3.6: Transmitter point ahead [20]

3.5.3. Acquisition, Tracking and Pointing Design

From the strict requirements of the ATP mechanism, it is required to have two subsystems to control the optical systems of both of the micro satellite and the GEO satellite. One subsystem is a coarse pointing system and the other one calls a fine pointing subsystem. As mentioned in section 3.5.2, at the first phase of communication, both satellites need to point toward each other using the orbital information that they receive from the ground or GPS satellites. While the GEO satellite uses the information to scan a region that the micro satellite is predicted to be appeared, the micro satellite also uses the information to point its optical system to the direction of the GEO one to catch the laser beacon. Because both of the satellites are moving with the velocity of several km/s, initially, the two optical systems must be controlled wide enough so that they can follow and cover the range of movement of the two spacecraft. This is the main responsibility of the coarse pointing subsystems. In order to do that, two components are included in the coarse pointing subsystem. They are a Charge-Coupled Device (CCD) sensor and a driver unit. After two optical systems are pointed to each other roughly by using the coarse pointing subsystems, a fine pointing mechanism must be needed to make the communication happen. It is impossible to use only the coarse pointing subsystems to achieve sub-microradian level of the pointing accuracy requirement as mentioned in section 3.2. Therefore, the fine pointing subsystems will be in charge of correcting the direction of the laser beams in the presence of vibration of two platforms. In contrast with the coarse pointing mechanism, fine pointing must be done very fast and in an extremely small range of movement. One design can be used as the fine pointing subsystem consists of a Fast Steering Mirror (FSM), piezo actuators and a quadrant detector (QD) position sensor.

A block diagram of the ATP systems of the two satellites is shown as in Figure 3.7.

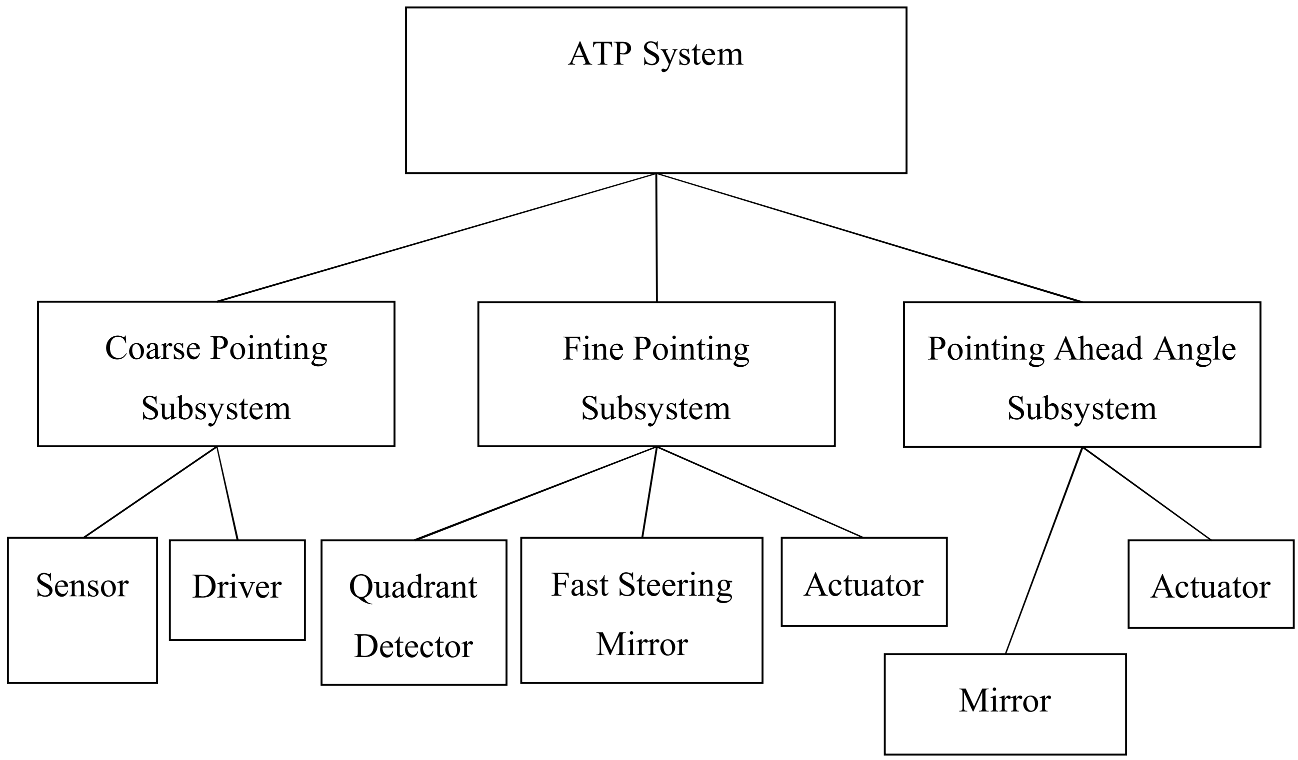


Figure 3.7: Block diagram of ATP system

Then, Figure 3.8 shows the relationship between the subsystems inside the ATP system and how laser communications can be done by using it. As discussed above, the coarse and fine pointing subsystem control the optics so that the two optical systems can point to each other accurately, thus maintain the communication link. After that, before generated laser signals are transmitted to the counter satellite, the PAA subsystem will add a calculated angle to control these signals so that they can be emitted to the predicted position because of relative motion of the two satellites. Several hardware components of the ATP system are described in the next sections.

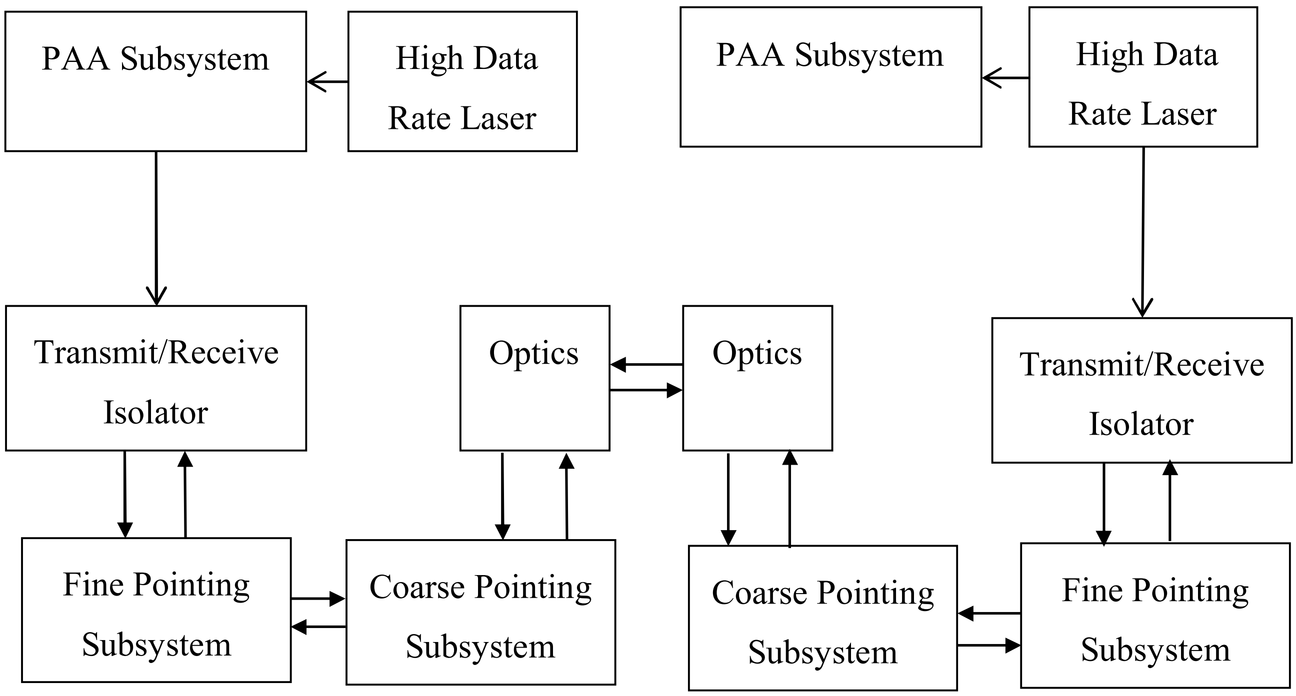


Figure 3.8: Laser communications is implemented by using the ATP system

3.5.3.1. Fast Steering Mirror

Fast steering mirrors (FSM) are used in many optical system applications. A FSM can be used to perform several functions including tracking, scanning, pointing, line of sight stabilization, and alignment. It represents a mirror that is mounted over actuators in order to produce fast and precise movements. To perform tilting around the axis, the linear actuators are arranged in twos per axis. The working principle of a FSM is shown as in Figure 3.9.

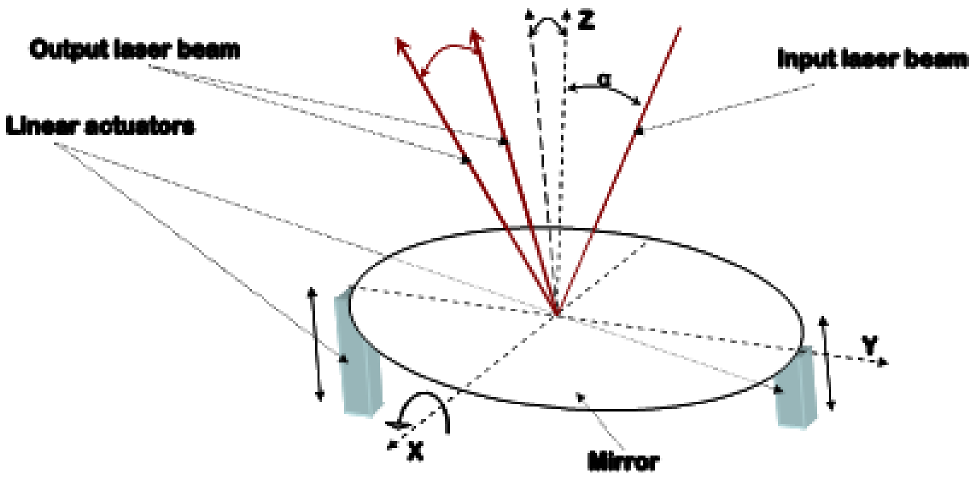


Figure 3.9: Fast Steering Mirror principle [21]

As can be seen in Figure 3.9, a coordinate system is attached to the mirror with origin which is the center of the mirror. The linear movement along the Z axis of actuators creates a torque then leads to a rotation of the mirror along the Y axis. When the mirror is rotated, the input laser beam will be reflected with the different angle α, which furthermore allows introducing a control over the pointing of the output signal along the X axis. The Figure 3.9 shows the relationship between the change of mechanical angle around one axis of the XY plane and the change of the reflected angle of the output beam. That is the change of the optical angle of the output beam is twice the change in the mechanical angle around one axis of the XY plane. The requirement for this special component is that it needs to be made with high quality enough so that it can reflect laser light accurately.

3.5.3.2. Actuators

In order to control a FSM quickly and accurately, an actuator system is needed. Normally, there are 3 types of actuators which are used to control FSMs. The first type is the piezo actuator. The working principle of piezo actuators is using the effect of crystals and ceramics. Fundamentally, when high voltage is applied across the crystal, the dimensions of the crystal or ceramic will be changed. This material will expand in the direction of the electrical field. Reversely, it is shortened in the direction which is perpendicular to the electrical field. As the result, the FSM will be controlled in a proper manner. Two couples of the piezo actuators are enough to support the FSM movement to track laser lights. Working range of this type of actuators is in the micrometer region. The advantage of this actuator is generating large pushing force for small movements. However, this device needs high voltage range to make the piezo effect happen and also consuming power. An example of piezo actuators is shown in Figure 3.10.

Figure 3.10: Physik Instrumente S-334 device (piezo driven) [22]

Another common type of actuator is voice coil actuators. The working principle of voice coils for FSM is based on the interaction between a fixed magnet and an electromagnet, formed by a coil around a magnetic core. When current is flowing through the coil the electromagnet gets polarized interacting with the magnetic field of the fixed magnet. A push pull configuration is achieved and the electromagnet moves towards or against the fixed magnet when the polarity of the current is varied. Voice coil mirrors are able to achieve a good resolution with less power than for the piezo driven ones. However, their bandwidth is smaller.

Figure 3.11: Sapphire TT25 (with voice coils) [23]

The last type of actuator is motorized actuators which based on stepper or dc servo motors. This type can be used for slow speed and low resolution control. The disadvantage of this actuator is the friction between the rotor and the mirror mount. Therefore, it is not suitable for using this type to control in some applications that require fast and precise motion. In this research, piezo type is chosen as the actuator for the fast steering mirror. The resolution requirement for this component is less than 5 μrad.

3.5.3.3. Position Sensor

The sensor which is used to detect and correct the laser beam position in the fine pointing subsystem is a quadrant detector. It is a silicon photo detector with four active photodiode areas. This detector has the ability to measure extremely small changes in the position of a light beam. Four photodiodes in a quadrant detector are equal and separated by small gaps. The arrangement of the four photodiodes is shown in Figure 3.12. When the light hit to these photodiodes, they convert it to current which is then transformed into relative voltage levels with a specific gain by the operational amplifier circuits. By comparing the signal received from each of the four separate photodiodes, the position of the incident light, relative to the center of the device, can be determined. If the beam is in the perfect center, the currents of the four photodiodes will be the same. The equations express for the x and y displacements relative to the center of the quadrant detector are as in Eq. 6 and Eq. 7:

$$x = \frac{(B + C) - (A + D)}{A + B + C + D} \tag{6}$$

$$y = \frac{(A + B) - (C + D)}{A + B + C + D} \tag{7}$$

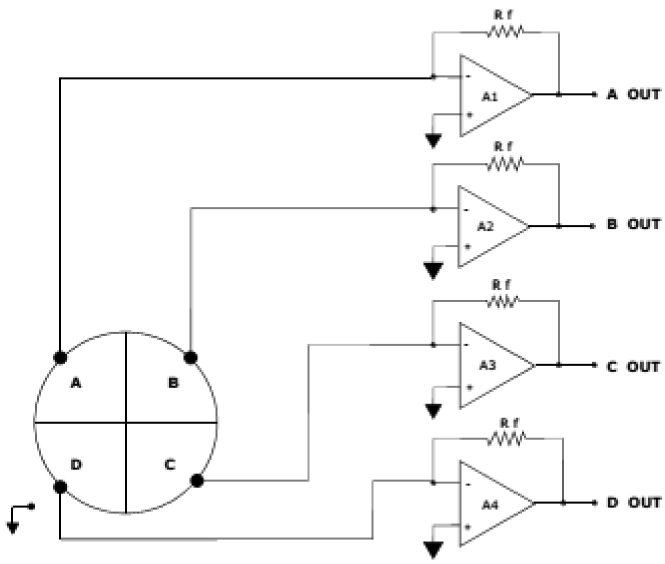


Figure 3.12: Quadrant Detector of EOS [24]

CHAPTER 4. SIMULATION AND ANALYSIS

4.1. Simulation of the Communication Link

A model of the laser communications link from the micro satellite to the GEO satellite is built by the Optisystem software. Several parameters can be changed as the input for the communication model such as transmitting laser power, antenna diameters, transmitting pointing error, receiving pointing error, etc… while the BER will be the output of the model. At the receiver side, noise of the avalanche photodiode is considered. According to the article "Integrated approach to airborne laser communications" [25], thermal noise and shot noise are two typical sources of noise of laser communications. Then, when the simulation is started, input parameters are tuned to see how they affect to the communication link. The objective of this simulation is to verify the communication link between the micro satellite and the GEO satellite and find out a good design point for the optical communications system. The diagram of the communication model is shown in Figure 4.1.

