Master Thesis

Feasibility Study of Free-Space Optical Links for Micro- and Nano- Satellites

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Abstract

Free space laser communications allow the operations of high performance communication links, while reducing mass and power requirements when compared to radio frequency terminals developed to achieve similar mission goals, and featuring no regulatory bandwidth allocation constraints, to date.

Nevertheless, new challenges are brought in by laser terminals such as higher pointing accuracy requirements, which traditionally prevented their consideration on small satellite platforms. However, as the performance and capabilities of small satellites keeps growing, it is of interest to assess the feasibility of laser communications on micro- and nano-satellites, and potentially devise novel strategies to implement laser terminals on those platforms. Planned attempts to implement laser communications in small satellites include the Japanese Very Small Optical Transponder (VSOTA), to be launched on board the 50 kg RISESAT satellite to perform ground downlink at the rate of 10 Mbps, and the upcoming AeroCube-OCSD mission led by the Aerospace Corporation. Both missions focus on space-to-ground laser communications, and employ relatively large apertures on the ground to close the link. Yet, there is an opportunity to investigate possibilities in space-to-space laser communication links between small satellites, which could be potentially deployed for space telecommunication purposes as in data relay service constellations in Low Earth Orbit.

The goal of this thesis is to assess the feasibility of laser communication links between micro- and nano-satellites. The study considers different modes of operation, i.e. space-to-space and space-to-ground, characterizing the most relevant trade-offs and system-level performance. Specifically, the thesis develops an integrated payload-spacecraft design analysis tool, which consists of an integrated small satellite and payload model applied to selected operational scenarios and system-level requirements.

For the small satellite and payload models, the thesis accounts for state-of-the-art subsystems
capabilities of micro- and nano-satellites and current parameters of commercial-off-the-shelf optical systems, including lasers and telescopes. The analysis considers a direct-detected pulse position modulated (PPM) signal as a baseline mode of operation. An approximate link equation is used that captures the first order parameters. The link budget model is then integrated in an end-to-end spacecraft simulation model, in order to assess system-level outcomes in terms of performance. The proposed approach allows quantifying the high level engineering trade-offs between system-level parameters such as transmitter power versus required satellite budgets and transmitter aperture areas versus pointing and tracking requirements.

The results obtained, as well as the novel operational strategy show that the current technical characteristics of micro- and nano-satellites and available optical systems allow for laser communication for space-to-ground and space-to-space links in Low Earth Orbit.
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Chapter 1

Introduction

1.1 Background and Context

Advances in electronics have enabled unprecedented data collection and storage capabilities in satellites of all sizes. To be more precise, data rates of imaging instruments can easily exceed 200 Mbits/s [4]. For the entire Low Earth Orbit (LEO) that will require more than 100 Gbyte of storage capacity. A terabyte of data can be readily stored even on CubeSats, satellites with 10cm x 10cm x 10 cm size.

Since high performance payloads are becoming lighter and smaller, in many cases there is no longer a need to build big satellite platforms to bring them into space. Small platforms are chipper and can be built faster. There are two types of small satellites that gain particular attention in the recent years. Those are micro-satellites, defined as having the mass of less than 100 kg and nano-satellites, defined as having the mass of less than 10 kg.

While storing terabytes of data is easy, sending it to the ground is hard. Power, mass and size limited small satellite platforms nowadays can achieve up to 100 Mbps data rate using X-band radio antenna for micro-satellites [5] and up to 2 Mbps using S-band radio antenna for nano-satellites [6]. Assuming a Low Earth Orbit (LEO) mission and one ground station, a spacecraft will have 4 communication windows per day (optimistic case) with an average duration of 10 minutes. In order to downlink 1 terabyte of data, micro satellite will need 34 days, while nano satellite - almost 2 years. Since for a given orbit the duration of the communication window is constant, there are two ways to download the mission data faster. Either more ground stations have to be built or data rate has to be increased.
Expanding a ground infrastructure is economically inefficient, therefore the second solution is typically considered. One way to substantially increase the data rate for space applications is to move from the traditionally used radio to the optical part of the spectrum. Free-Space Optics (FSO) communication has particular advantages compared to the radio frequency (RF) carriers. For the same mass and power requirements, optical communication payloads provide data rates by 1 and even 2 orders of magnitude higher than those achieved by RF payloads. Besides, it features no regulatory bandwidth allocation constraints, to date. And finally, laser beam directivity provides better security features that reduce the probability of its interception.

Nevertheless, new challenges are brought in by laser communication, such as high pointing requirements which have traditionally prevented technology from being considered for small satellites, and strong attenuation in the atmosphere.

Let us make a short overview of the successful optical communication demonstrations that has been carried out to date. The highest data rate was achieved by joint attempt of German Aerospace Center (DLR) and National Aeronautics and Space Administration (NASA) in 2007. The former agency has launched 1230 kg TerraSAR-X satellite, while the latter - 494 kg NFIRE. Both satellites were operating on LEO, having on-board 35 kg and 120 W power consumption TESAT laser communication terminal (LCT). This terminal has a separate gimbaled pointing system providing 50 microradian angular beam width. Two modes of operation were demonstrated [7]. Bidirectional inter-satellite link achieved the maximum data rate of 5.625 Gbps, while having approximately 700 Mbps in a nominal regime. The second mode, which is space-to-ground link, was demonstrated by NFIRE and also achieved 5.625 Gbps of maximum data rate. Both modes have shown robust performance with 10E-7 and 9.4E-7 bit error rate (BER) for space-to-space and space-to-ground scenarios respectively (BER of the same order is achieved by RF communication).

Another important demonstration was conducted by European Space Agency (ESA) in 2014. It was a link between 6600 kg Alphasat relay satellite on Geostationary Earth Orbit (GEO) and 2300 kg Sentinel 1A imaging satellite on LEO [8]. Both spacecrafts had TESAT LCTs aboard with the same characteristics that was listed above. GEO - LEO optical link and GEO - Ground were successfully performed achieving 1.8 Gbps data rate, with the design that could scale up to 7.2 Gbps in the future.

This experiment paved a way for the launch of European Data Relay System (EDRS), which
will start in 2015 and is the first GEO data relay system that will use optical communication to receive the data from LEO satellites.

Besides successful near-Earth laser communication demonstrations, in 2013 NASA performed a first laser link between Moon orbiting LADEE spacecraft and Earth-based ground station \[9\]. Laser terminal was produced by MIT Lincoln Laboratory and features the following characteristics: 32 kg mass, 137 W power consumption and 10.16 cm optical antenna diameter. As well as TESAT terminal, it is a gimbaled system that operates using a narrow angular beam width. The data rate of 622 Mbit/s was demonstrated, which is 6 times higher than the previous Moon-to-Earth downlink speeds. Moreover, this particular LCT is half a mass and quarter of a power consumption of a RF terminal with the same performance \[4\].

Both TESAT and Lincoln Laboratory laser terminals will obviously not fit in the micro- and nano-satellites. But, eliminating optical gimbal and increasing the angular beam width will significantly reduce the size and the mass of such a terminal. This approach implies body-pointing of a spacecraft and uses an advantage of low moments of inertia of small satellites and their ability to perform fast slew maneuvers.

To the best knowledge of the author, no demonstrations in the micro- and nano-satellite domains have been made, but there are several attempts briefly described below.

The design of the optical payload for 1.5 U CubeSat (to be launched in 2015 by Aerospace corporation within Optical Communication and Sensor Demonstration (OCSD) program) follows the body-pointing approach described earlier \[4\]. The goal of the program is to perform a space-to-ground downlink using an optical communication payload. The satellite will operate on LEO. In the nominal regime the laser is to have 1.4 deg beam width enabling the nominal data rate of 5 Mbps. The target data rate is 50 Mbps with 0.5 deg beam width. 50 Mbps is by one order of magnitude higher than the data rate of the state-of-the-art RF antenna available for nano-satellite. There was another effort to design the laser communication terminal for micro satellite. It was made by National Institute of Information and Communications Technology for Japanese 50 kg RISESAT satellite \[10\]. On the bread board model stage authors reported the following characteristics of the gimbaled terminal: 5.3 kg mass, 22.8 W of power consumption, 347 and 147 microradian beam divergence for two transponders respectively. The targeted data rate of the system is 10 Mbps. The launch was planned for 2014, but was postponed.
1.2 Research Questions and Objectives

The main challenge of using optical communications for micro- and nano-satellites is pointing accuracy, because small platforms can not orient very precisely and for the space distances a small offset angle results in a big translation error on the receiving side. Current capabilities are approximately 0.01 deg for micro- and 0.1 deg for nano-satellite. While all the demonstrations for big satellites were using very narrow laser beams, here we assume that due to mass, power and size restrictions of small platforms, LCT can not be complex enough to have a separate pointing and stabilization system that exceeds pointing capabilities of a hosting satellite. Therefore, we consider body-pointing and in order to account for limited accuracy we let the beam divergence to be several orders of magnitude higher than it is typically a case for big satellites.

The general goal of this thesis is to analyze the operational scenario of optical communication link that follows the ideology described in the previous paragraph and is applied to the micro- and nano- class of satellite platforms.

The specific objective is to consider near-Earth applications for both inter-satellite and space-to-ground links.

Let us further expand the specific objectives by stating the research questions. These are as follows: 1) Is laser communication feasible for micro- and nano-satellites? 2) What are the engineering trade-offs involved? 3) What are the benefits of using optical compared to RF communication applied to micro- and nano-satellites? 4) What are the technological barriers for using laser terminals on-board micro- and nano-satellites?

1.3 Structure of the Thesis

The remainder of the work is organized as follows: Chapter 2 continues the literature review, Chapter 3 gives a description of research approach and relevant modeling, Chapter 4 outlines case studies and discusses the results. Finally, the limitations of the work and conclusions are presented in Chapters 5 and 6, respectively.
Chapter 2

Literature Review

This chapter aims to make an overview of the literature relevant to the topic of the thesis. It will first describe the methodology that was developed by Homero L. Gutierrez to design high precision space interferometers and filled-aperture telescopes on a conceptual design phase. It will be followed with an overview of the papers dedicated specifically to feasibility studies of using optical terminals on small satellites. In the next section, a series of papers devoted to the development of link budget for deep-space applications will be analyzed. The methodology of the design of satellite subsystem’s introduced in ”The Space Mission Analysis and Design Process” book [11] will conclude the chapter.

2.1 Integrated Modeling for High Precision Space Systems

The work of Gutierrez [1] develops a complete end-to-end methodology which incorporates disturbance, sensitivity and uncertainty analysis within a common state-space framework. The work has appeared as a response to two space observatories that had to be in operation during the first decade of the 21st century, Space Interferometry Mission and Next Generation Space Telescope. These systems were designed to achieve significant improvements in angular resolution and sensitivity compared to ground-based and space-based systems of that time (1999).

The integrated modeling methodology was developed for the conceptual design phase which is a stage during which various system architectures are analyzed and enabling technologies
are identified. The allocation of design requirements and resources during this early stage of a program is based on preliminary analysis using simplified models that capture the behavior of interest. These models are generally suitable for judging relative merits between competing designs in a trade study.

Quantitative analysis tools have been developed by Gutierrez for disturbance, sensitivity and uncertainty analysis of the space telescope system.