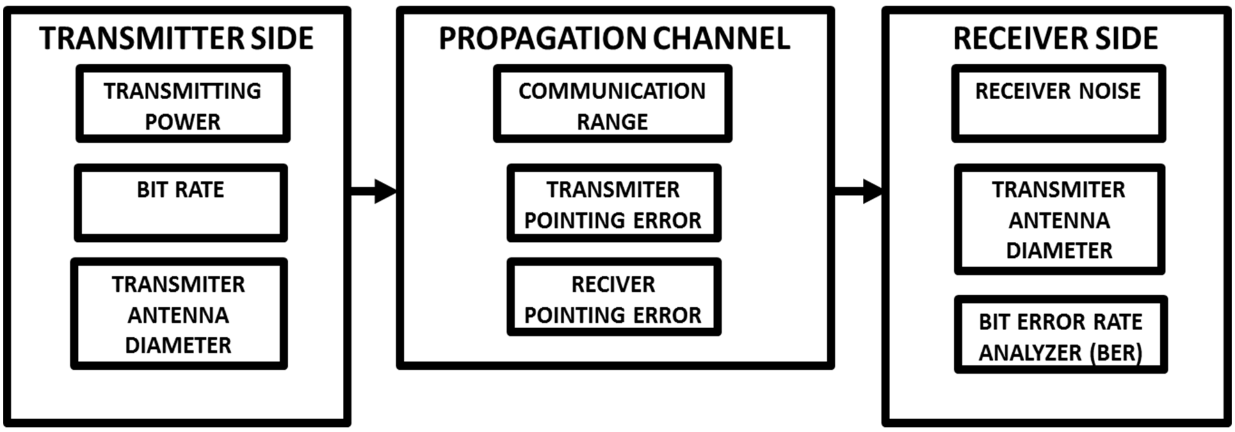


Figure 4.1: Block diagram of the communication link

The Figure 4.1 shows the communication of both directions. The first direction is from the micro satellite to the GEO one while the second direction is on the reverse way. The goal of the research is focused mainly on the link from the micro satellite to the GEO satellite. The link simulation is built as in Figure 4.2 by the Optisystem Software.

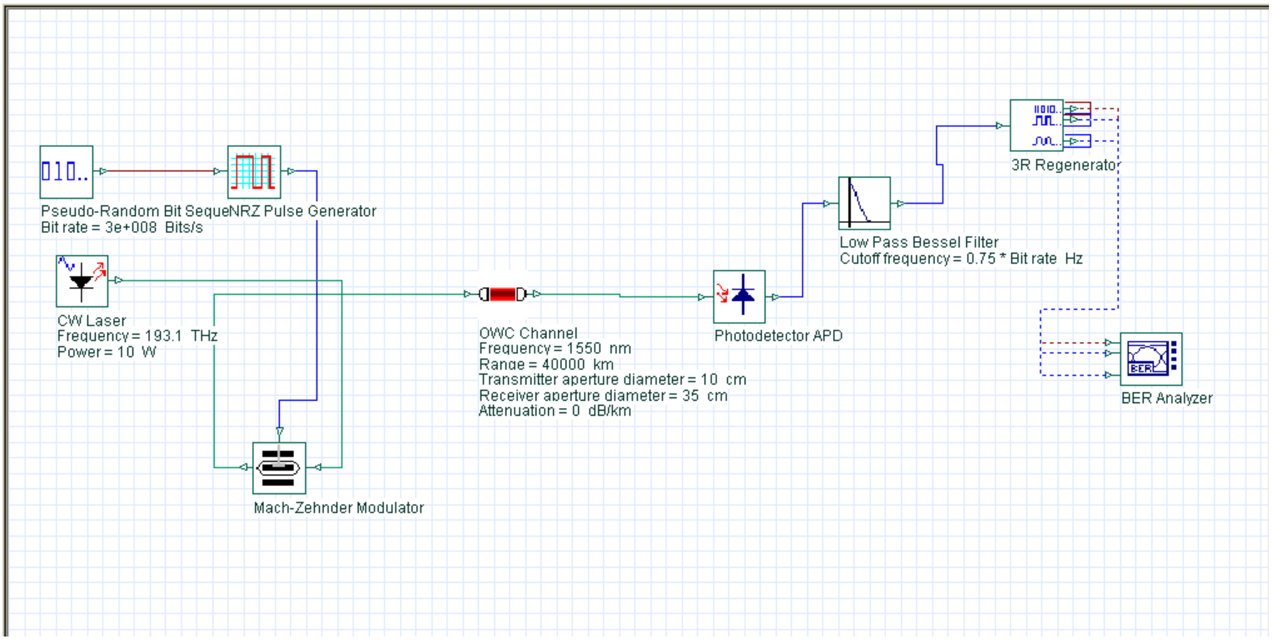


Figure 4.2: Layout of the link simulation

Optisystem is a simulation software produced by Optiwave Company. This software is a professional tool to simulate communication links of many advanced optical systems. It includes a library of optical components so that designers can choose to create optical networks that they want. Besides, measurement and analysis tools are also available to check the operation performance and visualize results to the users.

In the communication link in Figure 4.2, the transmitter includes a pseudo random generator, non-return-to-zero (NRZ) modulator, continuous wave laser and a MachZehnder modulator. The first component of the transmitter side is the pseudorandom bit sequence generator (PRBS). This generator represents the stream of data that will be transmitted. This data which depends on missions is acquired from the payload subsystem of the satellite. The second component of the transmitter side is the NRZ pulse generator. The data from the pseudorandom bit sequence generator will be encoded by this component. The MachZehnder Modulator is the last component which is included in the transmitter side. It is an optical modulator whose functions are to vary the intensity of the light source according to the output of the NRZ pulse generator. In Optisystem simulation, the Optical Wireless Communication (OWC) channel represents for the propagation environment between the two satellites. The output of the MachZehnder modulator is transmitted to the counter satellite through this channel. The free space between two connecting satellites is considered as OWC channel which is the propagating medium for the transmitted light. In the OptiSystem software, the OWC channel is between an optical transmitter and optical receiver with 5 – 10 cm optical antenna at the side of micro satellite and 35 – 45 cm antenna at the side of the GEO satellite. The transmitter and receiver gains are 0 dBm. Optical efficiency of the transmitter and receiver antenna are assumed is equal to 0.9. There is no attenuation due to atmospheric effects between the micro satellite and the GEO satellite. The receiver is constructed of an avalanche photodiode, low pass filter and 3R regenerator. The photodiode is considered as a receiver that receives the optical signal and converts it into electrical signal. The APD photodiode has an internal gain mechanism to increase sensitivity of optical detection systems. The Low Pass Filter (LPF) after the photodiode is used to filter out the unwanted high frequency signals. This Bessel LPF is used with cutoff frequency of 0.75 x bit rate of the signal. The 3R regenerator is the component which is used to regenerate the electrical signal corresponding to the original bit sequence and the electrical signal is analyzed by the BER analyzer and Eye Diagram Analyzer.

4.2. Sensitivity Analysis

Initially, the simulation of communication from the micro satellite to the GEO one is conducted. In the reference [26], an ATP system was developed for quantum communication. In the experiment, the ATP system was put in a helicopter to make the communication with a ground station. The result in this paper shows that the pointing accuracy of 4.6 μrad could be achieved. Therefore, while the transmitting pointing error of the optical system of the micro satellite is chosen as 4.6 μrad, the receiving error of the GEO satellite is 0.9 μrad. In the reference [27], the authors discussed the key design features of LEO to GEO communication in case that the satellite in LEO, SENTINEL-1A, has the mass of about 2 tons. Referring to a table in this reference, 2 W is first considered as the transmitting power in the simulation. The aperture of the optical telescope in the micro satellite is 5 cm. On the receiver side, the diameter of the telescope is 35 cm. According to the book “Concise encyclopedia of magnetic and superconducting materials” [28], the Stir-ling system of a conventional GEO communication satellite can cool the temperature down to 77 K. This number is assumed as the temperature of the receiver in GEO orbit in this simulation. The distance between two spacecraft is 40,000 km and the data rate is 300 Mbps as mentioned in section 3.2. All of the parameters are summarized as in Table 11.

Table 11: Input parameters for the first configuration

Transmitting pointing error (μrad)	4.6
Receiving error (μrad)	0.9
Power (W)	2
Bit rate (Mbps)	300
Range (km)	40,000
Receiving diameter (cm)	35
Transmitting aperture (cm)	5

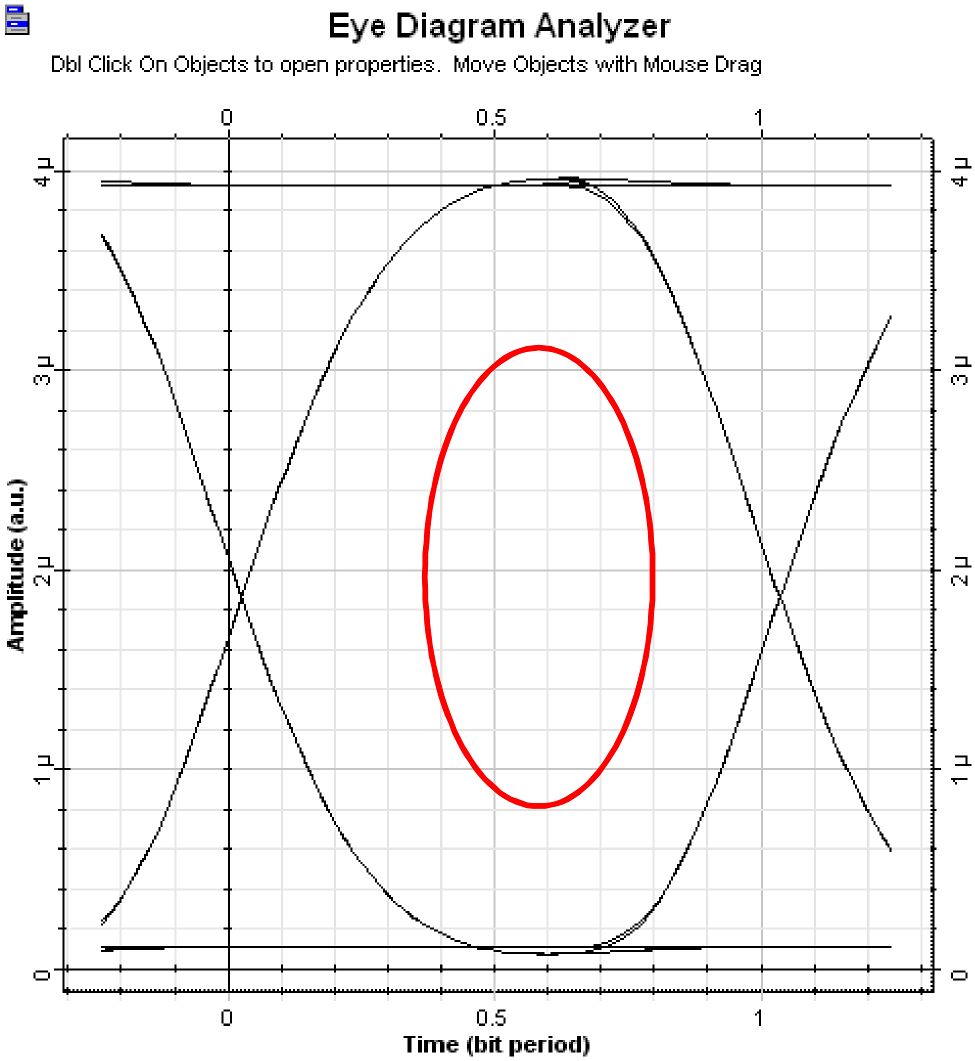


Figure 4.3: Eye diagram of the first configuration's simulation when no noise is considered

Both of thermal noise and shot noise of the avalanche photodiode receiver have not been considered this time yet. Therefore, BER in this simulation is 0. That means laser communications in this case is perfect. That can be seen in Figure 4.3 which the eye diagram is very clear. This eye diagram or eye pattern is another indicator of the optical communication performance. Ideally, eye diagrams look like an opening eye. When the signal strength is not strong enough or noise levels are too high, the eye will be deformed and show the bad communication performance. To check how noise affect to the laser link, first, thermal noise is added to the photodiode receiver. The result is shown in Figure 4.4.