The block diagram of the approach developed in [1] is depicted in Figure 2.1. The goal of the approach is to take the conceptual design, systematically identify the important characteristics of the design, and suggest improvements to the design. Performance outputs $z$ are identified by Gutierrez based on system outputs that must meet specified requirements.

Figure 2.1: Block Diagram for Gutierrez Integrated Model [1]

Unsatisfactory results lead to a system improvement phase during which modifications to the design are considered. The objective is to suggest modifications that lead to acceptable design margins. A sensitivity analysis is used to identify the critical parameters to which the performance is most sensitive, and these parameters are targeted for redesign.

After validation, the integrated model has been applied for performance analysis of Space Interferometry Mission, and a set of recommendations for design improvements were obtained.

A reader can refer to [12], [13], [14] and [15] which also use integrated modeling for conceptual design and initial feasibility assessment of space based optical instruments.

The approach of integrated modeling is a reference framework for this thesis.
2.2 Feasibility of Optical Communication for Small Satellites

This section makes an overview of several papers that discuss feasibility of using optical communication systems on small satellites and will describe existing attempts to build the actual payloads for both micro- and nano-satellites.

Paper [16] proposes a system level design of a laser communication system for CubeSats and focuses on inter-satellite links. It does not pretend to build a general methodology for assessing feasibility of optical communication for CubeSats, it rather provides a discussion and some quantitative estimations, including link budget for the considered operational scenario. First, a study of the laser crosslink system of large satellite is provided. Then, the subsystems of the large satellite laser communications are analyzed for suitability in a CubeSat frame. Each subsystem is further analyzed in terms of functionality, contribution to the weight of optical payload and power requirements. The parameters of the larger system are then redesigned to meet the size, weight and power payload constraints of 3U CubeSat, which are $10\,cm \times 10\,cm \times 30\,cm$, 1.5 kg - 2 kg and 3 W - 5 W respectively. The new system is simulated for performance and various candidate scenarios are discussed.

It is important to mention that the aperture of the transmitting/receiving optics is 10 cm which means a narrow beam width, compared to one used by TerraSar and NFIRE satellites (0.003 deg). In order to account for the narrow beam, the pointing acquisition and tracking (PAT) system is designed to have 1 microradian precision. The results of the work suggest a design of the optical communication system which meets the volume and weight requirements of the CubeSat, but does not meet power requirements due to the high power consumption of the pointing acquisition and tracking (PAT) subsystem (1.5 W in tracking and 5 W - 16 W in acquisition mode) and the high operating voltage of the detector (15 V - 30 V). However, authors claim that a viable alternative is to deploy the payload on a nano-satellite which will meet not only the size and mass constraints of the nano-satellite, but power requirements as well.

However, there is a program of Aerospace Corporation, that aims to fit a laser communication payload in 1.5 U CubeSat. The project [4] considers space-to-ground downlink with a targeted data rate of 50 Mbps. The results suggest the feasibility of the proposed scenario. Unlike in
the previous paper, an optical output of the system is designed to have a beam width roughly by one order of magnitude higher (0.5 deg). For this reason no separate PAT subsystem is considered, and closed loop pointing and tracking are supposed to be performed by the satellite itself. Moreover, LCT is designed as a main payload of a platform, and hence has 50 W of input and 14 W of output power. Again, no general approach for assessing the feasibility of using LCTs on CubeSats is developed, instead the paper gives a system level design overview of the proposed solution, including description of attitude determination sensors, optical ground station and concept of operation. Link budget is not presented.

Let us now overview the design efforts of fitting laser terminal on micro-satellites.

The attempt to design a Small Optical Transponder (SOTA) for 50 kg RISESAT satellite has been made by the National Institute of Information and Communications Technology (NICT), Japan [10]. First bread board model was developed, followed by engineering and SOTA proto-flight model (PFM). SOTA has been designed to perform space-to-ground communication from the Low Earth Orbit targeting the data rate of 10 Mbps. Authors has reported the following characteristics of the SOTA PFM: 0.002 deg and 0.008 deg beam width for two transponders with 975 nm and 1543 nm wavelength respectively, 5.3 kg mass and 22.8 W power consumption. Acquisition, pointing and tracking functions are realized by a 2-axis gimbal and related sensors.

Along with SOTA the development of Very Small Optical Transponder (VSOTA) takes place in NICT [17]. VSOTA is based on the Laser Diode Driver electronics and some of the collimators of the SOTA system with slight modifications in its mechanical and optical interfaces. VSOTA does not have internal gimbal mechanism, and the transmission direction is mechanically fixed with the satellite structure. Therefore, the satellite attitude shall be controlled to point the laser beams to a ground station. VSOTA features the following characteristics: 0.7 kg mass, <10W power consumption. As expected, it is mentioned that beam divergence of VSOTA is bigger compared to SOTA, but exact figure is not given. The Attitude Determination and Control Subsystem of RISESAT is able to provide 3-axis 0.04 deg of pointing accuracy. Transponder is designed for a 1 Mbps maximum data rate.

To conclude the section, in the literature assessing feasibility of using optical terminals on micro- and nano-satellites no general methodology was found. Papers that were considered here in general present an overview of different LCTs design efforts on bread board model, engineering model and proto-flight model stages. What has to be outlined is there are two
approaches for designing LCTs for small satellites that exist. First implies narrow laser beam and separate PAT subsystem of the LCT. Second approach suggests excluding separate PAT subsystem and perform body pointing, while increasing the beam width. First concept of operation has an advantage of higher data rate (10 times, in case of SOTA and VSOTA), but having more complex design imposes higher requirements for mass, power and size allocations. As it is shown in [4] despite the simple design, the second approach potentially promises the data rate by one order of magnitude higher than current capabilities of RF antennas. Both schemes are proved as feasible for micro- and nano-satellites.

2.3 Link Budget for Deep-Space Optical Communication

The work of Biswas and Piazzolla [2] presents a framework for quantifying optical communication channel used for deep-space communication. In this article an optical communications link is studied for the case of downlink from the Mars-orbiting spacecraft to the Earth-based ground station. The goal is to establish the preliminary bounds on the achievable data rates. An end-to-end systems analysis is presented to provide the expected signal and noise photons as functions of communication distance. To predict the data rates, the signal and noise photons are treated assuming an ideal Poisson communication channel.

Authors use the following equation for link budget, which determines the relation between the mean received signal power \( (P_{\text{avg}})_{\text{recd}} \) and transmitted power \( (P_{\text{avg}})_{\text{trans}} \):

\[
(P_{\text{avg}})_{\text{recd}} = (P_{\text{avg}})_{\text{trans}} \times G_T \times \eta_T \times L_{TP} \times L_s \times \eta_{\text{atm}} \times \eta_R \times G_R \times L_{\text{other}},
\]

where

- \( G_{T,R} \) is transmitter and ground receiver gains
- \( L_{T,P} \) is the loss allocated for imperfect pointing of the narrow laser beam
- \( L_s \) is the free-space loss
- \( L_{\text{other}} \) is a miscellaneous loss term
- \( \eta_{T,\text{atm},R} \) is the transmitter, atmospheric and receiver efficiencies at the laser wavelength

Fixed and variable loss and gain components, listed in Figure 2.2 are considered. In this article the detector is treated as an ideal, therefore no losses are associated with it.

The work emphasizes the atmospheric contributions to system background-noise, which have very serious impact on the link performance. Authors consider the following sources of noise:
sky radiance, stray light, and mars light. They build a simple model to estimate sky radiance, but MODTRAN [18] is used for more accurate predictions. The paper also characterizes signal attenuation in the atmosphere and Doppler effect.

Another important article [19] from Jet Propulsion Laboratory (JPL) also deals with deep-space communication. It develops a simplified link equation for an optical communication and demonstrates its accuracy by comparing its predictions with those produced by a link budget tool developed at JPL. Besides that, authors state that for the range of targeted data rates \(10^5 b/s - 10^9 b/s\) and background noise levels \(< 10^{-12} W\), the most power efficient and practically implementable method to signal at optical frequencies is to use intensity modulation at low duty cycles with photon-counting detectors, which may be modeled as Poisson channel (particularly, Pulse Position Modulation (PPM) is considered). For that authors refer to their previous work [2].

The link equation presented in this work captures first-order parameters of the link, in a sense that some of the low-level details involved in a more accurate link budget are not considered. This approach is good to see the high-level trade-offs and their first-order impacts on link performance. Besides, this is motivated when one wants to perform trade studies, when low detailed models might be computationally prohibitive.

To derive a link equation authors first relate the received power to the radiated power, using
a classical equation 2.1. Then, referring [20] they approximate the capacity of the Poisson PPM channel by

\[ C_{OPT} \approx \frac{1}{E\ln(2)} \left( \frac{P_r^2}{\ln(M)} + P_n^2 \frac{M - 1}{M} + P_r^2 \frac{MT}{\ln(M)E} \right), \] (2.2)

where \( P_r \) is detected signal power and \( P_n \) is detected noise power. Substituting expression 1.1 for received power and expression for noise power (which follows the deprivation of [2]), the link equation (which represents a clause to close the link) is formulated as

\[ R_b \leq C_{OPT} \] (2.3)

The full expression is not given due to its relative complexity.

The accuracy of the simplified link equation is determined by comparing supportable data rates predicted with the link equation to that predicted by the Strategic Optical Link Tool (SOLT). SOLT was designed to generate link budgets with accuracy sufficient for mission design. The agreement of predictions is reported as good enough.

The next work of Moision et al. [21] further expands research that has been done in the previous paper by providing an approximation to the losses due to log-normal fading, which is used to model scintillation. The novelty is introduced here by characterizing the losses of the detector. Particularly, authors provide approximations for the loss due to photo-detector blocking and jitter. Also, a methodology to compute the required power to support a targeted data rate is presented.

The paper develops a complete link budget and concludes considering a sample case of deep-space optical link at \( R = 0.5 \) AU. This case will be further used to validate the link budget developed in this thesis.

### 2.4 Design of Satellites’ Subsystems

"Space Mission Analysis and Design" book [11] presents an end-to-end methodology for designing a space mission. Among other topics it discusses space mission geometry, astrodynamics, spacecraft subsystems design and sizing, communications architecture. Besides, presenting a general methodology to design a space mission, authors develop particular methodologies to design each subsystem of a spacecraft.

The book begins with setting mission objectives (requirements) and constraints. Then it proceeds to define a space system that will meet them with the lowest possible cost. It is done
by combining models of each subsystems in an integrated model and conducting an iterative refinement of both requirements and methods to achieve them. Essentially this approach represents an integrated modeling methodology, that was described earlier in the first section of this chapter. But no sensitivity and uncertainty analysis frameworks are introduced.
Chapter 3

Approach

Previous chapter clearly identified the literature gap in feasibility studies of using optical communications payloads on-board small satellites. While there are the works that discuss the certain design efforts, no articulated system-level analysis was found that proves the feasibility of laser terminals for micro- and nano-satellites in near-Earth applications. Besides the feasibility it is interesting to address the design challenges that laser communications terminal (LCT) imposes on the satellite subsystems (such as ADCS\textsuperscript{1}, EPS\textsuperscript{2}, TT&C\textsuperscript{3}, etc.) and benefits associated with replacing the traditional radio frequency communications technology with optical communications. The author attempts to fill this gap using the integrated modeling framework discussed in sections 3.1.

The literature review discussed in Chapter 2 also demonstrated that existing design efforts of implementing LCTs on-board small satellites tend to reduce the complexity of LCTs (compared to LCTs of big platforms) and to point the communication payload by changing the attitude of the spacecraft. This thesis analyzes and expands this concept of operation. We address the relevant requirements exerted on the ADCS subsystem of a spacecraft in section 3.2.

The remainder of the chapter is organized as follows: section 3.3 describes in more detail the disciplines that constitute the integrated model, section 3.4 overviews the optimization routine that is present in the work, in section 3.5 we validate the integrated model, and the last section summarizes the chapter.

\textsuperscript{1}Attitude Control and Determination
\textsuperscript{2}Electric Power Subsystem
\textsuperscript{3}Telemetry, Tracking and Command
3.1 Approach Description

In order to answer the research questions stated in chapter 1, it is not enough to just consider a link budget as it was done for example in [2], [21], and [19]. The link budget can characterize the performance of optical link in terms of maximum achievable data rate for fixed system parameters such as output power, telescope diameters, link range, and other characteristics of the channel. However, when studying a complex problem in the context of satellite dynamics, there are two time-dependent parameters. The first is the slant range that changes according to the laws of orbital mechanics and the second is pointing error (the angle between the direction towards the optical center of the recipient’s telescope and the actual direction of the emitted beam) as a function of the satellite’s jitter. Besides, power, mass, pointing and size budgets of the hosting platform introduce additional constraints to the laser terminal, which are exceptionally important in the case of small satellites.

The question of applicability of optical communications for space platforms is in its nature very similar to the problem of meeting the required high precision performance of optical space telescopes discussed in [1] and [12]. On the other hand, this thesis does not deal with the conceptual design phase, instead it explores a wide system-level trade space capturing high-level trade-offs between parameters and their first order impacts on the performance of the system.

The idea of integrated modeling fits very well in the context of this work. In order to analyze the feasibility, benefits, trade-offs and technological barriers of optical communications applied to micro- and nano-satellites, the following major disciplines have been modeled:

1) optical link budget
2) optical antenna performance
3) pointing losses
4) orbital mechanics
5) power generation and storage
6) telemetry, tracking and control

Each discipline will be discussed in section 3.3 in more depth.

The integrated model that has been developed and used in this thesis is presented as a simplified block diagram in Figure 3.1. The diagram captures the constituent models for each of the disciplines mentioned earlier and the main parameters exchanged between them.
Figure 3.1: Simplified Block Diagram of the Integrated Model

- Pointing Loss Model
- TT&C + Payload Subsystem Models
- Data/Com Session
- Link Budget Tool
- Orbit Propagator
- Power Subsystem Model
- Optical Antenna Model

Symbols:
- $L_P$
- $T_{orba}$
- $G_R, G_T$
- $R$
- $P_t$
- $T_{doppler}, T_{eclipse}, I$
Visual inspection of Figure 3.1 allows to see that the feasibility is assessed based on the output of the Link Budget Tool, specifically link margin. A 3 dB link margin is assumed as a threshold for the link closure, hence feasibility.

Besides, Figure 3.1 outlines the main performance metrics of the modeling, which is the data that can be transmitted during the communication session, Data/Com Session. For the fixed system parameters that would be defined further in the text, the maximum data that can be transmitted per communication session, further denoted as $D_{\text{com}}$, characterizes the performance of the optical communication system for the given platform. The benefits of using optical communication are assessed based on the $D_{\text{com}}$ parameter.

To address the feasibility and benefits of optical communications the integrated model is used in the so-called constrained regime. This means that the size, power and pointing accuracy constraints of the spacecraft are considered. These constraints refer to the state-of-the-art sub-system’s capabilities, allowing therefore to assess the upper bound of the performance metrics.

The following algorithm further explains the use of the integrated model in the constrained regime.

**Constrained Regime Algorithm**

1) Set the orbit (in space-to-ground mode) or set two orbits (in space-to-space mode)
2) Set the communication session (initial true anomaly angle, location (in space-to-ground mode) or trajectory (in space-to-space mode) of the receiver, session duration)
3) Set the size of the receiver (diameter)
4) Specify pointing accuracy capability of the platform
5) Set the maximum available area of the satellite’s solar arrays
6) Set spacecraft subsystems’ power consumption and duty cycles, except communications sub-system
7) Set the available communications subsystem power budget
8) Run $D_{\text{com}}$-optimizing algorithm for [Pointing Loss Model] + [Optical Antenna Model] + [Orbit Propagator] + [Link Budget Tool] integrated time-domain simulation of a communications session
9) Evaluate the feasibility, based on the link margin derived on the previous step. If not feasible - stop. If feasible - continue with step 9
10) Access the benefits by linking the \( D_{com} \) to the data generated by the main payload per orbit and by comparing it to the performance of the RF technology.

Table 3.1 links each step of the algorithm to the relevant constituent model.

Table 3.1: Relation of the Constrained Regime Algorithm Steps to the Constituent Models of the Integrated Model

<table>
<thead>
<tr>
<th>Model</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link Budget Tool</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical Antenna Model</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Pointing Loss Model</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Orbit Propagator</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
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<tr>
<td>Power Subsystem Model</td>
<td></td>
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<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
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</tr>
<tr>
<td>TT&amp;C Subsystem Model</td>
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<td>X</td>
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<td></td>
</tr>
</tbody>
</table>

While only size, power and pointing budgets of small satellites are addressed in this work, future analysis will need to consider mass, thermal and cost constraints.

The trade-offs of the system are addressed in section 3.4, while to answer the question of technological barriers, the integrated model is used in the so-called relaxed regime. This means that keeping two of the above mentioned constraints fixed, the third one is relaxed. Iterating this procedure for all of the possible constraint sets allows us to analyze the sensitivity of the performance metrics to all constraints.

The following algorithm shows the example for the power-relaxed regime.

**Power-Relaxed Regime Algorithm**

1) Set the orbit (in space-to-ground mode) or set two orbits (in space-to-space mode)
2) Set communications session (initial true anomaly angle, location (in space-to-ground mode) or trajectory (in space-to-space mode) of the receiver, session duration)
3) Fix the size of the receiver
4) Fix pointing accuracy capability of the platform
4) Relax the power budget
5) Run $D_{\text{orb}}$-optimizing algorithm for [Pointing Loss Model] + [Optical Antenna Model] + [Orbit Propagator] + [Link Budget Tool] integrated time-domain simulation of a communications session for the set of available power allocations

8) Analyze the technical barrier imposed by the power subsystem

The size-relaxed and pointing accuracy-relaxed regimes employ the same algorithm, but instead the size and pointing accuracy constraints are relaxed respectively.

The function of the TT&C subsystem model is to access the benefits of optical communications by linking the main performance metrics, $D_{\text{com}}$, to the state-of-art data rates of the satellite instruments.

Since no particular section discusses the size limitations, we will set them here. The diameter of the receiver for the micro-satellite is constrained by 20 cm, for nano-satellite we have 10 cm, and for the ground based receiver we assume a 1 m diameter.

The validation of the integrated model is conducted in two steps. On the first step, we validate two of the constituent models, which are the Link Budget Tool, and the Orbit Propagator. We do not consider Optical Antenna Model and Pointing Loss Model separately here, because their outputs are directly integrated into the Link Budget Tool. Besides, we do not validate the Power Subsystem model and the TT&C model, since they follow the standard design practice of [11]. We compare the models’ predictions to the relevant case studies found in the literature. In doing it, we assume that the constituent model is accurate enough if the relative error is less than 1 %.

On the second step of validation we compare the data rate predicted by the integrated model to the published expectations of Optical Communications and Sensor Demonstration (OCSD) [4] program. Since we develop a simplified system-level model that aims to capture the first-order impacts, on this step we will confirm the model as validated if the results of the integrated model will differ by maximum 10 % from the expectations of data rates of OCSD program.

### 3.2 Laser Communications Terminal Concept of Operation

As it was described in the first chapter, laser communications terminals have been traditionally complex, with a mass of no less than 35 kg and power consumption of no less than 120 W.
These characteristics were driven by high performance requirements for laser terminals (Gbps data rate) and enabled pointing accuracy of approximately 0.0003 deg\(^4\) which exceeded pointing capabilities of the hosting satellites by several orders of magnitude.

While the recourses of large satellites allow to host such terminals on-board, they will obviously not fit into the sub - 100 kg micro- and sub - 10 kg nano-satellites. But, eliminating optical gimbal and increasing the angular beam width of the output signal will significantly reduce mass, size and power consumption of such terminals. This approach considers body-pointing and takes an advantage of small satellites to perform fast slew maneuvers. Therefore, we are restricted by the pointing accuracy of 0.01 deg and 0.1 deg of micro- and nano-satellites, respectively. This accuracy leads to the beams of a degree and sub-degree widths (exact numbers will be derived further in the text). This beam divergence range is not able to handle Gbps for small satellites. But, since the beam width is still much less than it is a case for RF, this concept of operation provides substantial increase of data rate compared to radio carrier (one order of magnitude increase is reported in [4]).

In order to understand if this concept of operation is feasible from the perspective of small satellite’s slew maneuver capabilities, let us calculate the required angular rates of rotation for both space-to-ground and space-to-space links.

If the satellite communicates with the ground station, we assume that the position of the latter is fixed. Therefore, having a relatively narrow optical beam width the satellite needs to constantly track the station by rotating its body.

When considering the space-to-space communications, both the transmitting and the receiving spacecrafts are moving following the dynamics prescribed by their orbits. In this case we also assume that the transmitting satellite must contentiously rotate in order to point directly to its recipient.

For inter-satellite communications we will consider a classical constellation design with a group of satellites flying on the circular orbits of the same inclination and height. The parameters that change are the so-called right ascension of the ascending node (RAAN) which characterizes the rotation of the orbit plane about the axis of Earth rotation, and the true anomaly angle, which specifies the position of the spacecraft on the certain orbit.

\(^4\)This number comes from the 50 microradian beam width reported in [7], and the approximate requirement for the pointing accuracy needed to provide robust link with a given beam width which is \(\frac{1}{11}\).
The opportunistic space links, implying absolutely random orbits of communicating satellites are not considered in this thesis presenting a subject for the future research.

Figure 3.2 shows the required angular rate of satellite’s rotation for LEO orbits in space-to-ground downlink mode. An overhead satellite pass above the ground station is considered with 15 minutes of communications duration. A Low Earth Orbit (LEO) is defined as an orbit around Earth with an altitude between 160 km and 2000 km. Therefore, two extreme cases and a “middle” case for the orbit having altitude of 1000 km are depicted. One can see that the maximum angular rate required is less than 0.05 rad/s.

The ordinary micro- and nano-satellite platforms can easily meet this requirement. For example, micro-satellite Constella [22] has a speed of slew maneuver equal to 0.087 rad/s. The NASA-OCSD CubeSat [4] (nano-satellite) can rotate with the speed of 0.17 - 0.34 rad/s.