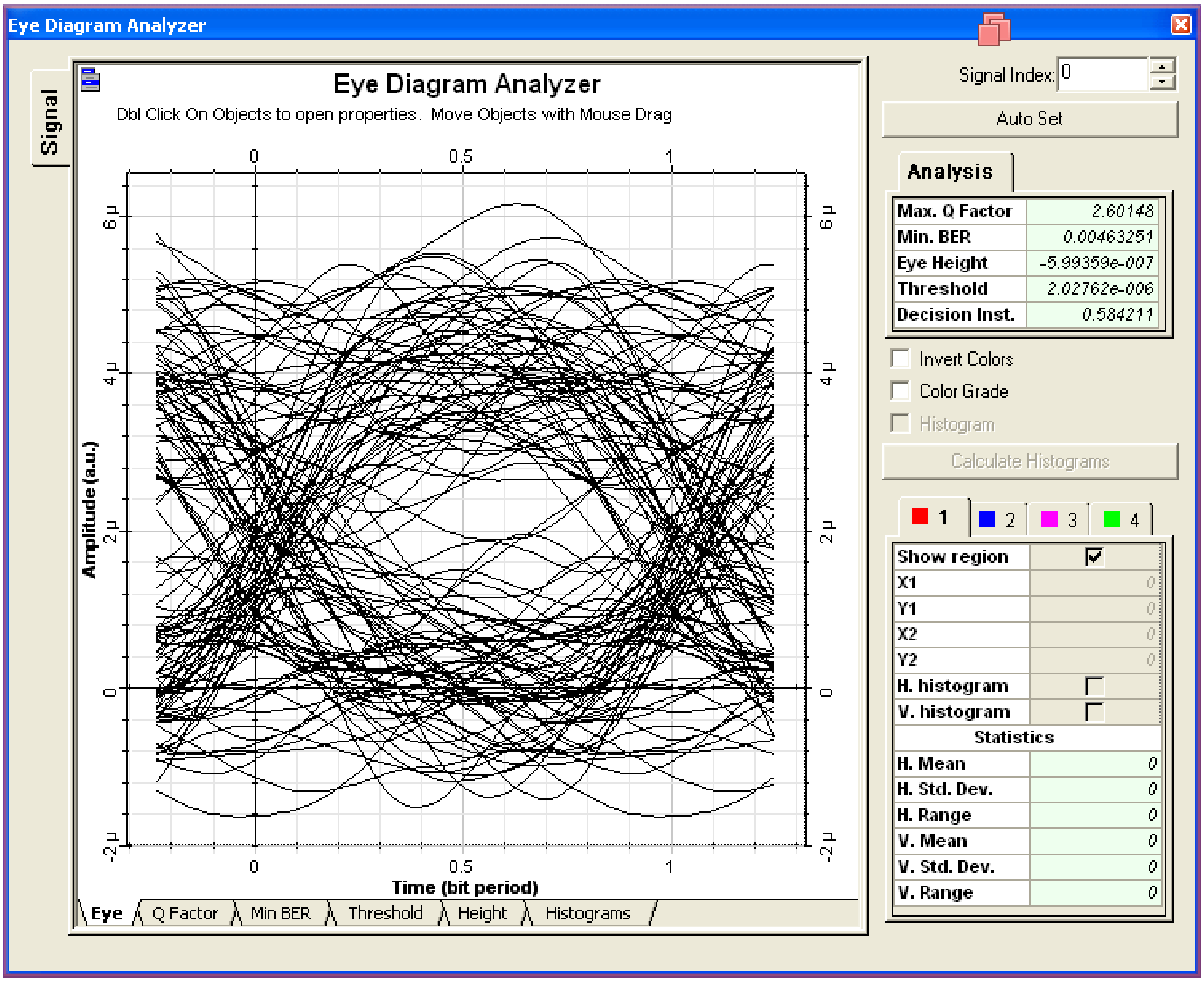


Figure 4.4: The BER performance of the first configuration when only thermal noise is added

As mentioned in Section 3.2, the BER requirement for successful communication is 10^{-6}. The result in Figure 4.4 shows that in this case, the BER is about 0.005 which can not satisfy the requirement. The eye diagram also shows the communication performance is not good enough for successful communication. Obviously, the eye is deformed significantly when thermal noise is considered in the receiver side comparing to the case of no noise. The similar situation happens when shot noise is added to the receiver instead of thermal noise.

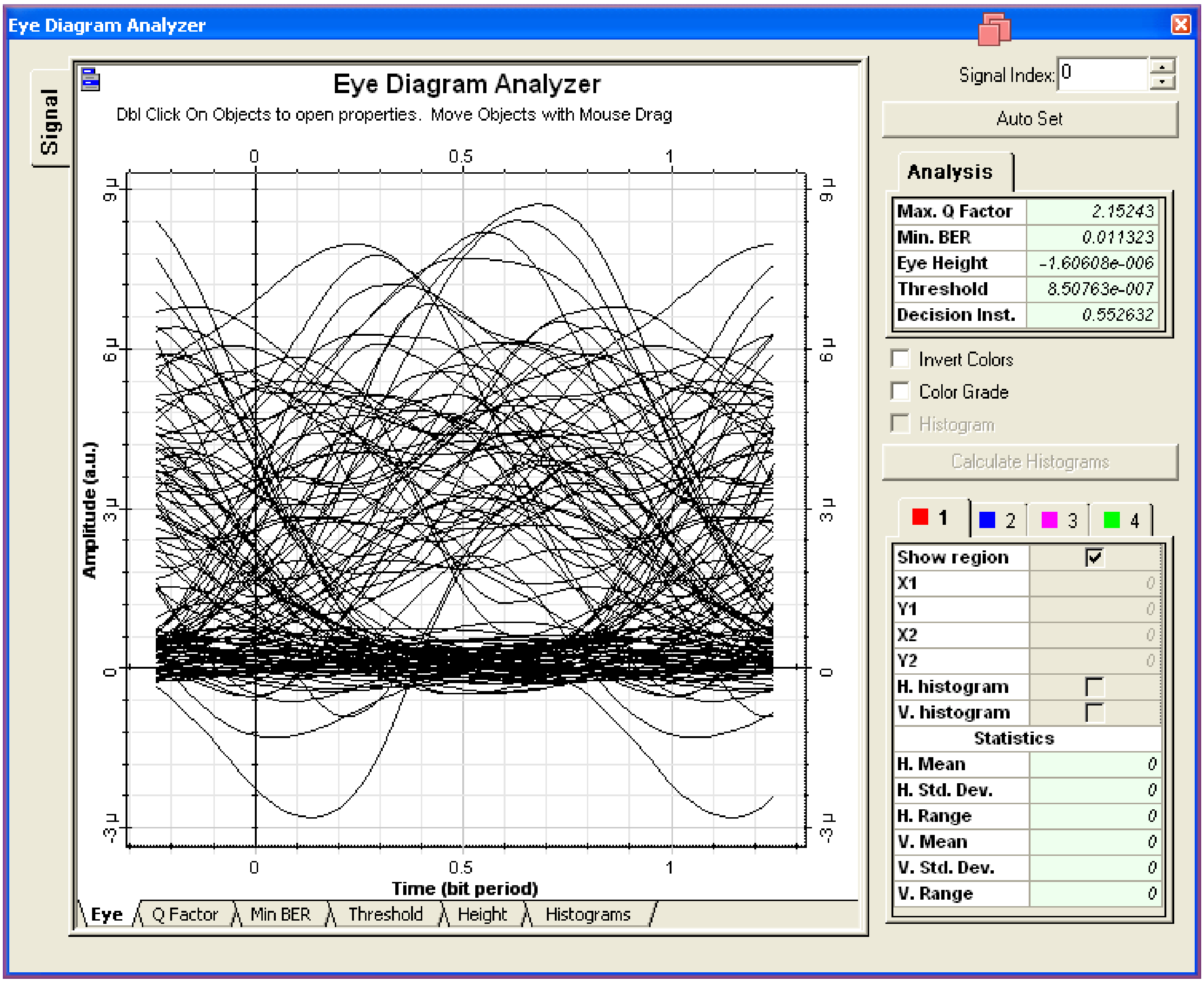


Figure 4.5: Eye diagram of the first configuration's simulation when only shot noise is considered

The eye diagram in Figure 4.5 shows that the communication performance is even worse than the case when there is only thermal noise. This can be also indicated in BER which is only about 0.01, much worse than the BER requirement for successful communication.

Final trial with the configuration shown in Table 11 is conducted with the presence of both of thermal noise and shot noise. The result shows in Figure 4.6. Communication in this case is impossible when BER becomes 1 and there is no opening eye in the eye diagram. Obviously, the communication performance depends considerably on how the two types of noise are processed in reality.

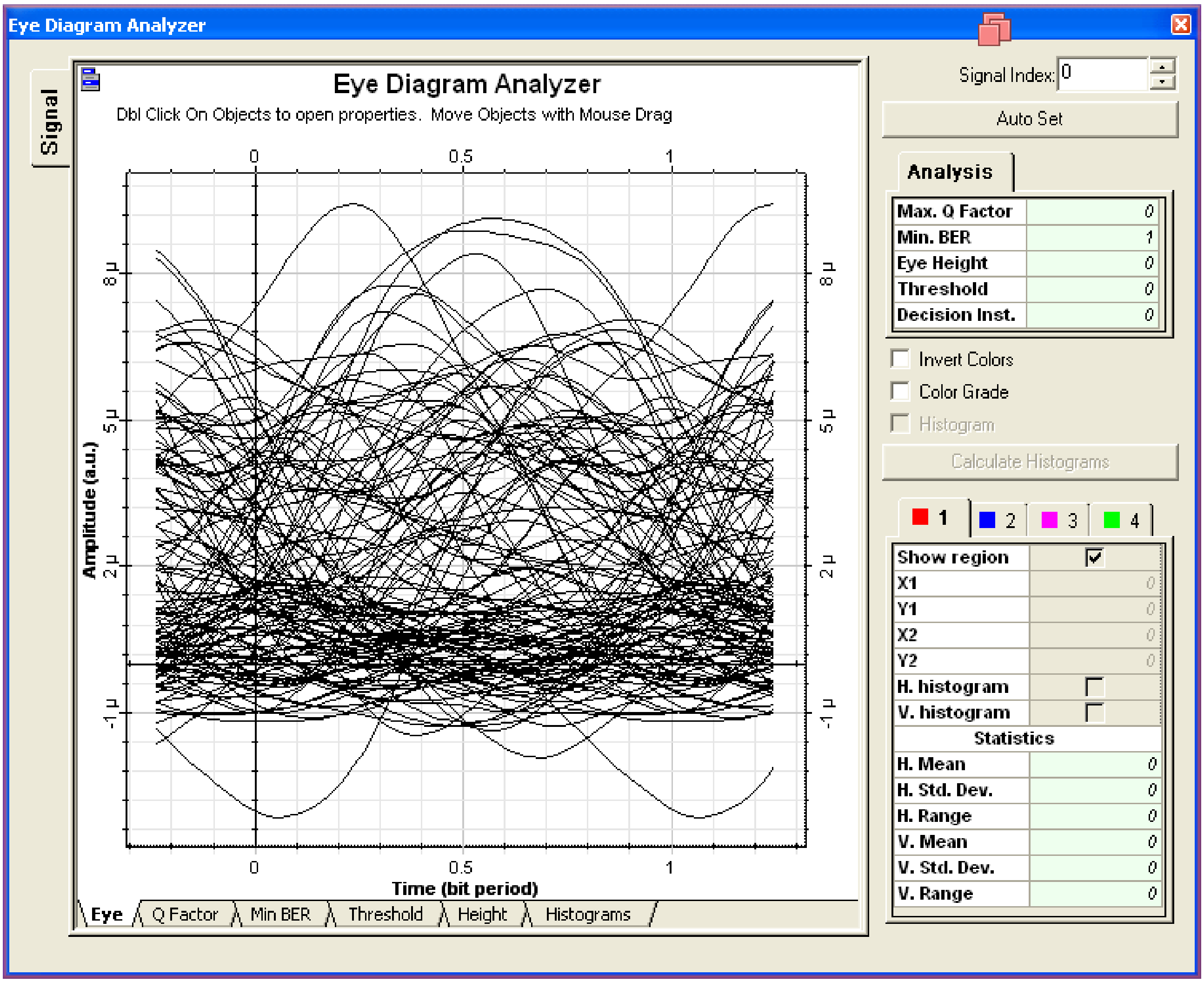


Figure 4.6: Eye diagram of the first configuration's simulation

when thermal noise and shot noise are both considered

Even when the aperture diameter of the telescope in the GEO satellite is increased to 45 cm at maximum and the temperature of the receiver is decreased considerably to 40 K which was achieved by the Japanese AKARI satellite [29], the communication link cannot be done successfully as shown in Figure 4.7.