Figure 3.2: Requirement for Angular Rate of Satellite Rotation in Case of Space-to-Ground Downlink

Figure 3.3 presents the required angular rate of rotation in case of inter-satellite link for the whole orbital period. As it was outlined above, the simulation considers a link between two satellites on the circular orbits of the same altitude, but with different right angle os ascending...
node (RAAN). RAAN of one satellite is fixed at 0 rad, while RAAN of another satellite takes different values in a 0 to $2\pi$ range. The exact values of RAAN of the second satellite are presented in the legend to the figure. The difference between the true anomaly angles is kept fixed (particularly - 0.14 rad). Since, lower orbits imply higher speeds of satellite and smaller inter-satellite distances, they set higher requirements for the angular rate. Therefore, in order to asses feasibility, only the extreme case of the lowest orbit (160 km) is considered here. The corresponding inter-satellite distances can be found in Figure 3.4.

Figure 3.3 also depicts the achievable speeds of slew maneuver for OCSD CubeSat and for Constella platform that were discussed earlier. One can see that in the majority of the cases the required speed of angular rotation is by one order of magnitude lower than this for space-to-ground link. There is a critical case for RAAN = 3.0 rad, which corresponds to the situation where two satellites go almost towards each other. This case causes a noticeable ”blind spot” for micro-satellite, but for nano-satellite the ”blind spot” is negligible.

Figure 3.3: Requirement for Angular Rate of Satellite Rotation in Case of Space-to-Space Link
Figure 3.4: Dynamics of Inter-Satellite Distances


3.3 Integrated Modeling

Definition: Integrated modeling is understood in this thesis as a process of development and analysis of an overall system model, consisting of a link budget model, pointing loss model, transmitting optical antenna model, orbital mechanics model, power subsystem model and TT&C model.

The general framework used to assemble the integrated model is a dynamic time-dependent simulation. Since the full time domain simulation is computationally heavy and seems unreasonable for the goals of this research, only the time dependence of communications range is modeled. The pointing error is treated as a random variable, and characterized using worst case value for the given mean and variance of the pointing error distribution.

3.3.1 Optical Antenna Modeling

This subsection will present the gains of the transmitting and receiving optical antennas (telescopes).

The most frequently used types of telescopes in free space optics are Cassegrain and Gregorian. The main difference between Cassegrain and Gregorian optical systems is that Gregorian telescopes employ a concave secondary mirror beyond the focus of the primary mirror, which lead to the longer tube length (see Figure 3.5 for comparison).

Therefore Cassegrain telescopes are more common, especially for space applications where size is one of the system constraints. For that reason we will assume Cassegrain telescope throughout the thesis.

Let us first consider the transmitting antenna.

Assuming a Gaussian beam at the input to the telescope and the observation point at \((r_1, \theta_1)\), the optical antenna gain is defined as

\[
G(r_1, \theta_1) = \frac{I(r_1, \theta_1)}{I_0}
\]

or the ratio of an intensity radiated in the direction of the telescope optical axis, \(I(r_1, \theta_1)\), over the intensity of a unity power isotropic radiator, \(I_0\), with

\[
I_0 = \frac{1}{4\pi r_1^2}
\]
Figure 3.5: Cassegrain (above) and Gregorian (below) Telescopes (Picture from [3])
and

\[
I(r_1, \theta_1) = \frac{k^2}{r_1^2} \int_b^a \sqrt{\frac{2}{\pi \omega}} \frac{1}{2} e^{\frac{-r_0^2}{\omega^2}} e^{j kr_0^2/2} \left( \frac{1}{r_1} + \frac{1}{R} \right) J_0(kr_0 \sin \theta_1) r_0^2 dr_0^2
\]  

(3.3)

where \( k = \frac{2\pi}{\lambda} \) is a wavenumber for a laser wavelength \( \lambda \), \( \omega \) is the \( \frac{1}{e^2} \) radius of the Gaussian beam being coupled to the telescope optics, and \( R \) is the radius of curvature of the beam front at the telescope aperture plane. The geometry of the problem is presented in Figure 3.6. The radii of the primary and secondary mirrors are \( a \), and \( b \) respectively.

Figure 3.6: Geometry of the Gaussian Beam Coupled to the Cassegrain Telescope Optics (Picture from [2])

For the on-axis transmitter efficiency (\( X = 0 \)), and for far field (\( \beta = 0 \)):

\[
g_T(\alpha, 0, \gamma, 0) = \frac{2}{\alpha^2} [exp(-\alpha^2) - exp(-\gamma^2 \alpha^2)]^2
\]  

(3.4)

And it can further be shown, that optimal transmitter efficiency is obtained by satisfying the approximate relation

\[
\alpha \approx 1.12 - 1.30 \gamma^2 + 2.12 \gamma^4
\]  

(3.5)

Equation 3.5 is accurate to within \( \pm 1\% \) for \( \gamma \leq 0.4 \). Thus for \( \gamma = 0 \) a ratio of 1.12 of the aperture and beam width will optimize the transmitter gain efficiency.
For the receiving optical antenna we also assume that the signal source is sufficiently far away, so that plane waves are impinge on the receiver aperture. And following the methodology for transmitting antenna, the receiver gain is specified as \[ \frac{4\pi A}{\lambda^2} \left(1 - \gamma^2\right) \] (3.6)

where \( \gamma = \frac{b}{a} \) with \( a \) and \( b \) being as previously defined the radii of the secondary and primary mirrors respectively, and \( A = \pi a^2 \) is the primary area of the telescope.

A model of transmitting optical antenna was implemented in Matlab [25]. This model allows to characterize a spatial gain distribution of a given antenna. Example of the model results is presented in Figure 3.7. The graphs describe antennas with fixed diameter \( D = 10cm \), fixed \( \alpha = 1.12 \), but with different \( \gamma \). The transmitter gain is specified in dB in the figure. The x-axis is the normalized radial angle, defined as \( \theta \times \left(\frac{D}{\lambda}\right) \).

The gain distribution fixes the angular beam width \( \Theta \), which is defined in this work as the full-width at half-maximum \( \Theta_{3dB} \).

Figure 3.7: Spatial Gain Distribution for Transmitting Antennas with Different \( \gamma \)

Figure 3.8 captures how the transmitting telescope gain changes varying the diameter of the antenna \( D \) with \( \alpha = 1.12 \) and \( \gamma = 0 \) fixed. As expected the gain increases with increase in
antenna’s diameter.

Figure 3.8: Spatial Gain Distribution for Transmitting Antennas of Different Diameter

While in this work we assume the retractor telescope as an optical system to form the output laser beam, the results of the analysis presented in Chapter 4 suggest that for the body-pointing operations this optics is not justified, leading to very small diameter of the transmitting apertures. As the first approximation, we will continue to work with the model of Cassegrain telescope, but another optical system (probably a simple collimator) giving more realistic results should be considered in future work.

3.3.2 Pointing Loss Modeling

Pointing loss is a result of any mispointing of the laser beam that causes the receiver to be located off-axis from the far-field irradiance profile.

Traditionally, optical communications systems have tried to keep misalignments within a fraction of the beam width defined earlier. But, while the gain of the optical antenna increases with the bigger apertures, the beam width decreases implying tougher requirements for pointing
accuracy. This is a well-known system trade-off. Figure 3.9 presents the beam width as a function of transmitting antenna diameter for $\alpha = 1.12$ and $\gamma = 0$.

![Figure 3.9: Beam Width as a Function of Telescope Diameter](image)

The pointing loss is defined as the ratio of the off-axis gain to the on-axis gain. It is quantified with the following expression:

$$\eta_{pt} = \left( \frac{\alpha^2}{\exp(-\alpha^2) - \exp(-\gamma^2\alpha^2)} \right)^2 \left| \int_{\gamma^2}^{1} \exp(j\beta u)\exp(-\alpha^2 u)J_0[X(u)^2]du \right|^2$$  (3.7)

The pointing loss model developed in Matlab [25] allows to predict the loss for the given parameters of the telescope and mispointing angle.

In Figure 3.10 the pointing loss as a function of the mispointing angle is plotted for the 10 cm telescope, with $\alpha = 1.12$ and obscuration ration ranging from 0 to 0.3.

Besides characterizing the pointing loss itself, there is a need to model the cause of this loss which is the random pointing error. Deriving the probability density of the pointing-error random process is the main goal of this subsection. In doing it, we will follow the approach developed in [26].

Consider the detector plane which contains the detector and is perpendicular to the on-axis
direction (Figure 3.11). Assume then, that the beam direction is declined from the on-axis direction by the error angle $\theta_e$.

For small $\theta_e$, the pointing error can be conventionally decomposed into orthogonal compo-
ments $\theta_x$ and $\theta_y$, where

$$\theta_x = \theta_e \cos \psi$$  \hspace{1cm} (3.8)$$

$$\theta_y = \theta_e \sin \psi$$  \hspace{1cm} (3.9)$$

and

$$\psi = \arctan\left(\frac{\theta_y}{\theta_x}\right)$$  \hspace{1cm} (3.10)$$

Let us now assume that $\theta_x$ and $\theta_y$ are independent Gaussian random variables with mean values $\eta_x$ and $\eta_y$, and variance $\sigma_x^2$ and $\sigma_y^2$ respectively. The total pointing error process can then be described with the mean value

$$\eta = \left[\eta_x^2 + \eta_y^2\right]^{1/2}$$  \hspace{1cm} (3.11)$$

and variance

$$\sigma^2 = \sigma_x^2 = \sigma_y^2$$  \hspace{1cm} (3.12)$$

It is shown in [26] that under this assumptions the probability density function of the total pointing error $\theta_e$ can be expressed as

$$p(\theta_e) = \frac{\theta_e}{\sigma^2} e^{\frac{1}{\sigma^2} \left(\theta_e^2 + \eta^2\right)} I_0\left(\frac{\theta_e \eta}{\sigma^2}\right)$$  \hspace{1cm} (3.13)$$

which is a well-known Rice density function. $I_0$ in (3.13) is a modified Bessel function of order zero.

The graphical representation of Rice density can be seen in Figure 3.12. The plots are given for different values of mean $\eta$ and standard deviation $\sigma$ as shown in the legend.

Once, we have models for both pointing-error random process (equation 3.13) and pointing loss as a result of this mispointing (equation 3.7), we can fully characterize the pointing loss term $\eta_{pt}$ in the range equation 3.15. There are several ways to do it. The two most common are to define a mean loss, or a worst case (outage) loss. Here we will use a worst-case loss.
Suppose we want to have the link operational a fraction $1 - p_{\text{out}}$ of the communication link duration. We say that $p_{\text{out}}$ is the outage probability. From equation (3.13), an outage probability of $p_{\text{out}}$ corresponds to the pointing error $\theta$ that satisfies the Marcum-Q function:

$$p_{\text{out}} = \int_{\theta}^{\infty} \frac{\theta e}{\sigma^2} \exp\left[-\frac{1}{2\sigma^2}(\theta^2_e + \eta^2)\right] I_0\left(\frac{\theta_e \eta}{\sigma^2}\right) d\theta_e$$  \hspace{1cm} (3.14)

Then, solving (3.14) for $\theta$ as a function of $p_{\text{out}}$ and substituting this $\theta$ into equation (3.7) yields the pointing loss for the specified outage probability and pointing error distribution.

For the ADCS subsystem performance we refer to the state-of-the-art pointing accuracies of small platforms which are 0.01 deg and 0.1 deg for micro- and nano-satellite respectively. We further assume that the satellites’ jitter is present within the angular range equal to pointing accuracy, in other words, that $\sigma = \eta$. For both space-to-space and space-to-ground links the acceptable probability of outage is set to 1%.

These numbers result in 0.07 deg beam width for micro-satellite and 0.7 deg for nano-satellite.
3.3.3 Optical Link Budget Modeling

Developing a link budget, we will largely rely on [21], which first derives received and noise powers following approach in [2]. Then the signal and noise powers are mapped to achievable data rates using analysis from [27].

As is it defined in [21], the purpose of a link budget is to determine if a communications link can support a target data rate, and, if so, with what margin. To determine this we first find the received signal power incident on a detector $P_r$. The signal is received in a presence of spatial and temporal distortions and background noise. These phenomena need to be characterized and used to determine the required power, $P_{req}$, incident on a detector to support the desired data rate. The margin is the difference $P_m = P_r - P_{req}$.

Throughout this discussion we assume that the signal is modulated with a pulse-position-modulation (PPM), and that the received optical signal is direct-detected with a photon-counting device. We choose this modulation and detection as it represents current state-of-the-art system for transmitting at high power efficiencies (bits/photon) with optical carriers for both deep-space and near-Earth optical links [28].

Received Signal Power

The power incident on the receiver detector is determined using the conventional range equation:

$$P_r = P_t G_t G_r L_s L_o \eta_{pt} \eta_t \eta_r$$  \hspace{1cm} (3.15)

where $P_t$ is the transmitted power, $G_t$ is the transmitter gain, $G_r$ is the receiver gain, $L_s$ is the space loss, $L_o$ is the atmospheric loss, $\eta_{pt}$ is the pointing loss, $\eta_t$ is the transmitter efficiency, and $\eta_r$ is the receiver efficiency.

Pointing loss and optical antenna gains were quantified in detail earlier, so let us now characterize the remaining gains and losses in equation 3.15.

**Space Loss** Space loss in 3.15 is defined as

$$L_s = \left( \frac{\lambda}{4\pi R} \right)^2$$  \hspace{1cm} (3.16)

where $R$ is the range, and $\lambda$ is the carrier wavelength.
**Atmospheric Loss**  There are a lot of undesirable features of atmospheric channel that lead to serious signal fading, or even to a complete loss of signal. These are comprised of absorption and scattering due to particulate matter in the atmosphere that may significantly decrease the transmitted optical signal, and random atmospheric distortions due to turbulence that may significantly degrade the quality of a signal-carrying wave-front, causing intensity fading and random signal losses at the receiver.

Atmosphere induced losses can span from several dB to hundreds of dB [29]. Accurate modeling of the atmospheric effects is a complicated task and probably a topic of another thesis. The authors of the majority of the papers reviewed in this thesis used commercially available Modtran [18] software package to model signal propagation through the atmosphere in space-to-ground optical downlink mode.

Integrating Modtran to the integrated model is definitely a good objective for the future work, but as a first approximation the reasonable fixed atmospheric losses were assumed for space-to-ground and space-to-space links, 30 dB and 1 dB respectively.

**Transmitter and Receiver Efficiencies**  The transmitter efficiency captures losses due to coupling the laser beam to the optical system and propagation of the beam through the optical system at the transmitter. Transmitter efficiencies in the range of 1.4 dB to 2.3 dB have been reported in [2].

The receiver efficiency captures losses due to transmission through a narrow band filter and polarizing optics, mirror losses, and if present coupling losses to a fiber. Receiver efficiencies on the order of 3.0 dB to 4.0 dB have been reported [2].

**Required Power**

In the previous subsection we determined a received signal power in the receiver focal plane. Here we determine a required power in the focal plane in order to close the link with the targeted data rate.

The data rate of a PPM modulation signal of order $M$, with error control code (ECC) rate $R_{ECC}$, and with slot width of duration $T_s$ is given by

$$R_b = R_{ECC} \frac{\log_2 M}{M T_s}$$  \hspace{1cm} (3.17)
A bit error rate (BER) modeling was not done within the scope of this work. Accurate BER model is another important future step. For now, we assume that $R_{ECC} = 1/2$ allows to transmit the data with acceptable BER.

According to [30] the capacity of the Poisson PPM channel for non-zero background noise power is

$$C_{PPM} = \frac{1}{MT_s} \left( D(p_1|p_0) - D(p_y|p_{y|0}) \right)$$  \hspace{1cm} (3.18)

where $D(f|g) = E_f \log_2 \frac{f}{g}$ is the relative entropy, $p_1$ and $p_0$ probability mass functions of a signal and noise slot, and $p_y$ and $p_{y|0}$ are the probability mass functions of a random PPM symbol and noise vector, respectively. The form of equation 3.18 is not reasonable for the purpose of this work which derives a simple link equation, because evaluation of 3.18 requires one to perform a multidimensional infinite sum or perform a Monte Carlo simulation. Authors of [21] derive a closed-form approximation of 3.18 combining a number of bounds on $C_{PPM}$:

$$C_{PPM} = \frac{1}{E_\lambda \ln 2} \left( \frac{P_i^2}{P_{in(M)}} + \frac{P_n^2}{M^{2-M-1}} + \frac{P_i^2}{E_\lambdaMT_s} \right)$$  \hspace{1cm} (3.19)

where $P_i$ is the detected signal power, $p_n$ is the detected noise power, and $E_\lambda$ is the energy of a single photon of a $\lambda$ wavelength ($E_\lambda = \frac{hc}{\lambda}$).

For the fixed $M$, $T_s$, $R_b$, and noise power $P_n$, let $P_i$ be the signal power satisfying

$$C_{PPM} = R_b$$  \hspace{1cm} (3.20)

Then, $P_i$ represents the lower power required in the receiver focal plane to close the link.

**Noise Power**  A thorough treatment of noise power is given in [2]. We assume a photon-counting detector which converts incident photons into electrons and enables to estimate the number of photon-arrivals by its voltage output. Besides the signal photons, there are three sources of noise that enter the receiver and decrease the theoretical channel capacity described by equation 3.19. These are photo-electrons generated by incident background light, dark-noise electrons generated by the detector, and the thermal noise of the receiving system. We capture the contribution of the latter in the receiver efficiency term, referring by noise power only the background and dark noise electrons.
For the background radiance we neglect the point sources and only account for sky radiance as a primary extended source:

\[ P_{n}^{sky} = I_{b}(\lambda)\delta_{\lambda}\Omega_{det}\left(\frac{\pi D_{r}^{2}}{4}\right)\eta_{det}\eta_{r}\eta_{pol} \tag{3.21} \]

where \( I_{b}(\lambda) \) is the incident sky radiance at wavelength \( \lambda \), \( \delta_{\lambda} \) is the narrow band filter bandwidth, \( \Omega_{det} \) is the detector field-of-view, \( \eta_{r} \) is the receiver efficiency and \( \eta_{pol} \) is the polarization rejection.

The dark noise power is quantified with

\[ P_{n}^{dark} = 4\delta^{2}l_{d}E_{\lambda} \tag{3.22} \]

where \( l_{d} \) is the detector dark rate, and \( 2\delta \) is the detector spatial width.

**Link Budget Tool Validation**

In order to validate the link budget tool implemented in Matlab, we will compare the results of this model to the sample link budget in [21]. Particularly, we will compare two outputs of the models: the received power \( P_{r} \) and the required power \( P_{i} \). Table 3.2 contains the input parameters used for the sample link budget. The reason for the minor difference of the results is different approaches adopted to estimate noise power. While we referred [2] for this estimation, authors of [21] did not outline their approach explicitly.

Table 3.3 contains the outputs of both models. The predictions differ by 0.1 % for the received power and by 0.47 % for the required power. Both numbers lie within the 1 % error allocation which we consider as sufficient for the model to be validated.

### 3.3.4 Orbital Mechanics Modeling

The purpose of the orbital mechanics modeling in this work is to quantify the dynamics of the optical communications range in both space-to-space and space-to-ground scenarios.

To characterize the orbital motion we use the widely known orbital elements (defined for example in [11]). We assume the Earth as an ideal spherical body, and neglect the perturbation forces that degrade the orbit.

The orbit propagator was developed in Matlab [25]. The inputs of the model are the orbital elements, and the outputs are the position and velocity vectors as the functions of time.
Table 3.2: Input Parameters for Link Budget Model Validation

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>Communications Range</td>
<td>0.5 AU</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
<td>1.55 $\mu$m</td>
</tr>
<tr>
<td>$I_b$</td>
<td>Sky Radiance</td>
<td>$5.0 \times 10^{-4}$ W cm$^{-2}$ sr$m^{-1}$$\mu$m$^{-1}$</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Slot Width</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>$M$</td>
<td>PPM Order</td>
<td>32</td>
</tr>
<tr>
<td>$R_{ECC}$</td>
<td>ECC Code Rate</td>
<td>1/2</td>
</tr>
<tr>
<td>$D_t$</td>
<td>Transmitter Aperture Diameter</td>
<td>0.22 m</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>Transmitter Obscuration Ratio</td>
<td>0</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>Beam Width to Aperture Ratio</td>
<td>1.12</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Mean Pointing Error</td>
<td>0.00 $\mu$ rad</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard Deviation of Pointing Error</td>
<td>0.7 $\mu$ rad</td>
</tr>
<tr>
<td>$p_{out}$</td>
<td>Outage Probability</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$\eta_t$</td>
<td>Transmitter Efficiency</td>
<td>0.7</td>
</tr>
<tr>
<td>$D_r$</td>
<td>Receiver Aperture Diameter</td>
<td>10.0 m</td>
</tr>
<tr>
<td>$\gamma_r$</td>
<td>Receiver Obscuration Ratio</td>
<td>0.0</td>
</tr>
<tr>
<td>$\Delta \lambda$</td>
<td>Band-Pass Filter Bandwidth</td>
<td>$2 \times 10^{-4}$ $\mu$m</td>
</tr>
<tr>
<td>$\eta_r$</td>
<td>Receiver Efficiency</td>
<td>0.39</td>
</tr>
<tr>
<td>$\eta_{pol}$</td>
<td>Polarization Rejection</td>
<td>0.5</td>
</tr>
<tr>
<td>$\eta_{det}$</td>
<td>Detector Quantum Efficiency</td>
<td>0.4</td>
</tr>
<tr>
<td>$2\delta$</td>
<td>Detector Width</td>
<td>15 $\mu$m</td>
</tr>
<tr>
<td>$l_d$</td>
<td>Dark Electron Rate</td>
<td>$10^6 \frac{e}{\text{smm}^2}$</td>
</tr>
</tbody>
</table>
Table 3.3: Outputs of the Link Budget Tool

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Prediction of the Model</th>
<th>Prediction from [21]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter On-Axis Gain</td>
<td>112.1 dB</td>
<td>112.1 dB</td>
</tr>
<tr>
<td>Space Loss</td>
<td>-355.7 dB</td>
<td>-355.7 dB</td>
</tr>
<tr>
<td>Receiver Gain</td>
<td>146.1 dB</td>
<td>146.1 dB</td>
</tr>
<tr>
<td>Received Power</td>
<td>-98.9 dB</td>
<td>-98.9 dB</td>
</tr>
<tr>
<td>Photon Energy</td>
<td>-188.9 dB</td>
<td>-188.9 dB</td>
</tr>
<tr>
<td>Noise Power</td>
<td>-139.6 dB</td>
<td>No explicit value</td>
</tr>
<tr>
<td>Required Power (Lower Bound)</td>
<td>-111.0 dB</td>
<td>-110.5 dB</td>
</tr>
<tr>
<td>Other Receiver Losses</td>
<td>-8.4 dB</td>
<td>-8.4 dB</td>
</tr>
<tr>
<td>Required Power</td>
<td>-102.6 dB</td>
<td>-102.12 dB</td>
</tr>
<tr>
<td>Margin</td>
<td>3.64 dB</td>
<td>3.12 dB</td>
</tr>
</tbody>
</table>

We validate the results of the orbit propagator by comparing them to the results of STK [31] which is widely used in academia and industry.