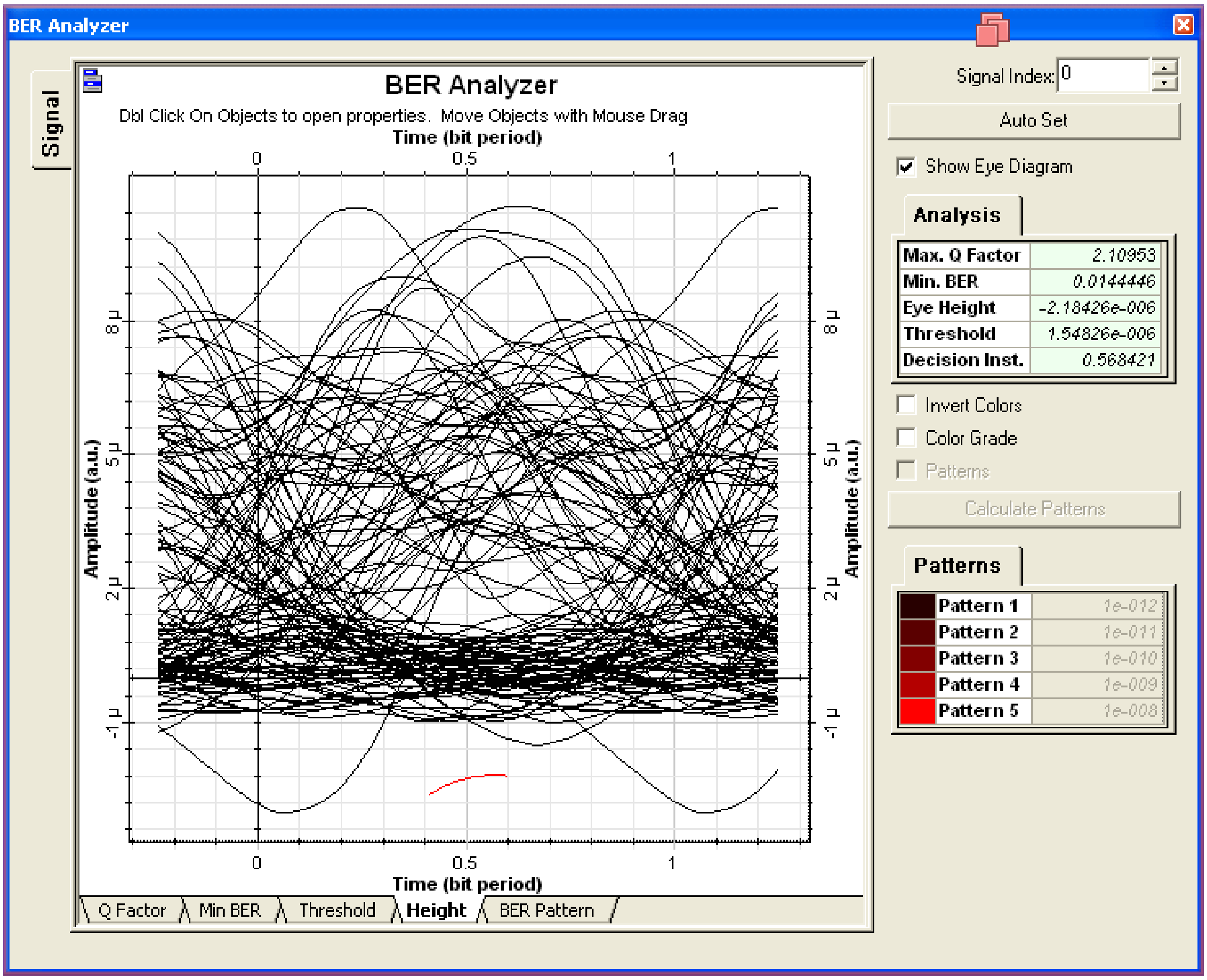


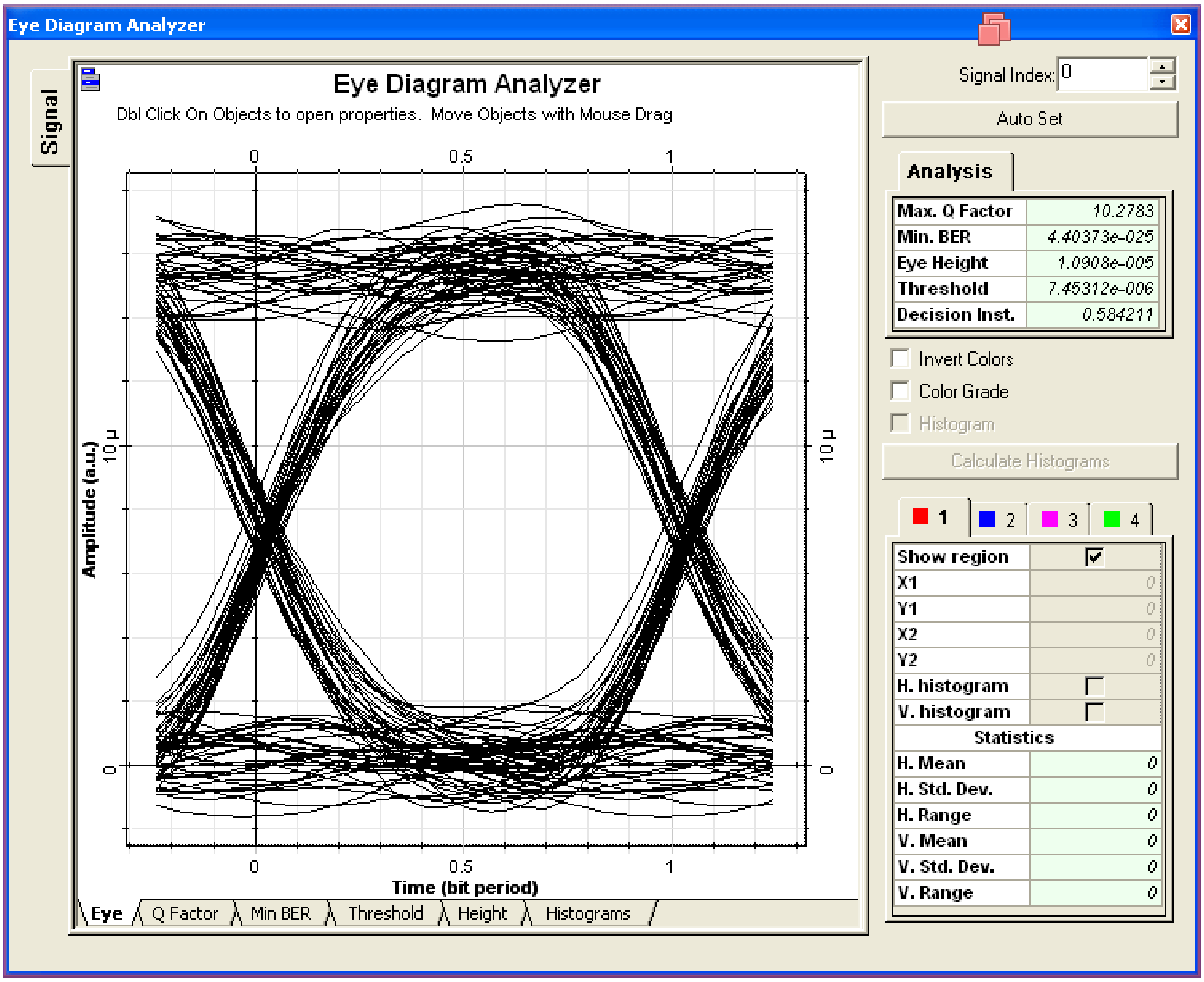
Figure 4.7: Eye diagram of the first configuration's simulation when the temperature of the receiver is 40 K and the aperture diameter of the telescope is maximized.

The above results of simulation pointed out that with the first designed set of parameters, communication from the micro satellite to the GEO satellite is not possible. Therefore, other two sets of designed parameters are tried for simulation. Following the constraints which were mentioned in section 3.2, one option is that all of parameters are in the middle of the constrained range whistle another one corresponds to the maximized values. They are summarized in Table 12. Based on the results of simulation, a good start point of designing might be found out.

Table 12: Input parameters for the second and third configuration

Transmitting pointing error (μrad)	4.6	4.6
Receiving error (μrad)	0.9	0.9
Power (W)	5	10
Bit rate (Mbps)	300	300
Range (km)	40,000	40,000
Receiving diameter (cm)	35	35
Transmitting aperture (cm)	7	10

At first, the temperature is still kept the same as in the simulation of the first configuration (77 K). Only thermal noise is added to the optical signal. Shot noise has not been considered this time yet. The result shows that in this simulation, the achieved BER for the second configuration is 4.4×10^{-25} while the result of the third configuration is 8.7×10^{-159} (Figure 4.8). These values totally satisfy the BER requirement. It can be seen from the figure that the opening eye is very clear because the quality of communication is very good.


Eye Diagram Analyzer
Signal
Eye Diagram Analyzer
Dbl Click On Objects to open properties. Move Objects with Mouse Drag
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0.5
1
Amplitude (a.u.)
10 µ
0
Time (bit period)
Eye
Q Factor
Min BER
Threshold
Height
Histograms
Signal Index: 0
Auto Set
Analysis
Max. Q Factor 10.2783
Min. BER 4.40373e-025
Eye Height 1.0908e-005
Threshold 7.45312e-006
Decision Inst. 0.584211
Invert Colors
Color Grade
Histogram
Calculate Histograms
1 2 3 4
Show region
X1 0
Y1 0
X2 0
Y2 0
H. histogram
V. histogram
Statistics
H. Mean 0
H. Std. Dev. 0
H. Range 0
V. Mean 0
V. Std. Dev. 0
V. Range 0

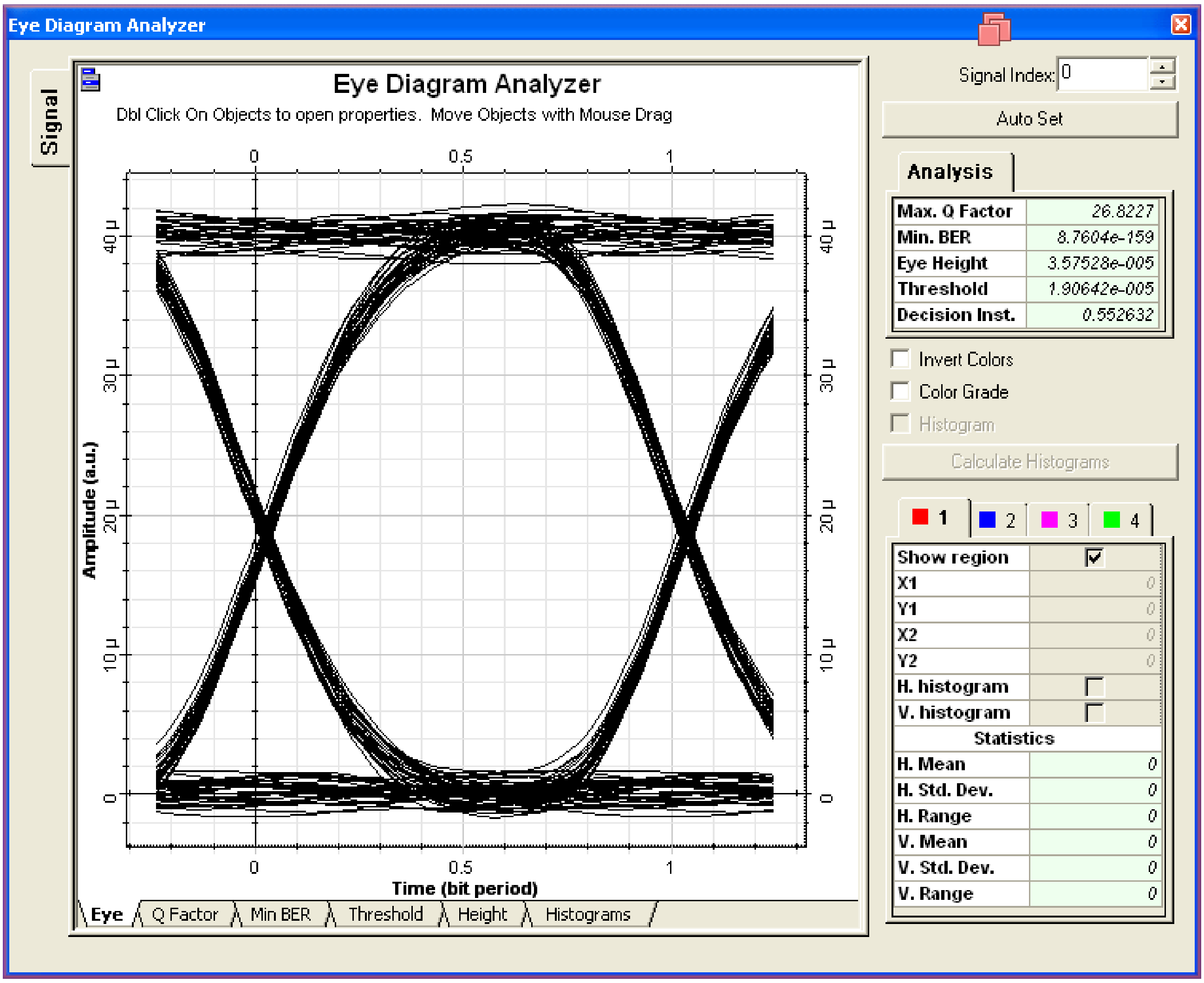
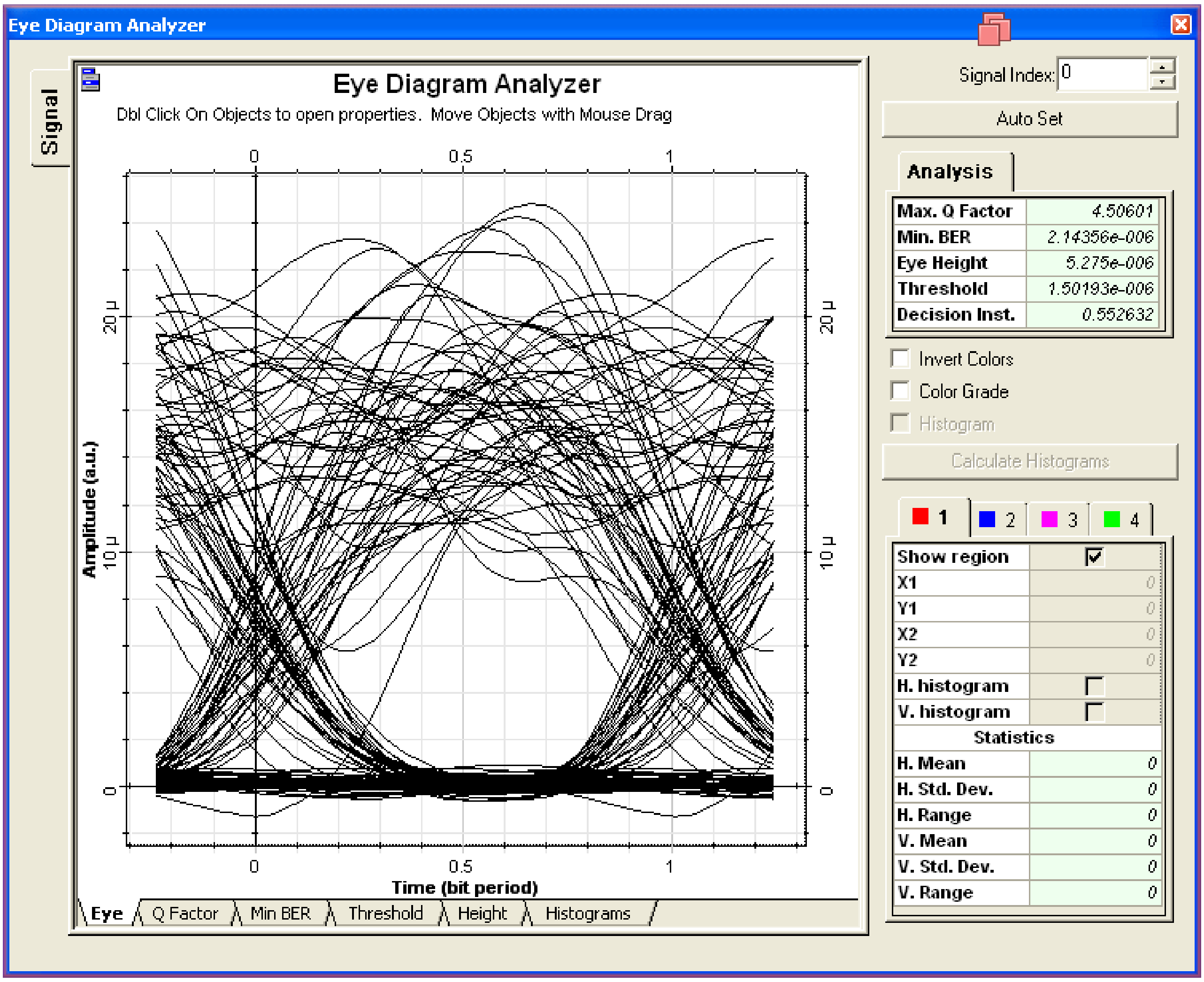


Figure 4.8: Two eye diagrams and BER of the second and third configuration's simulation when only thermal noise is considered

Another simulation is conducted when only shot noise is considered to affect to the communication link. The results are shown in Figure 4.9. In this simulation, the achieved BER are 2 x 10^{-6} and 4 x 10^{-12}. Comparing to the case of thermal noise, shot noise cause more severe degradation to the laser communications system than thermal noise.