Setting the same orbital elements and propagating the orbit in both tools for a single period, we then compare the lengths of the position vectors with 60 seconds time step. The results for the three different law Earth orbits are presented in Table 3.4.

The average mean difference of two predictions is $2.6^{-6}\%$ and the average maximum difference is $6.3^{-6}\%$. Since both values are far less than 1 $\%$, we conclude that the orbit propagator shows sufficient agreement with STK.

### 3.3.5 Power Subsystem Modeling

According to [11] the electrical power subsystem (EPS) has four primary functions: to provide, to store, to distribute, and to control spacecraft electrical power. In this thesis only the first two functions was modeled, making the reasonable assumptions about the three others.

**Power Source**

We consider the photovoltaic solar cell as the primary source of power on the spacecraft during the daylight. The secondary batteries recharged during the daylight supply power to the spacecraft during the eclipse. The following steps describe the design process that was implemented
Table 3.4: Orbital Mechanics Model Validation

<table>
<thead>
<tr>
<th>Orbital Elements</th>
<th>Orbit 1</th>
<th>Orbit 2</th>
<th>Orbit 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>7000 km</td>
<td>7000 km</td>
<td>7500 km</td>
</tr>
<tr>
<td>e</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>i</td>
<td>0.785 rad</td>
<td>0.785 rad</td>
<td>0.785</td>
</tr>
<tr>
<td>Ω</td>
<td>1 rad</td>
<td>3.14 rad</td>
<td>1 rad</td>
</tr>
<tr>
<td>ω</td>
<td>0.5 rad</td>
<td>0.5 rad</td>
<td>0.5 rad</td>
</tr>
<tr>
<td>ν</td>
<td>3.14 rad</td>
<td>3.14 rad</td>
<td>3.14 rad</td>
</tr>
<tr>
<td>Mean Difference</td>
<td>2.3×10^{-6} %</td>
<td>2.3×10^{-6} %</td>
<td>3.2×10^{-6} %</td>
</tr>
<tr>
<td>Max Difference</td>
<td>5.6×10^{-6} %</td>
<td>5.6×10^{-6} %</td>
<td>7.8×10^{-6} %</td>
</tr>
</tbody>
</table>

to model the power budget of the satellite.

**Step 1** At this step we need to specify the average power requirement in eclipse $P_{avg}^e$ and daylight $P_{avg}^d$, the lifetime of the mission, and the following orbital parameters: altitude, eclipse and daylight periods ($T_e$ and $T_d$ respectively).

The orbital parameters come as input from the orbit propagator model discussed earlier. For the micro- and nano-satellites the lifetimes of 5 and 3 years respectively were assumed. The average power requirement is determined by defining the operating powers of the satellite subsystems and their duty cycles. The following subsystems were considered: main payload, thermal subsystem, ADCS, EPS, communication, CD & H. Tables 3.5 and 3.6 present the micro- and nano-satellite power budgets used in case studies. For this data we refer to [32] and [33]. As it can be seen from the tables, we simply assume the duty cycles of one for all of the subsystems, letting only the duty cycle of the active mode of communications subsystem to vary. The duty cycle of the LCT is not an input of the model, but a by-product of the optimization algorithm that will be described in the next section. The power consumed by LCTs in the active mode are assumed to be the same as the current allocations for the RF (radio frequency) payloads.

Besides, in this work we assume the 30 % power efficiency of the laser diode, which is defined as the ratio of electrical input power and optical output power. This number is quite conservative compared to the recent advancements in laser diodes’ development. For instance a

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6Command and Data Handling
commercially available JDSU 6396 laser [34] achieves about 60% efficiency. Laboratory deceives are reported to achieve up to 76% with the goal of 80% [35].

The highest efficiencies are demonstrated for the relatively low output powers, 2 - 5 W. This range might be insufficient for space applications, where the number of devices that can be used in the fiber-coupled system is limited. However, while the JDSU 6396 referenced above is able to output 6.5 W of optical power, the recent achievements are > 10 W for the efficiencies of > 65% [36]. Therefore, the 30% efficiency assumed in this work and the stated input powers for both micro- and nano-satellites’ LCTs are quite reasonable.

Table 3.5: Power Budget of Micro-Satellite

<table>
<thead>
<tr>
<th>Duty Cycle</th>
<th>Power Consumption, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Payload</td>
<td>1</td>
</tr>
<tr>
<td>Thermal Subsystem</td>
<td>1</td>
</tr>
<tr>
<td>ADCS</td>
<td>1</td>
</tr>
<tr>
<td>Power Subsystem</td>
<td>1</td>
</tr>
<tr>
<td>Communication Subsystem (stand by)</td>
<td>1</td>
</tr>
<tr>
<td>Communications Subsystem (active mode)</td>
<td>varies</td>
</tr>
<tr>
<td>CD&amp;H Subsystem</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.6: Power Budget of Nano-Satellite

<table>
<thead>
<tr>
<th>Duty Cycle</th>
<th>Power Consumption, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Payload</td>
<td>1</td>
</tr>
<tr>
<td>Thermal Subsystem</td>
<td>1</td>
</tr>
<tr>
<td>ADCS</td>
<td>1</td>
</tr>
<tr>
<td>Power Subsystem</td>
<td>1</td>
</tr>
<tr>
<td>Communication Subsystem (stand by)</td>
<td>1</td>
</tr>
<tr>
<td>Communications Subsystem (active mode)</td>
<td>varies</td>
</tr>
<tr>
<td>CD&amp;H Subsystem</td>
<td>1</td>
</tr>
</tbody>
</table>
Step 2 Here we determine how much power, $P_{sa}$, the solar array must provide during the daylight in order to power the spacecraft during the entire orbit:

$$P_{sa} = \frac{P_e T_e}{X_e} + \frac{P_d T_d}{X_d}$$

(3.23)

where the terms $X_e$ and $X_d$ represent the efficiencies of the paths from the solar arrays through the batteries to the loads and from the solar arrays directly to the loads, respectively. In this work we will assume the peak-power tracking type of regulation with $X_e = 0.60$ and $X_d = 0.80$

Step 3 At this step we need to peak the type of the solar cell and estimate the output with the Sun normal to the surface of the solar array.

The efficiency of the solar cell is defined as power output divided by power input. In our case the input power is the solar illumination intensity that equals $1367 \text{W/m}^2$.

We will account for the GaAs (Gallium Arsenide) solar cell which is widely used nowadays by all types of space platforms and shows the space-qualified efficiency of 30 % [37].

Step 4 The realistic power production capability of a solar array at the beginning-of-life (BOL) is

$$P_{BOL} = P_0 I_d \cos \theta$$

(3.24)

where $I_d$ is referred as inherent degradation and $\cos \theta$ is so-called cosine loss.

The angle $\theta$ in the cosine loss term is the Sun incidence angle measured as the angle between the vector normal to the surface of the array and the Sun line. Since, the geometry changes throughout the mission and the exact time dependence profile of the $\theta$ angle is beyond the scope of our analysis, we assume the worst case angle of 23.5 deg (the angle between equatorial and ecliptic planes) for all types of orbits. For the inherent degradation we use the nominal value of 0.77 reported in [11].

Step 5 At the final step we will determine the realistic power output at the end-of-life (EOL) and size the solar array.
The power output is determined as

$$P_{EOL} = P_{BOL}L_d$$  \hspace{1cm} (3.25)

where $L_d$ is the coefficient that characterize solar array’s lifetime degradation estimated as

$$L_d = (1 - \text{degradation/year})^{T_{life}}$$  \hspace{1cm} (3.26)

where $T_{life}$ is the lifetime of a mission and typical degradation per year for GaAs cell is 2.75%.

Having the end-of-life power requirement, we can finally calculate the required area of the solar array

$$A_{sa} = \frac{P_{sa}}{P_{EOL}}$$  \hspace{1cm} (3.27)

For both constrained regime and relaxed regime algorithms (see section 1.1) we restrict the power allocation for the communications subsystem by the area of the solar array. We require the designs to be within 1$m^2$ and 0.05$m^2$ allocation for the micro- and nano-satellite respectively.

While using the nominal value for the LCT power consumption (see Tables 3.5 and 3.6) in the constrained regime, we will let the LCT input power to increase by the factor of two in the relaxed regime of the system, accounting for the potential increase of the solar cell efficiency.

### 3.3.6 TT&C Subsystem Modeling

The Tracking, Telemetry, and Command, as defined in [II], is the subsystem which provides the interface between the spacecraft and ground systems.

We investigate the following options for the TT&C interfaces:

1) *Fixed Ground Station*

2) *Relay Satellite (within the same constellation)*

As it was stated in section 1.1 the goal of the TT&C modeling in this work is to understand the benefits of optical communications. We do it by considering three parameters: the data that can be transmitted by the communications payload per session, the data volume generated by the main instrument and the storage capability of the satellite.

The operation cycle of the TT&C subsystem is as follows: 1) the instrument generates the data, 2) this data is stored on-board, 3) the accumulated data is downlinked.
Nowadays, the bottleneck of this scheme is an access to the ground stations. While there are high performing instruments and capacious hard drives that are readily exist for small satellites, these cannot unleash its potential due to the lack of data downlinking capability. For that reason the duty cycles of the instruments on small satellites are typically low. There are two ways to resolve this issue: 1) enhance the ground segment (build more ground stations), 2) enhance the space segment (increase the transmitting data rate of the spacecraft). In the present analysis we consider the second option, keeping the number of ground stations fixed and analyzing how much the optical link can increase the duty cycle of the spacecraft’s instrument comparing to RF (radio frequency) link.

We assume the passive imaging instrument for both of the platforms. While [4] states that the data rates of 200 Mbit/s are now achievable for the imaging payloads of all types of platforms, we will use the realistic numbers reported by the current missions. For the micro-satellite we refer to the hyper spectral imaging instrument of the Constella platform [38], and set the data rate at 20 Mbits/s, while for nano-satellite we assume 5 Mbits/s.

We also assume that we are not restricted by the storage capacity of the satellite.

To access the number of available downlinks for space-to-ground mode we use STK [31]. For space-to-space mode we make the reasonable assumption in the next chapter, because the number of accesses in this mode is highly dependent on the geometry of the constellation. For the first mode we compare the performance of the optical and RF communications in terms of data that can be downloaded per communication session and subsequent instrument duty cycle. Since, to the author’s best knowledge, there have not been noticeable inter-satellite RF communication demonstrations on small platforms, we compare the performance of space-to-space and space-to-ground optical downlinks.

### 3.4 Optimization Routine

Here we will describe the $D_{com}$-optimization algorithm that is used within the frame of the integrated model and that was mentioned earlier as step 8 in the constrained regime algorithm. First the data rate maximization problem would be described for the fixed communications range. Then, we will formulate $D_{com}$-maximizing problem for the dynamic range and propose the algorithm for its solution within the frame of integrated model. The trade-offs of the system
will be outlined.

If we fix the communications range and want to maximize the data rate of a given communications link, we need to solve the following problem

\[
\text{Maximize } R_b = R_{ECC} \frac{\log_2 M}{MT_s} \tag{3.28}
\]

\textbf{Subject To: } 

\begin{align*}
M & \in [2, 4, 8, ..., 2048] \tag{3.29} \\
T_s & \in [T_s^{min}, 1.26T_s^{min}, ..., 12.58T_s^{min}] \tag{3.30} \\
R_b & \leq C_{PPM} \tag{3.31}
\end{align*}

This is a single objective maximization problem that depends on two variables \(M\) and \(T_s\). The modulation order is a discrete quantity that takes only the values of natural powers of 2. As suggested above, we consider a finite set of \(M = 2\) to \(M = 2048\) which covers the practical designs. For the slot width we examine a finite set of eleven values with the 1 dB step relative to \(T_s^{min}\). The non-continuity of the slot width is caused by the hardware limitations which also restrict the \(T_s^{min}\), taken to be 0.5 ns in this work [19].

The last constraint of the problem demands the data rate implemented by the electronics not to exceed the theoretical capacity of the communications channel \(C_{PPM}\). \(C_{PPM}\) is fixed for the given signal and noise powers of the channel.

Besides the data rate, we also want to maximize the margin of the link to have the stable connection with the minimal bit error rate. Figure [3.13] presents the whole domain of possible \((M, T_s)\) pairs and the Pareto front for micro-satellite. The Pareto front characterizes the trade-off of the system between the data rate and the margin of the link. The optimization algorithm runs through all of the dots of Pareto front and choses the solution with the margin closest to the lowest acceptable value of 3 dB from the right hand side.

Figure [3.14] presents the same result but for the case of nano-satellite. For both cases we considered the range of 600 km, the nominal values of input powers, the nominal values of beam widths and the space-to-ground downlink mode with 1 m receiver diameter.

Since the domain of possible values is relatively small the optimization is implemented by simple enumeration. Figure [3.15] shows a graphical representation of the data rate maximization tool developed in Matlab [25], capturing the main inputs and outputs of the model.

Let us now consider the more complicated case of the changing communications range. The
Figure 3.13: Pareto front of Data Rate - Margin Trade-Off for Micro-Satellite

Figure 3.14: Pareto front of Data Rate - Margin Trade-Off for Nano-Satellite
optimization problem is now formulated as follows

\[
\text{Maximize } D_{\text{com}} = R_b \times T_{\text{com}} = R_{ECC} \frac{\log_2(M)T_{\text{com}}}{MT_s} \tag{3.32}
\]

\textbf{Subject To:} \quad M \in [2, 4, 8, \ldots, 2048] \tag{3.33}

\[T_s \in [T_{s_{\text{min}}}, 1.26T_{s_{\text{min}}}, \ldots, 12.58T_{s_{\text{min}}}]\tag{3.34}\]

\[R_b \leq C_{\text{PPM}}\tag{3.35}\]

\[T_{\text{com}} = T_{\text{com}}(C_{\text{PPM}}, R(t), M, T_s)\tag{3.36}\]

\[M, T_s = \text{const} \text{ for the given communications session}\tag{3.37}\]

where \(T_{\text{com}}\) is the duration of the communications session, \(R(t)\) is the time-dependent communications range.

While previously we were maximizing the data rate, in this case our objective is the data that can be transmitted per communications session \(D_{\text{com}}\). It is still a single objective optimization problem that has two variables - \(M\) and \(T_s\). But our objective function is now dependent on the additional parameter \(T_{\text{com}}\) that is implicitly connected to the main variables through the equality constraint 1.43. Besides the modulation order and the slot width, the session duration is also a function of the theoretical channel capacity \(C_{\text{PPM}}\) and the link range \(R(t)\). The last constraint reflects the notion of permanence of the modulation order and slot width throughout
the duration of the communications session.

As you can mention the problem is no longer static. The time dependence is introduced by the $R(t)$ term which we assumed to be constant in the data rate maximization problem.

In Figure 3.16 one can see an additional layer in the graphical representation of the nested Data Maximization Tool that is used to solve the $D_{com}$-maximization problem. This layer, called Orbit Propagator - Link Budget Tool Interface, captures the dynamics of the communications range propagating an orbit with the discrete time step of 3 seconds and passing the range to the Link Budget Model.

![Figure 3.16: Graphical Representation of Data Maximization Tool](image)

The optimization algorithm is similar to the one described earlier. The relatively small domain enables to detect the Pareto front again by enumeration. But since the problem is time dependent, the $D_{com}$-Margin trade-off is not as straight-forward as earlier.

To characterize this trade-off let us first describe how the algorithm calculates the duration of the communications session. Figure 3.17 shows an example of such a session for micro-satellite in space-to-ground mode from 600 km orbit. The plot captures how the link margin changes during the session for fixed $M$ and $T_s$. We say that the link is closed if the margin exceeds the 3 dB gap. Therefore, the beginning and the end of the session are easily recognizable (see Figure...
letting to calculate the duration as \( T_{\text{com}} = T_{\text{end}} - T_{\text{begin}} \).

Figure 3.17: \( T_{\text{com}} \) Derivation

Knowing \( T_{\text{com}} \) and having the data rate \( R_b \) that is defined by modulation order and slot width, we can calculate the data that can be transmitted during this communications session following equation 3.39. After running the same procedure for all of the possible \((M, T_s)\) pairs, we select the maximum \( D_{\text{com}} \).

Although we can not link a single value of \( D_{\text{com}} \) to the single value of the margin, we can link the \( D_{\text{com}} \) to the average margin of the communications session. Figures 3.18 and 3.19 present the Pareto fronts for the micro- and nano- satellites respectively. Both simulations considered the space-to-ground downlink from 600 km orbit, with the nominal values of power input, receiver size and beam width.

One can clearly see that there are some infeasible combinations of \((M, T_s)\) represented by the dots lying in the origin of the frame for micro-satellite. For nano-satellite the majority of the \((M, T_s)\) pairs are infeasible.

Among all of the solutions lying on the Pareto front, the optimization algorithm always chooses the one with the maximum \( D_{\text{com}} \) since the acceptable margin was already accounted for earlier when calculating the duration of the session \( T_{\text{com}} \).

The downturns on both of the graphs are due to the direct proportionality of \( D_{\text{com}} \) on both of the data rate \( R_b \) and the communications session duration \( T_{\text{com}} \). The first quantity increases,
while the second decreases for the decreasing $M$ and $T_s$. Therefore, the maximums of the curves for different modulation orders present the optimal balances between $R_b$ and $T_{com}$ that maximize $D_{com}$ for a given $M$.

### 3.5 Integrated Model Validation

Since there are only a few design efforts of setting up optical communication on micro- and nano-satellites, the amount of data points for validation is very limited. We validate the integrated model by directly comparing the predicted data rate to the expectations of Optical Communications and Sensor Demonstration (OCSD) program of Aerospace corporation [4].

Seeing that OCSD program develops a nano-satellite, we expand the validation discussion for the case of micro-satellite by comparing the main design parameters of its LCT used in the integrated model and the parameters of optical communication payload of Mexican SATEX 1 satellite [39].

The 1.5 U CubeSat of OCSD program targets to achieve 5 Mbps/s in the nominal regime
Figure 3.19: Pareto Front for the $D_{com}$ - Average Margin Trade for Nano-Satellite
and 50 Mbits/s as a maximum data rate. The parameters of the system that were found in open literature are presented in Table 3.7.

Table 3.7: OCSD System Parameters

<table>
<thead>
<tr>
<th>Targeted Data Rate</th>
<th>Emitted Power</th>
<th>λ</th>
<th>Beam Width</th>
<th>$D_r$</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Mbps</td>
<td>14 W</td>
<td>1064 nm</td>
<td>1.4 deg</td>
<td>0.3 m</td>
<td>600 km</td>
</tr>
<tr>
<td>50 Mbps</td>
<td>14 W</td>
<td>1084 nm</td>
<td>0.5 deg</td>
<td>0.3 m</td>
<td>600 km</td>
</tr>
</tbody>
</table>

Despite the small amount of information available about the demonstration, we can make the reasonable assumptions for the lacking parameters. The assumed values are contained in Table 3.8 and allow us to compare the predicted data rates by the order of magnitude. Note, that while no data is available about the modulation format of OCSD program, we use the PPM (pulse position modulation).

Table 3.8: Assumed Parameters for the OCSD Demonstration

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_b$</td>
<td>Sky Radiance</td>
<td>$5.0 \times 10^{-4} \frac{W}{cm^2 sr \mu m}$</td>
</tr>
<tr>
<td>$R_{ECC}$</td>
<td>ECC Code Rate</td>
<td>$1/2$</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>Transmitter Obscuration Ratio</td>
<td>$0$</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>Beam Width to Aperture Ratio</td>
<td>1.12</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Mean Pointing Error</td>
<td>0.1 deg (nano)/0.01 deg (micro)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard Deviation of Pointing Error</td>
<td>0.1 deg (nano)/0.01 deg (micro)</td>
</tr>
<tr>
<td>$p_{out}$</td>
<td>Outage Probability</td>
<td>1 %</td>
</tr>
<tr>
<td>$\eta_t$</td>
<td>Transmitter Efficiency</td>
<td>0.7</td>
</tr>
<tr>
<td>$\gamma_r$</td>
<td>Receiver Obscuration Ratio</td>
<td>0.0</td>
</tr>
<tr>
<td>$\Delta \lambda$</td>
<td>Band-Pass Filter Bandwidth</td>
<td>$2 \times 10^{-4} \mu m$</td>
</tr>
<tr>
<td>$\eta_r$</td>
<td>Receiver Efficiency</td>
<td>0.39</td>
</tr>
<tr>
<td>$\eta_{pol}$</td>
<td>Polarization Rejection</td>
<td>0.5</td>
</tr>
<tr>
<td>$\eta_{det}$</td>
<td>Detector Quantum Efficiency</td>
<td>0.4</td>
</tr>
<tr>
<td>$2\delta$</td>
<td>Detector Width</td>
<td>15 \mu m</td>
</tr>
<tr>
<td>$l_d$</td>
<td>Dark Electron Rate</td>
<td>$10^6 \frac{e}{s mm^2}$</td>
</tr>
<tr>
<td>$L_{receiver}$</td>
<td>Other Receiver Losses</td>
<td>-8.4 dB</td>
</tr>
</tbody>
</table>
Table 3.9 contains the outputs of the integrated model for the inputs specified above.