Eye Diagram Analyzer
Signal
Eye Diagram Analyzer
Dbl Click On Objects to open properties. Move Objects with Mouse Drag
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Q Factor
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Height
Histograms
Signal Index: 0
Auto Set
Analysis
Max. Q Factor 4.50601
Min. BER 2.14356e-006
Eye Height 5.275e-006
Threshold 1.50193e-006
Decision Inst. 0.552632
Invert Colors
Color Grade
Histogram
Calculate Histograms
1
2
3
4
Show region
X1 0
Y1 0
X2 0
Y2 0
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V. Std. Dev. 0
V. Range 0

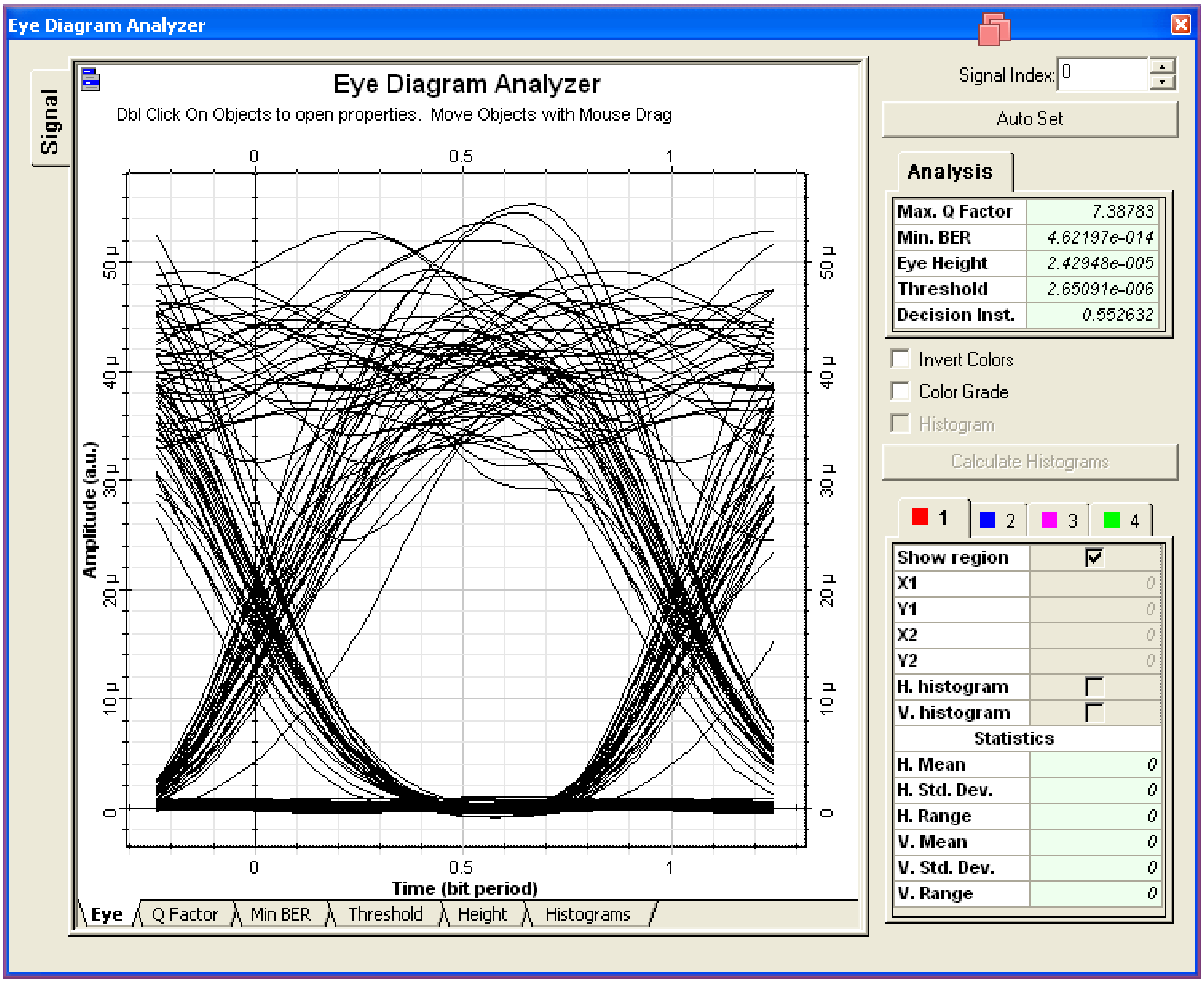

Figure 4.9: Two eye diagrams and BER of the second and third configuration's simulation when only shot noise is considered

However, when the shot noise is added to the simulation, the BER performance is degraded significantly. For the second and third sets of parameters, the BER results change to 3.3 x 10^{-5} and 2.58 x 10^{-12}, respectively (Figure 4.10 and Figure 4.11). Since the BER requirement is 10^{-6}, based on the results, the second configuration is selected as the good start designing point.

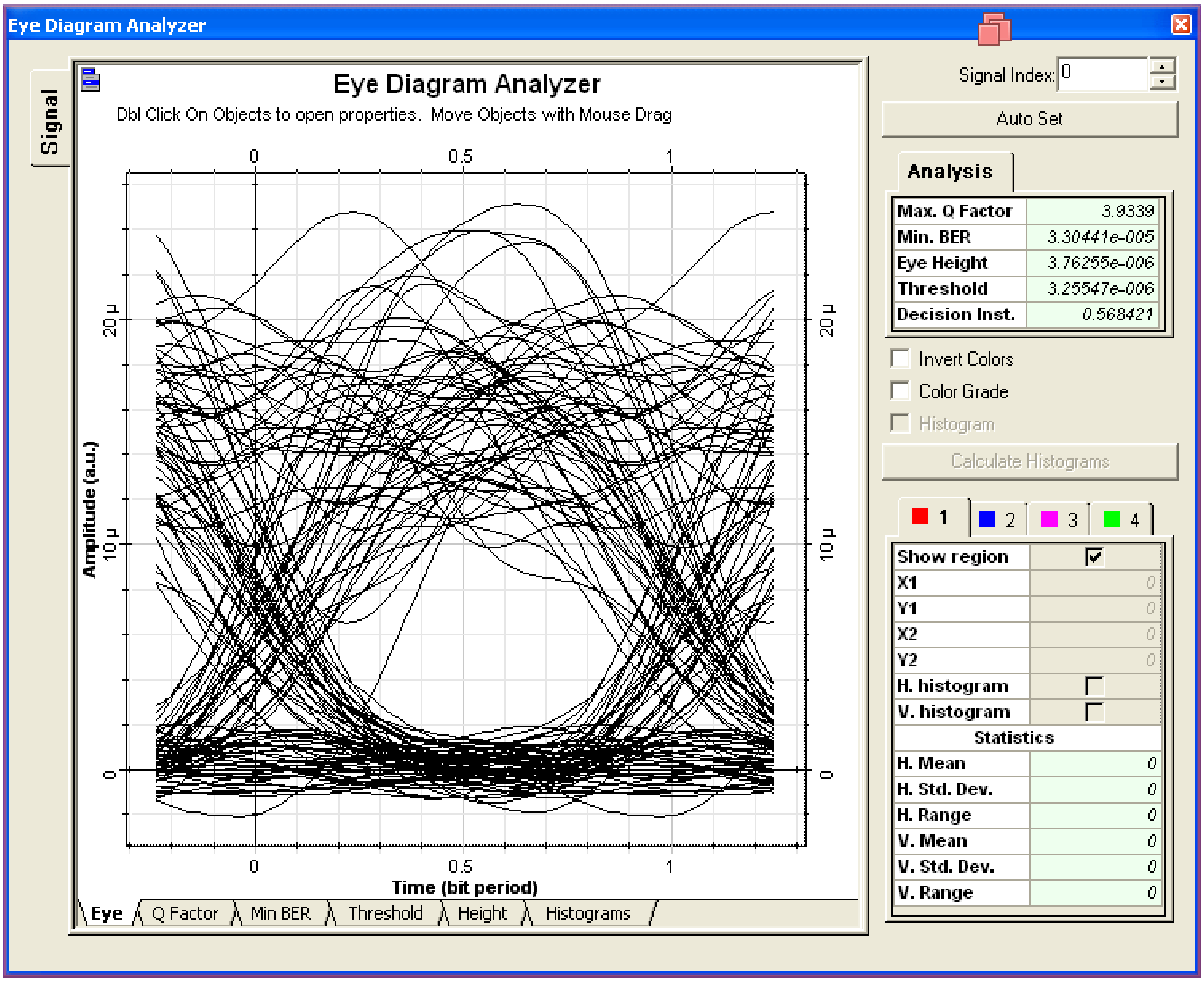

Figure 4.10: The eye diagram and BER performance of the second configuration's simulation when both of thermal noise and shot noise are added

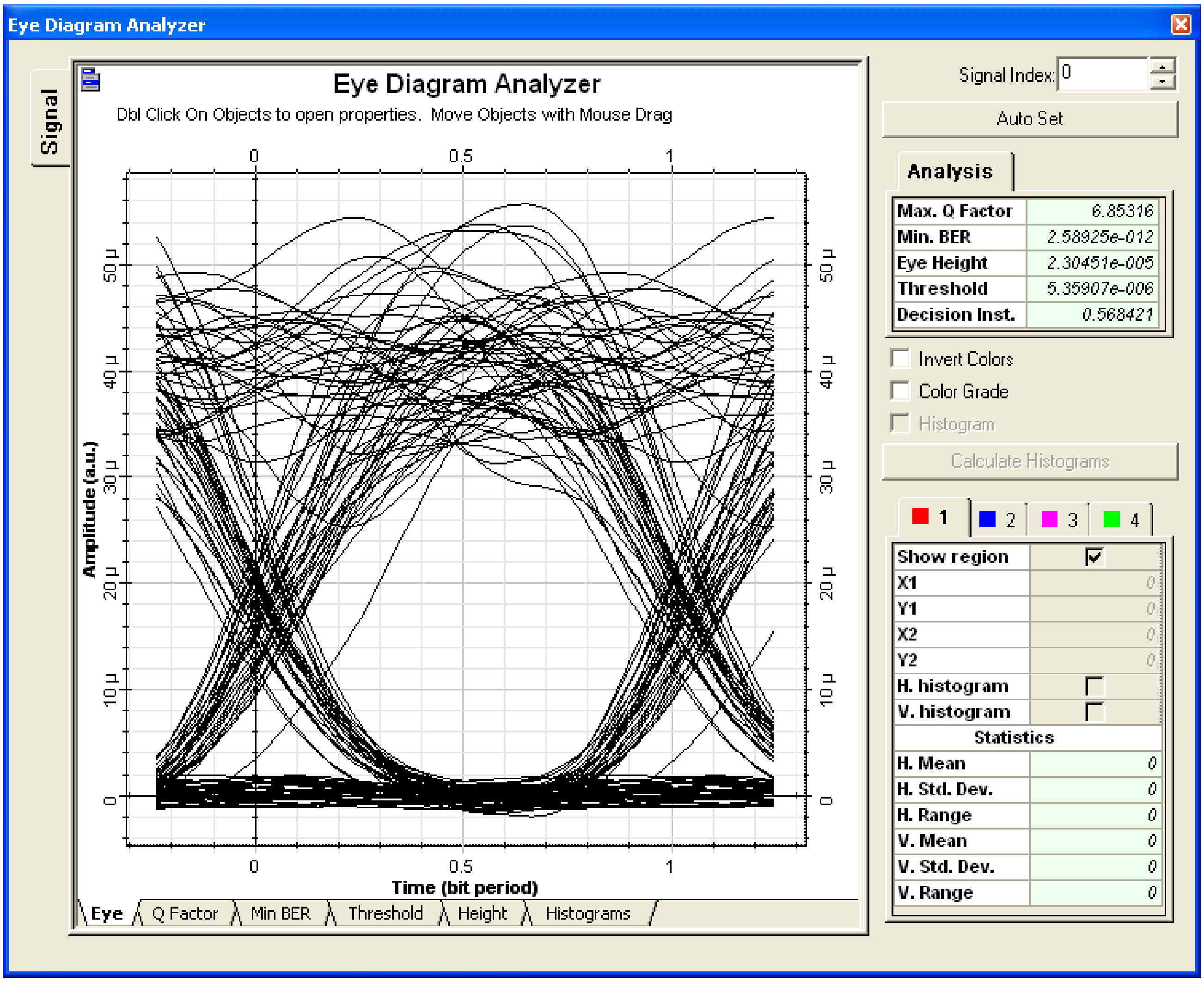

Figure 4.11: The eye diagram and BER performance of the third configuration's simulation when both of thermal noise and shot noise are added

At this moment, the BER of the second configuration's simulation can not satisfy the original requirement. However, depending on the types of users' data, in case that the BER requirement can be loosen to 10^{-5} or less, the second designed set of parameters will be able to become the best option for the micro satellite. In order to do that, instead of changing the configuration of the optical system in the micro satellite, the aperture of the telescope in the GEO terminal is swept from 35 cm to 45 cm to improve the performance. As can be seen in Figure 4.12, when the aperture diameter of the telescope in GEO is about 40 cm, 10^{-5} BER requirement can be achieved. Another solution to satisfy the BER requirement without changing the parameters of the micro satellite is decreasing the temperature in the receiver of the GEO terminal to improve sensitivity of the receiving sensor, then improve the communication performance. Using the value 40 K of the Japanese AKARI satellite, another simulation is conducted while the aperture of the telescope in the GEO satellite is kept as 35 cm. The final BER is approximate to 10^{-5}. In the case that the required BER is determined as 10^{-5}

or worse, a combination method between increasing the diameter of the telescope and decreasing the temperature of the receiver might be a good strategy to balance the resources of the GEO spacecraft.

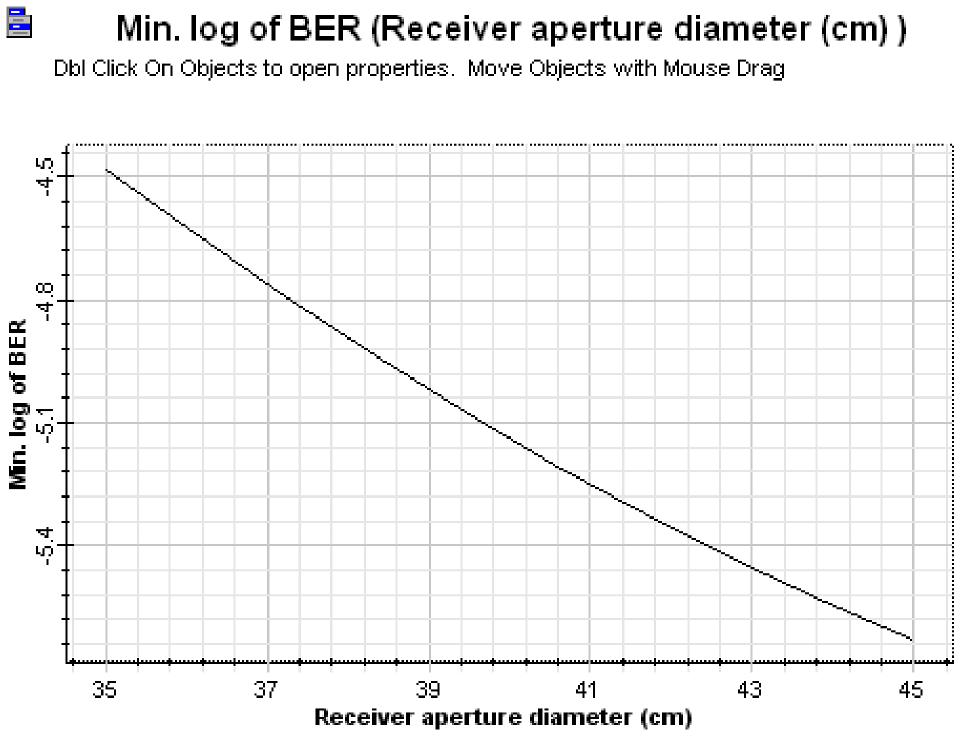

Figure 4.12: The improvement of BER when the size of the telescope of the GEO satellite increases

Coming back to the original BER requirement which was assumed as 10^{-6}, tuning parameters process is continued to find out the compromising point. Then, while the conditions of the model are kept the same, several parameters are swept to see their effect to improve the communication performance.

From the second configuration, the laser output power is swept from 5 to 10 W to find out the most appropriate value. Moreover, to compare the improvement of the communication performance between increasing the output power and increasing the aperture of the telescope, another simulation is conducted. In this simulation, from the second designed set of parameters, the aperture of the optical antenna in the micro satellite is varied from 7 cm to 10 cm.

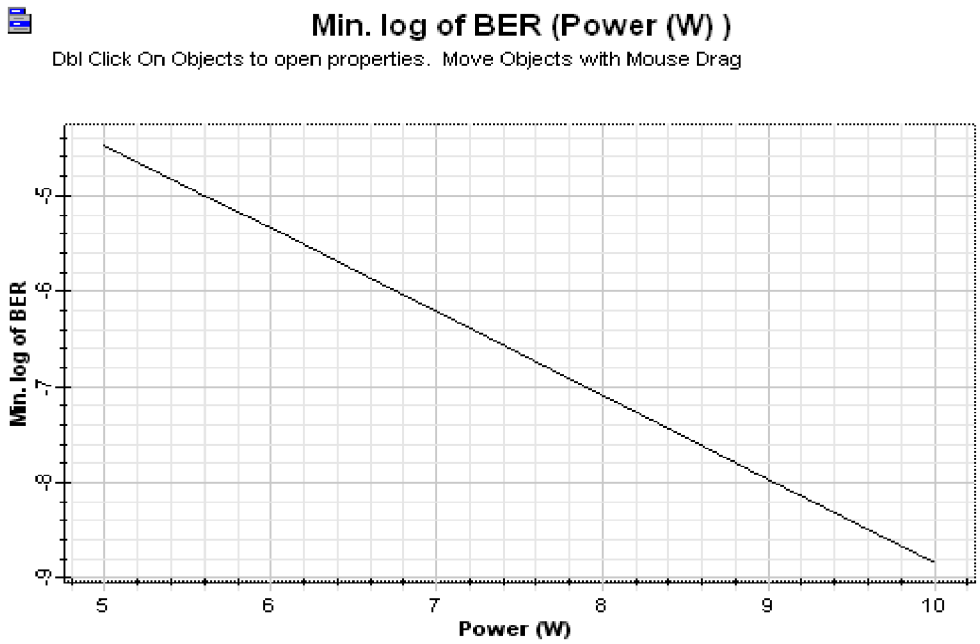

Figure 4.13: The improvement of BER when the laser output power increases

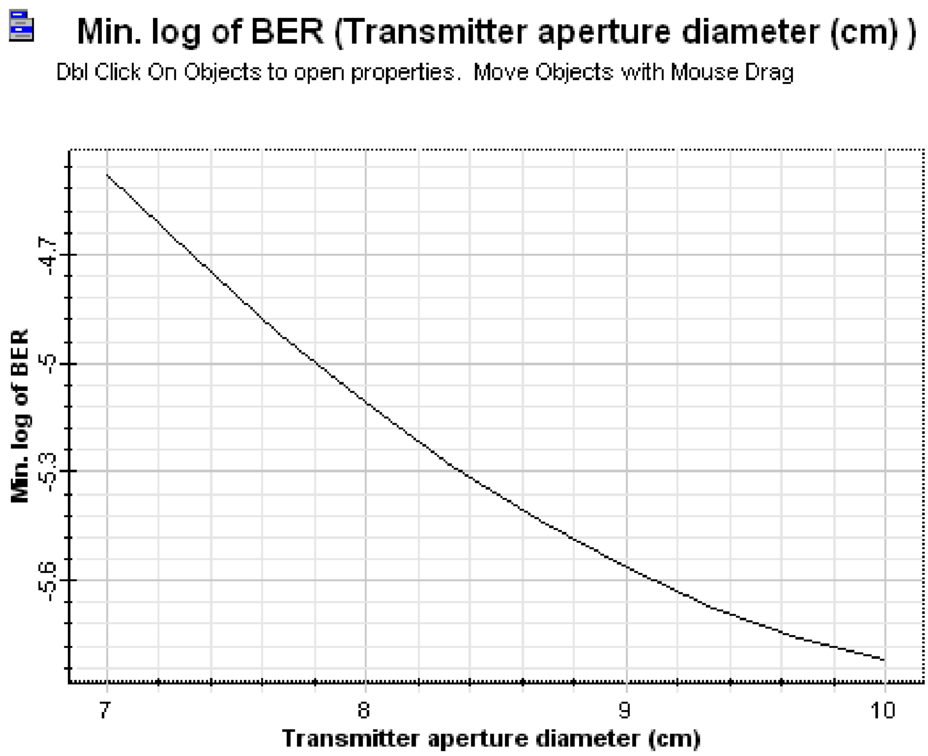

Figure 4.14: The improvement of BER when the transmitting aperture increases

The results in Figure 4.13 and Figure 4.14 shows the almost linear improvement of communication when the laser power is improved or the aperture of the telescope in the micro satellite becomes bigger. As can be seen from these figures, by increasing 1 W for laser output power, the final BER can improve about 10 times. Meanwhile, increasing 1 cm of the aperture of the telescope can only improve the BER about 2 times.

To verify the sensitivity of transmitting pointing errors and receiving errors which are very important in this model of communication, some adding simulations are conducted. From the second configuration, the transmitting power is changed to 7 W. Then, the transmitting error and receiving error are tuned to see how they affect to the link. The result shown in Figure 4.15 is the case when the transmitting error of the optical system in the micro satellite is swept from 4.6 μrad to 10 μrad. Meanwhile, Figure 4.16 shows the eye diagram and BER performance when the receiving error of the optical system in the GEO satelliteis loosen about 1 μrad.

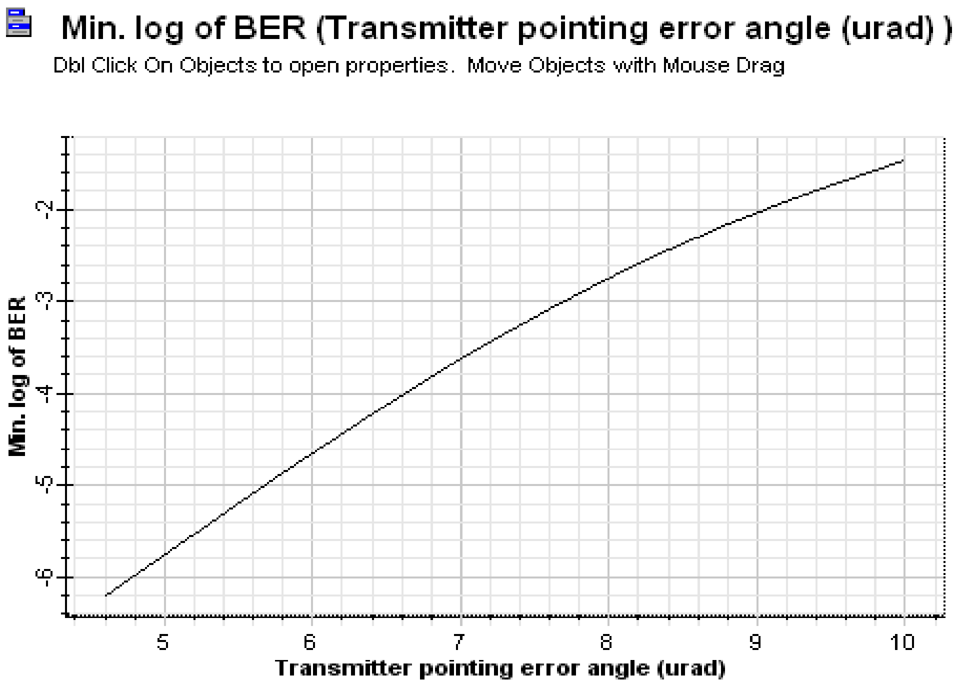

Figure 4.15: The degradation of the communication performance when the transmitting pointing error is worse

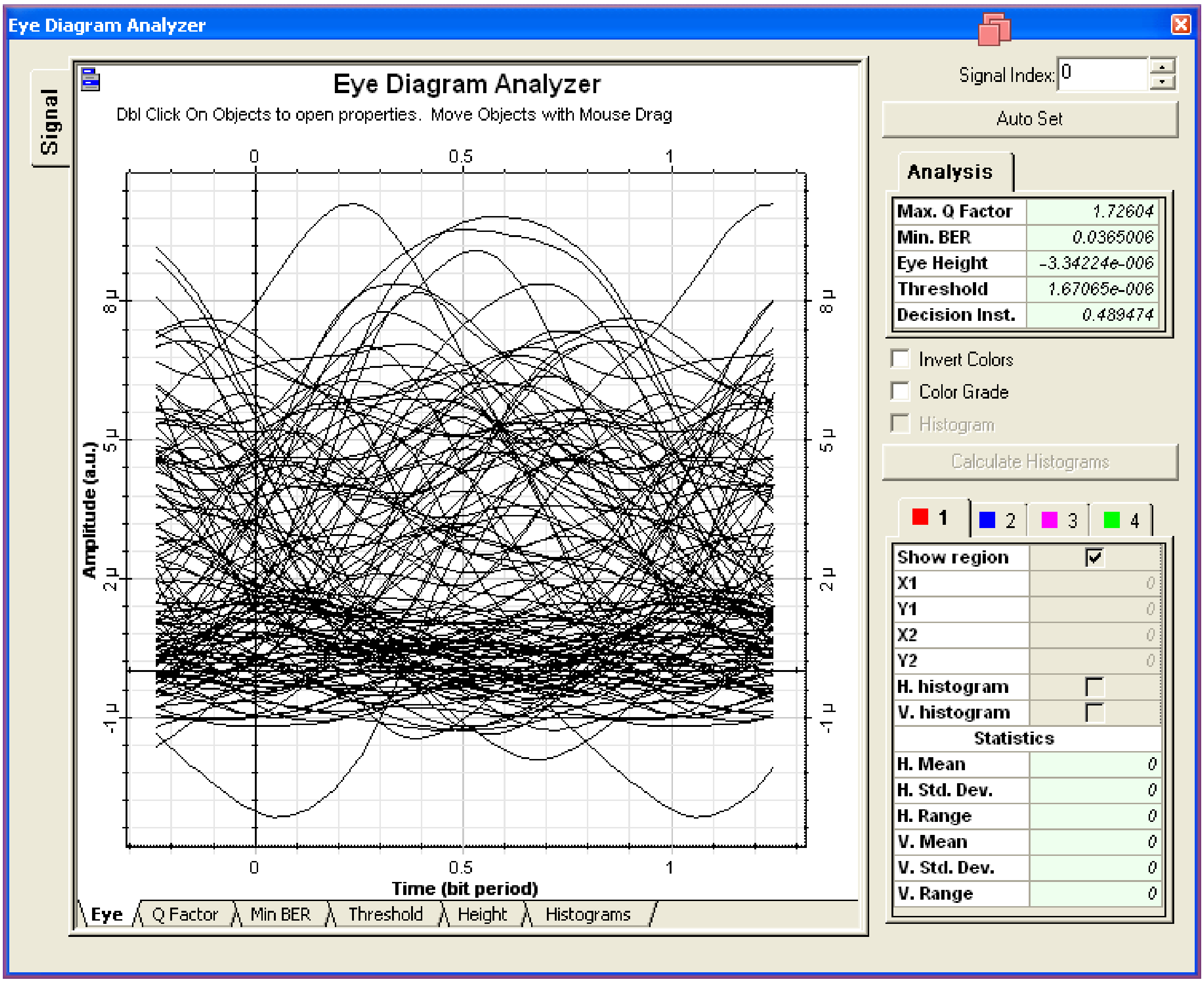

Figure 4.16: The degradation of the communication performance when the receiving error is worse

For 1 µrad which is loosen from the pointing requirement of the optical system in the micro satellite, the BER is degraded almost 10 times. From Fig. 7, it is said that to compensate for this degradation, 1 W can be added for the output power of laser. However, the similar situation does not happen when 1 µrad is loosen from the receiving error angle of the optical system in the GEO satellite. In this case, the BER performance decreases almost 50,000 times. Therefore, the accuracy of the optical system of the GEO satellite plays an extremely important role to make the LEO-GEO communication feasible. This high accuracy of the pointing requirement is very hard to realize by the ADCS systems of both of the satellites. Consequently, some gimbaled platform and a fine pointing mechanism and their accurate control system are required. Detailed analysis of the feasibility of achieving such high pointing accuracy is not shown in this research and will be the future work.

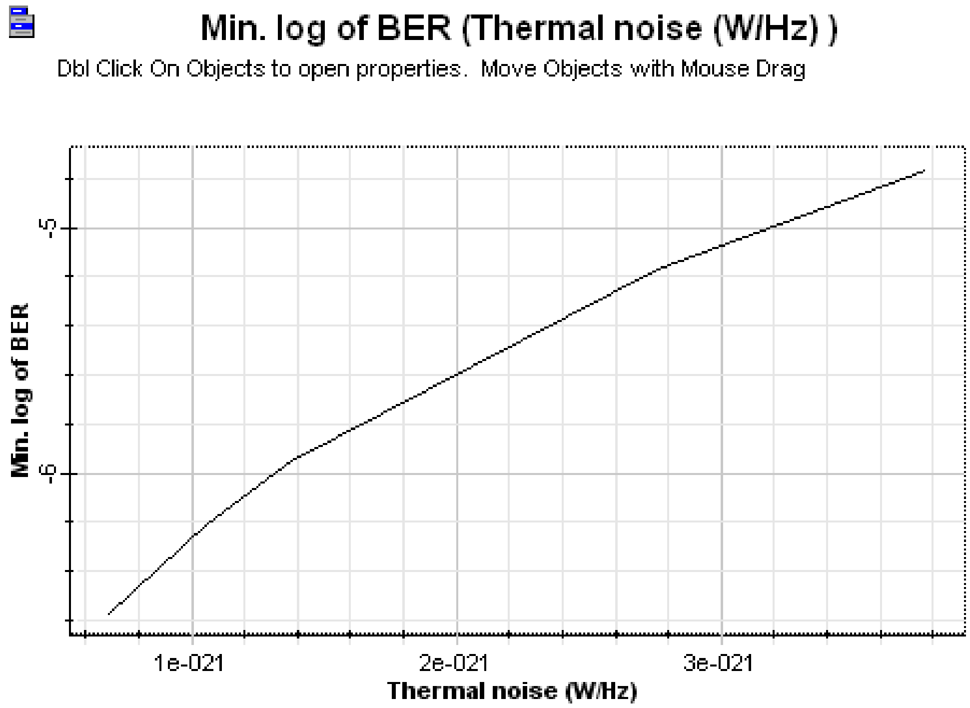

Figure 4.17: The degradation of the communication performance when the temperature of the receiver increases

Another parameter needs to be considered is temperature of the receiver in the GEO satellite. To see how temperature affects to the communication performance, five different thermal noise levels which correspond to five different temperature are simulated. The degradation of communication is shown in Figure 4.17. From the results, it can be seen that temperature of the receiver in the GEO satellite must be kept less than 100 K so that the BER requirement can be achieved.

CHAPTER 5. FEASIBILITY ASSESSMENT

5.1. Proposed Design Parameters

Through the previous discussion, some conclusions are given after the analyzing process:

- The improvement of the link performance is almost linear when antenna diameters or transmitting power are increased linearly.

- The more preferable parameter which should be improved to support the link is the transmitting power of laser rather than the size of the telescope of the transmitting side.

- In laser communications between the micro satellite and the GEO satellite, shot noise affects to the communication performance significantly. Therefore, dealing with this issue is very important to improve and make communication feasible.

- Receiving error of the optical system of the GEO satellite is an extremely important parameter to make the link feasible. Sensitivity analysis of it shows that with a slightly decreasing of the receiving error, communication cannot be done. Therefore, it must be required to develop the GEO satellite which is able to satisfy very stringent pointing requirement.

The result in Figure 4.13 shows that when the output power of the laser transmitter in the micro satellite is about 7 W, the BER can achieve the requirement value of 10^{-6}. Another simulation is conducted with the new set of parameters as in Table 13, the final BER that the optical system can achieve is 0.6 x 10^{-6} (Figure 5.1) which satisfies the requirement. Because the model of communication is asymmetric, low bit rate communication from the GEO satellite to the micro satellite can be achieved easily.

Table 13: The proposed set of parameters which satisfies the required BER

Transmitting pointing error (µrad)	4.6
Receiving error (µrad)	0.9
Power (W)	7
Bit rate (Mbps)	300
Range (km)	40,000
Receiving aperture (cm)	35
Transmitting aperture (cm)	7

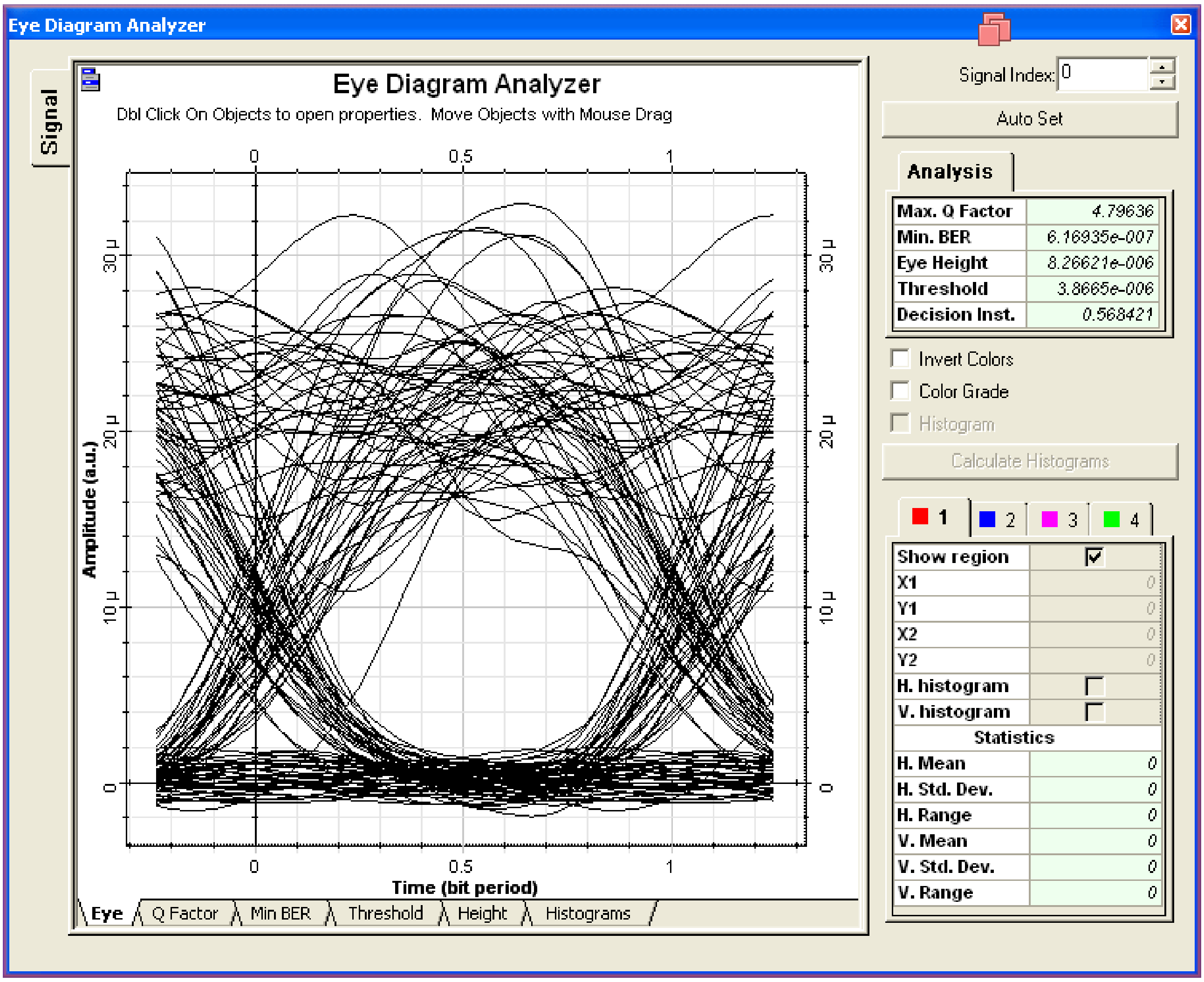

Figure 5.1: The final BER which satisfies the requirement

In Table 13, while receiving error of the optical system in the GEO satellite cannot be loosen, the other ones can be improved to support for the link. However, in terms of technology, improving each of parameter is very difficult.

5.2. Current technology of space laser communications

A survey of available components which can be used for laser communications of micro satellites is conducted to consider the feasibility of technology. From the side of the LEO satellite, the power efficiency of practical laser transmitters can be 25%. It means that about 30 W would be required for 7 W laser output power. From chapter 16 of the book “Aerospace Technologies Advancements” [13], which deals with the latest and most prominent research in space technology, the authors stated that power generation of micro satellites can reach 200 W or more in the future. In several completed micro satellite projects, the fact showed that with power generation of about 100 W, the power subsystems have enough capability to provide power for the whole operation of the satellites. Consequently, with 200 W of power can be generated, the requirement of power supply for the optical system of the micro satellite can be fulfilled. Besides, currently, laser diode transmitters can deliver several watts of output power [14] which can be used for the micro satellite. As mentioned above, 25% of these total weight which varies from 10 to 25 kg can be used for payloads. With the development of technology, this ratio even can reach 40% in near future when the mass of BUS systems has become smaller. Assuming that half of this weight is used for the optical system, the range will be from 5 to 13 kg. Last year, NICT developed the flight model of SOTA (Small Optical TrAnsponder), a laser communications system in space which was integrated in the SOCRATES micro satellite. With an aperture of 5 cm, the total mass of the optical system is 5.86 kg. Therefore, it might be feasible to build another optical system with a 7 cm aperture telescope which has the mass within the range of 5 to 13 kg. The most difficult challenge for laser communications of the micro satellite is to satisfy the stringent pointing requirement. This pointing issue can be solved by using a dedicated control system which was described in section 3.5.3. At present, a variety of famous companies over the world such as: Newport, Thorlabs and RUAG Group provide sets of advanced components including coarse pointing gimbals, fast steering mirrors, quadrant detectors. These systems with small size, low weight and low power consumption which are able to achieve pointing accuracy level of several μrad are fit for the configuration of micro satellites. In the GEO satellite, Stirling Cooler systems which are developed by Sumitomo Heavy Industries and JAXA are available. This cooling system is required to decrease the operating temperature of the optical system of the GEO satellite to less than 100 K, thus, improving the performance of laser communications. Through above discussion, optical components which have been developed by famous companies over the world can satisfy the design requirements individually. However, a more design study must be conducted to verify how they work as a whole system. Several laser components which are available in the commercial market are discussed below.

5.2.1. Laser Diode Transmitter

Intense Ltd., headquartered in Glasgow, UK, is a leading provider of single and multimode monolithic laser array products and high power laser diodes. According to the web link [30], this company has developed next generation semiconductor lasers, systems and solutions, and announced the new Series 2400 eye safe laser diodes at World of Photonics 2009 in Munich, Germany. This new series are 1550 nm short pulsed single emitters and stacks that have been redesigned for higher power and efficiency. They are designed for military and industrial applications. Two products of this family are 2410 @ 6W, 2424 @ 12W. With this wavelength and transmitting output power, they can be fit to the proposed configuration.

5.2.2. Acquisition, Tracking and Pointing System

RUAG Space (Rüstungs Unternehmen Aktiengesellschaft Group) is one of the largest supplier of space products to the industry in Europe. Total sales revenues of RUAG Space Swiss Francs achieved 322 million in 2014. RUAG Space offers space products in a variety of following areas to commercial customers:

+ Launcher Structures & Separation Systems
+ Satellite Structures, Mechanisms & Mechanical Equipment
+ Digital Electronics for Satellites and Launchers
+ Satellite Communication Equipment
+ Satellite Instruments

In the field of satellite communication equipment, RUAG has developed pointing and tracking components used for laser communications in space. For example, Figure 5.2 shows a coarse pointing assembly (CPA) which can be used for coarse control of the optical system of the micro satellite.

Figure 5.2: Coarse pointing assembly (CPA)

The CPA is a mass optimized and highly precise 2-axes Coarse Pointing Assembly for Laser communications Terminals. This component use Brushless DC motors in close loop control mode. It has highly stiffness and mass optimized mechanical design of beryllium alloys. 5 W as the power consumption is totally suitable for the micro satellite. However, mass of this component which is about 15 kg is a little big and needed to be miniaturized.

Table 14: Performance of CPA (RUAG)

Azimuth axis	
Angular range azimuth	$\pm 175_{o}$
Angular range elevation	-20/+200°
Elevation axis	
Angular range azimuth	$\pm 175_{o}$
Angular range elevation	$-20/+200_{o}$
Optical accuracy without calibration	±175 µrad
Optical accuracy with calibration	±50 µrad
Laser beam diameter	135 mm
Mass	>15 kg
Power consumption max	5 Watt

RUAG has also developed a fine pointing assembly (FPA) which is shown in Figure 5.3. This component combined with the CPA as a set will be a fully functional control system for the optical system.

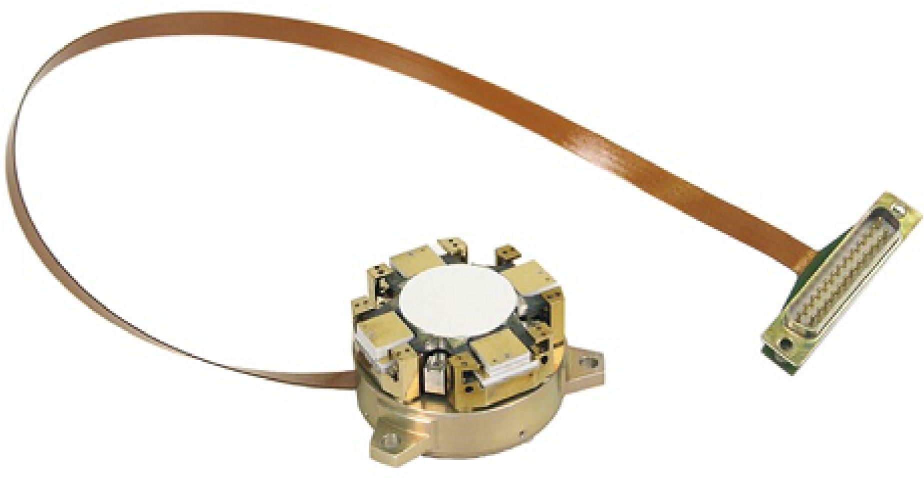

Figure 5.3: Fine pointing assembly (FPA)

The FPA is a dual axis single mirror mechanism that incorporates a high performance beryllium mirror. The mirror can rotate in tip tilt axes. Actuators and sensors are directly attached to the mirror. The actuators are of Lorentz type. The position is sensed using four sensors with an integrated preamplifier. The FPA control electronics linearises the sensor characteristic and implements a cascaded feedback scheme, with controllers and output current amplifiers to drive the actuators of the FPA mechanism [31]. Performance criteria of the FPA is described in Table 15.

Table 15: Performances of FPA (RUAG)

Aperture	19-27 mm
Scan angle	± 7 mrad (mechanical)
Bandwidth*	1000 Hz deg
Angular Noise	<1 ụrad (p-p) over 2.5 kHz
Mass	0.1 kg
Dimensions	0 55 mm, thickness 30 mm
Power consumption	2 W

Another good example was mentioned in section 2.2, NICT in Japan developed an optical system namely SOTA which was integrated in the SOCRATES micro satellite to demonstrate laser experiment between the satellite and the optical ground station. Figure 5.4 illustrates for the SOTA system.

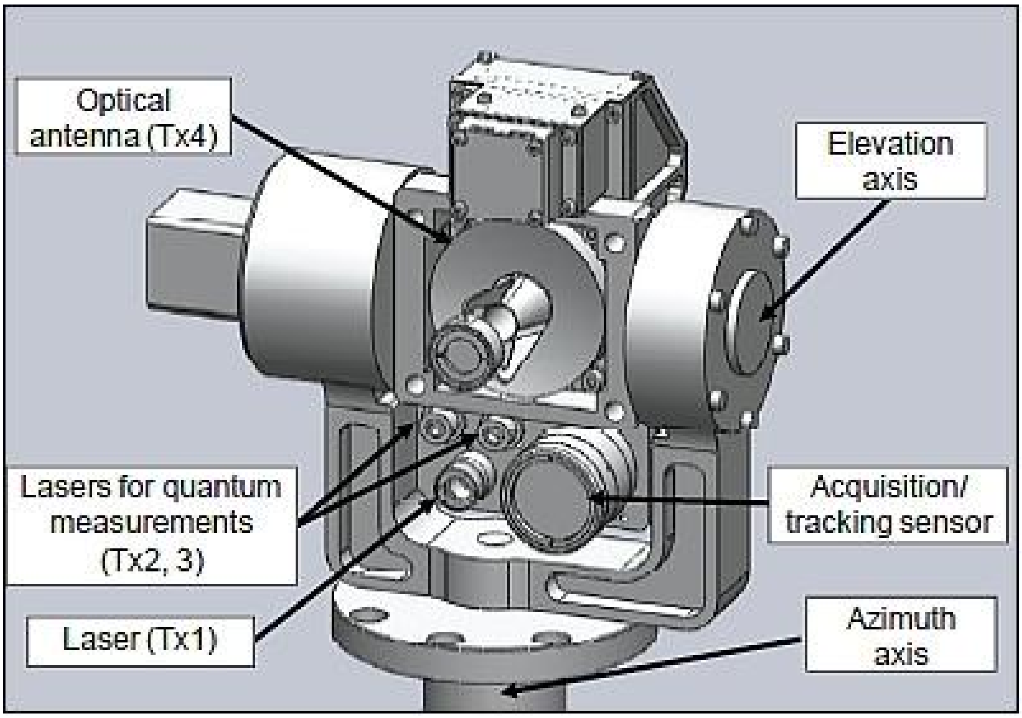

Figure 5.4: Illustration of the SOTA proto-flight model (NICT)

The acquisition, tracking and pointing functions are realized by a 2 axes gimbal, Fine Pointing Mechanism (FPM) and related sensors.

A minimum power consumption is expected as 28.1 W. When a transmitter and a receiver are operating simultaneously, the required power reaches 39.5 W. The total mass of SOTA is estimated to be ~ 6.2 kg. The size of SOTA-OPT is 177.5 W x 130 D x 264 H (mm). This configuration is totally suitable and demonstrated for the micro satellite. By modifying this SOTA equipment, it looks promising to develop an optical system which has mass and size within the limitations of the micro satellite to do laser communications with the GEO satellite.

5.2.3. Avalanche Photodiode

Hamamatsu is a famous Japanese company. One of the main domains of this company is researching, developing and manufacturing photodetectors, light sources, opto-semiconductor devices for optical communication. They also research on lasers and related technology to resolve problems facing humanity in various areas. Table 16 shows the specifications of the G8931-20 product which is available in the market. It is an InGaAs avalanche photodiode. Several parameters of this APD is quite close to the proposed design ones such as the sensitivity wavelength and photosensitivity.

Table 16: Specifications of InGaAs APD [32]

Number of elements	1
Photosensitive area	ϕ 0.2 mm
Package	Metal
Spectral response range (min.)	950 to 1700 nm
Peak sensitivity wavelength (typ.)	1550 nm
Photosensitivity (typ.)	0.9 A/W
Dark current (max.)	200 nA

Terminal capacitance (typ.)	1.5 pF
Breakdown voltage (min.)	40 V
Breakdown voltage (max.)	60 V
Measurement condition	Ta=25°C

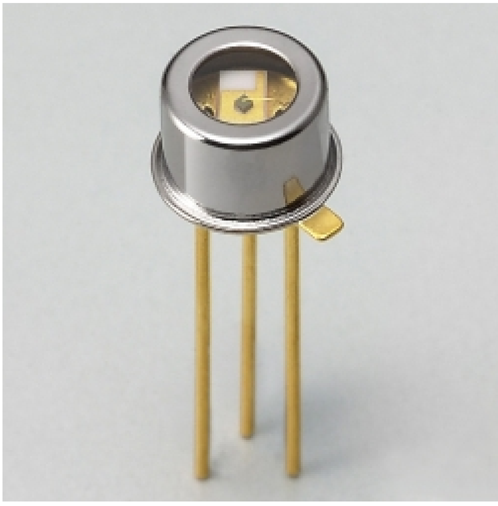

Figure 5.5: G8931-20 InGaAs Avalanche Photodiode

Besides, a variety of quadrant detectors or CCD sensors which can be used for the optical control systems is also developed and manufactured by the Hamamatsu company. This can be a reference source for another research which focuses on a detailed design of the ATP system.

5.3. Questions Survey

For the purpose of validation, a list of questions which is related to the possibility of developing and manufacturing the laser components and subsystems with the proposed design parameters is created. NASA Technology Readiness Level is considered as the reference of this assessment (Table 17). This list is distributed to experts of satellite communication, especially of laser communications in space to consult their opinions. According to several specialists of an industrial company, it is hard to answer every questions because such a laser system for micro satellites has not been researched and developed yet. However, based on their experience, developing and manufacturing laser transmitters and avalanche photodiodes with the proposed parameters are possible. At present, in commercial markets, there exists a variety of components which can satisfy the requirements but they are needed to be developed and tested so that they can operate in harsh conditions of space. Regarding to the optical control system, based on the development and testing of the SOTA equipment, it seems feasible to develop this system which has mass in range from 5 to 13 kg. Nevertheless, the pointing accuracy in the presence of vibration cannot be stated without a real demonstration. About the power requirement issue, other expert at a Japanese university who have lots of experience in developing micro satellites mention that this requirement can be satisfied by using solar panels and battery systems of the micro satellite. Moreover, as discussed above, the GEO satellite plays an extremely important role to make the communication link feasible. Therefore, the questions about the configuration of the GEO satellite is also distributed to experts at the 30th International Symposium on Space Technology and Science (ISTS) conference in Kobe, 2015. According to a specialist who gave a presentation about laser experiments in space at the conference, the stringent pointing accuracy requirement of the GEO satellite and its optical system can be satisfied with current technology. A real system may have been developing and testing.

1. At which level of the NASA standard (Table 17), an optical system with 7 cm aperture which has mass in range from 5 to 13 kg can be developed? If there exists such a system, how much power will be required to control it. If the system does not exist currently, how long does this take to develop and make such a system?

2. Currently, at which level of the NASA standard, there is an available laser diode transmitter can generate 7W as the output power? How much power consumption is needed for this transmitter? If with current technology, such a transmitter cannot be developed, how long does this take to create this device?

3. What is the highest accuracy that an optical control system can achieve? What is the mass and dimension of that system? At which level of the NASA standard, an optical control system can achieve 4.6 μrad accuracy? What can be the size, mass and power consumption of such a system?

3. Currently, which GEO satellite has the biggest telescope for laser communications? If there is no GEO satellite which has 35 cm aperture of the telescope, at which level of the NASA standard, such a satellite can be developed?

4. Currently, what is the highest level of pointing accuracy of optical systems in GEO satellites? At which level of the NASA standard, an optical system of GEO satellites can achieve less than 1 μrad accuracy.

5. Is there any GEO satellite which is integrated with cooling systems? If not, at which level of the NASA standard, a cooling system can be manufactured for GEO satellites to decrease the temperature to less than 100 K? What might be the lowest temperature?

4. Currently, how much internal gain is typical for avalanche photodiodes which can receive 1550 nm laser? At present, is there any available type of APD which satisfies assumptions in the research? If not, at which level of the NASA standard, such an avalanche photodiode can be made?

Table 17: NASA Technology Readiness Level

Technology Readiness Level	**Description**
TRL 1	Basic or fundamental research
TRL 2	Technology concept and/or application
TRL 3	Proof-of-concept
TRL 4	Concept validated in laboratory
TRL 5	Concept validated in relevant environment
TRL 6	Prototype demonstration in relevant environment
TRL 7	Prototype demonstration in operational environment
TRL 8	System demonstration in an operational environment
TRL 9	System totally operational

CONCLUSION AND FUTURE WORK

The goal of this research is to prove the feasibility to have laser communications between the micro satellite and the GEO satellite at very beginning steps. Overall design of the communications system which includes the micro satellite, the GEO satellite and the communication link between them is discussed. A model of the communication link between the micro satellite and the GEO satellite is built and verification is done by using the Optisystem software. Sensitivity analysis is conducted to realize some insights which may help to make the link feasible. Finally, a set of design parameters of the communications system which can satisfy the requirements is proposed. Through a discussion of current technology, the feasibility of applying this configuration for the micro satellite can be visualized. With the development of technology of both micro satellites and optical systems, it looks promising to demonstrate laser communications between micro satellite and GEO satellites in near future. The high accuracy of the pointing requirement will be hard to realize by micro satellite's attitude control only, and therefore some gimbaled platform and a fine pointing mechanism with their accurate control systems are required. Detailed analysis of the feasibility of achieving such high pointing accuracy using ”local control” is not shown in this research and can be the future work. Besides, a detailed design of this control system in the micro satellite using available components can also be done in another research.

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APPENDIX

ABBREVIATION LIST

ADCS	Attitude Determination and Control Subsystem
ARTEMIS	Advanced Relay and Technology Mission Satellite
ATP	Acquisition, Tracking and Pointing
BER	Bit Error Rate
C&DH	Command and Data Handling subsystem
CCD	Charge-Coupled Device
CCS	Computer Command subsystem
CDS	Command and Data subsystem
COM	Communication Subsytem
CNES	Centre National d'Etudes Spatiales
CPA	Coarse Pointing Assembly
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
EPS	Electric Power Subsystem
EDRS	European Data Relay Satellite
ESA	European Space Agency
ETSI	European Telecommunication Standard Institute
FDS	Flight Data Subsystem
FPA	Fine Pointing Assembly
FPM	Fine Pointing Mechanism
FSM	Fast Steering Mirror
Gbps	Gigabit per second
GEO	Geostationary Orbit
InGaAs	Indium Gallium Arsenide

ISAS	Institute of Space and Astronautical Science
ISTS	International Symposium on Space Technology and Science
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
K	Kelvin
LADEE	Lunar Atmosphere and Dust Environment Explorer satellite
LCT	Laser communications Terminal
LLCD	Lunar Laser communications Demonstration
LOS	Line of Sight
LPF	Low Pass Filter
Mbps	Megabit-per-second
NASA	National Aeronautics and Space Administration
NICT	National Institute of Information and Communications Technology
NFIRE	Near Field Infrared Experiment
NRZ	Non-Return-to-Zero
OBC	Onboard Computer
OICETS	Optical Inter-Orbit Communications Engineering Test Satellite
PAA	Point Ahead Angle
PASTEL	PAssager SPOT de Técommunication Laser
PFM	Proto-Flight Model
PD	Photodiode
QD	Quadrant Detector
RF	Radio Frequency
RUAG	Rüstungs Unternehmen Aktiengesellschaft
SDM	System Design and Management
SILEX	Semiconductor Intersatellite Link Experiment
SOCRATES	Space Optical Communications Research Advanced Technology Satellite

SOTA	Small Optical TrAnsponder
SAR	Synthetic Aperture Radar
UNIFORM-1	University International Formation Mission-1
USA	United States of America
VNSC	Vietnam National Satellite Center