Table 3.9: Integrated Model Outputs for the Baseline 30 dB of Atmospheric Loss

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Nominal Regime</th>
<th>Targeted Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal $M$</td>
<td>2048</td>
<td>1024</td>
</tr>
<tr>
<td>Optimal $T_s$</td>
<td>2.0008 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Optimal $T_{com}$</td>
<td>201.7 s</td>
<td>171.6 s</td>
</tr>
<tr>
<td>Optimal Data Rate</td>
<td>1.3 Mbps</td>
<td>9.76 Mbps</td>
</tr>
<tr>
<td>OCSD predictions</td>
<td>5 Mbps</td>
<td>50 Mbps</td>
</tr>
<tr>
<td>Results Difference</td>
<td>74 %</td>
<td>80.5 %</td>
</tr>
</tbody>
</table>

The predictions of the model are of the same order of magnitude, but still differ much from the targeted data rates of OCSD program. The reason for that might be a hard atmospheric loss that we assumed in this work - 30 dB. If we decrease it to 20 dB, the model predictions are much closer to the expectations of Aerospace corporation for the targeted data rate, but for the nominal operation the difference is still high (See Table 3.10). Therefore, for the nominal regime we further decrease the minimal slot width to the value of $T_{s_{min}} = 5$ ns (compared to 0.5 ns used throughout the thesis). This is a logical assumption, because when not targeting the maximum data rate, decreasing the slot width leads to the higher link margins and more stable communication. Using the new set of slot widths the difference between the predictions for the nominal regime is 10 % (see Table 3.10).

Table 3.10: Integrated Model Outputs for the 20 dB of Atmospheric Loss

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Nominal Regime ($T_{s_{min}} = 0.5 \times 10^{-9}$ s)</th>
<th>Nominal Regime ($T_{s_{min}} = 0.5 \times 10^{-8}$ s)</th>
<th>Targeted Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal $M$</td>
<td>1024</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Optimal $T_s$</td>
<td>0.5 ns</td>
<td>5 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Optimal $T_{com}$</td>
<td>225.7 s</td>
<td>279.9 s</td>
<td>189.6 s</td>
</tr>
<tr>
<td>Optimal Data Rate</td>
<td>9.8 Mbps</td>
<td>5.5 Mbps</td>
<td>54.7 Mbps</td>
</tr>
<tr>
<td>OCSD predictions</td>
<td>5 Mbps</td>
<td>5 Mbps</td>
<td>50 Mbps</td>
</tr>
<tr>
<td>Results Difference</td>
<td>96 %</td>
<td>10 %</td>
<td>9.4 %</td>
</tr>
</tbody>
</table>

Our goal is to consider a normal mission having an access to ground stations located around the globe and having an objective to download the data as fast as possible to decrease the latency. As the weather conditions significantly differ at different locations on the Earth, we keep the atmospheric loss equal to 30 dB in this thesis to be more realistic.
Since for the both regimes we eventually came to the difference which meets the 10 % requirement (outlined in section 1.1 as sufficient for model to be validated), we confirm the integrated model as validated. The reason for the difference between the predictions of the integrated model and the expectations of OCSD program might be a use of modulation format that is different from PPM, or the assumptions that are different from those presented in Table 3.8.

In order to expand the validation for the case of micro-satellites, let us now compare the main design parameters of micro-satellite’s LCT used in the integrated model and the parameters of optical communication payload of SATEX 1 [39]. We compare these quantities instead of data rate because the latter is not published in the literature for SATEX 1. Table 3.11 outlines the differences between the beam widths and the transmitting telescope diameters. These parameters are the by-products of the integrated model. First parameter is driven by the pointing accuracy and stabilization capability of the satellite, while the second parameter is dependent on the first one and the optical system used in LCT.

Table 3.11: The Comparison of Main Design Parameters of LCTs for Micro-Satellites

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>SATEX 1</th>
<th>Integrated Model</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Width</td>
<td>0.09 deg</td>
<td>0.07 deg</td>
<td>22.2 %</td>
</tr>
<tr>
<td>Transmitter Diameter</td>
<td>0.0025 m</td>
<td>0.0015 m</td>
<td>40 %</td>
</tr>
<tr>
<td>Optical Power</td>
<td>0.1 W</td>
<td>7.5 W</td>
<td>N/A</td>
</tr>
<tr>
<td>Wave Length</td>
<td>830 nm</td>
<td>1550 nm</td>
<td>N/A</td>
</tr>
</tbody>
</table>

As it is expected the beam width of SATEX 1 is bigger than the one we use in the integrated model. The reason for that is increased pointing capability of current micro-satellite platforms compared to SATEX 1 which was developed in 2001. This allows to have the same probability of outage operating with narrower beam width. The difference between the transmitter diameters is driven by different beam widths, and different types of optics. Satex 1 was supposed to use a simple collimator, while in this work we assume the reflector optical antenna.

The optical power and wave length parameters given in Table 3.11 are the inputs of the integrated model, therefore no comparison is done for them. As it was discussed earlier, the recent advancements of laser diodes enabled higher operating powers, therefore the input power that we use in the integrated model is significantly different from the one of SATEX 1. While
there are no limitations on the wave length, in this work we refer to 1550 nm, which was used by the recent European laser communication demonstrations on big satellites.

### 3.6 Summary

The integrated modeling approach having six constituent models was presented in this chapter. To answer the specific research questions we introduced the so-called *constrained* and *relaxed regimes* of the system model. Finally, we presented an optimization algorithm that is an essential part of the integrated modeling.

As the new demonstrations of laser communications are coming now for small platforms, the system level integrated modeling and subsequent analysis will help to identify the key trades and to access the benefits of optical communications technology.

The contributions of this work are mainly related to the development of analysis and optimization tools. Nevertheless, the novelty is introduced by studying the new concept of operation for laser terminals, which is a body pointing.
Chapter 4

Case Studies and Results

As it was outlined in the previous chapter our goal is to study the space-to-ground and space-to-
space optical links for micro- and nano- satellites. In this chapter we will first use the integrated
model in the constrained regime (as defined in Chapter 3) to address the feasibility of optical
communications for the particular scenario and the benefits associated with this technology.
Then, we will switch to the relaxed regime consideration to analyze the technological barriers.

4.1 Constrained Regime. Feasibility

In this section we examine the feasibility of space-to-ground and space-to-space downlink mode
accounting for the state-of-the-art subsystem capabilities. Since the Law Earth Orbit is defined
in the range between 160 km and 2000 km, we consider seven circular orbits in space-to-ground
mode starting from 200 km with the step of 300 km.

When investigating inter-satellite communication we fix the orbit height of the constellation
at the nominal value of 500 km and vary the RAAN (right angel of ascending node) of the
receiving platform. Figure 4.1 illustrates this concept by depicting the top view (looking from
the north pole direction) on the satellite constellation. We fix the RAAN of the transmitting
(black square) satellite and vary the RAAN of the receiving satellite (gray square). Since, the
RAAN ranges $[0; \pi]$ and $[\pi; 2\pi]$ of the receiving platform are identical in terms of dynamics of
the communications distance, we consider only the first range. Particularly, we fix the RAAN
of the transmitting satellite at 0 rad, and let the RAAN of the receiving satellite vary taking
values starting from 0 rad (the same orbital plane) with the step of 0.5 rad.
Table 4.1 contains the exact orbital elements of the orbits that were used in the proceeding simulations of space-to-space links.

<table>
<thead>
<tr>
<th>Element</th>
<th>Transmitting Satellite</th>
<th>Receiving Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-Major Axis</td>
<td>6871 km</td>
<td>6871 km</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Inclination</td>
<td>0.785 rad</td>
<td>0.785 rad</td>
</tr>
<tr>
<td>RAAN</td>
<td>0 rad</td>
<td>varies</td>
</tr>
<tr>
<td>Argument of Perigee</td>
<td>0.5 rad</td>
<td>0.5 rad</td>
</tr>
<tr>
<td>True Anomaly</td>
<td>3.14 rad</td>
<td>3 rad</td>
</tr>
</tbody>
</table>

Figure 4.2 presents the dynamics of the inter-satellite distances for the cases outlined above and for the one orbital period.
Figure 4.2: Dynamics of the Inter-Satellite Distances for the Changing RAAN of the Receiving Satellite
4.1.1 Micro-Satellite (sub-100kg). Space-to-Ground

For the specified orbit, we simulate a 15 minutes long pass of the spacecraft over a fixed ground station, assuming an overhead pass. The actual duration of the communications session with the link closed is a side-product of the $D_{\text{com}}$-optimization algorithm.

In Figure 4.3 the communications margins are presented as functions of time. Since the lower orbit imply higher speeds, the shape of the graph for 200 km height is the sharpest, while the other plots become smoother as the orbit height increases.

Figure 4.3: Communications Margins as Functions of Time for Micro-Satellite in Space-to-Ground Mode

As it was stated in the approach description we assume a 1 m diameter for the ground receiver and 25 W for the LCT input power. The operating beam width of the laser beam that accounts for the pointing performance of the micro-satellite platform is 0.07 deg. Table 4.2 contains the simulation results.

The areas of the solar arrays satisfy the constraint of $1m^2$ for all of the orbits.
Table 4.2: Integrated Model Outputs for Micro-Satellite in Space-to-Ground Mode

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Session Duration</th>
<th>Orbit Period</th>
<th>Duty Cycle</th>
<th>Eclipse Period</th>
<th>$A_{sa}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 km</td>
<td>358.2 s</td>
<td>88.4 min</td>
<td>6.7 %</td>
<td>37.2 min</td>
<td>0.81 $m^2$</td>
</tr>
<tr>
<td>500 km</td>
<td>352.2 s</td>
<td>94.5 min</td>
<td>6.2 %</td>
<td>35.7 min</td>
<td>0.75 $m^2$</td>
</tr>
<tr>
<td>800 km</td>
<td>544.8 s</td>
<td>100.7 min</td>
<td>9%</td>
<td>35.1 min</td>
<td>0.71 $m^2$</td>
</tr>
<tr>
<td>1100 km</td>
<td>520.7 s</td>
<td>107.1 min</td>
<td>8.1 %</td>
<td>34.8 min</td>
<td>0.68 $m^2$</td>
</tr>
<tr>
<td>1400 km</td>
<td>839.8 s</td>
<td>113.7 min</td>
<td>12.3 %</td>
<td>34.8 min</td>
<td>0.67 $m^2$</td>
</tr>
<tr>
<td>1700 km</td>
<td>815.7 s</td>
<td>120.3 min</td>
<td>11.3 %</td>
<td>34.8 min</td>
<td>0.65 $m^2$</td>
</tr>
<tr>
<td>2000 km</td>
<td>767.5 s</td>
<td>127.1 min</td>
<td>10 %</td>
<td>35.0 min</td>
<td>0.63 $m^2$</td>
</tr>
</tbody>
</table>

The results of the simulations suggest that the space-to-ground links are feasible with significant margins for all types of LEO orbits. Let us now assess the performance of these links.

The maximum amount of data that can be downloaded per communications session, $D_{com}$ is presented in Figure 4.4 for all of the orbits, while the optimal data rate is presented in Figure 4.5.

The results of the simulation suggest that the performance of the optical link is gradually decreasing with higher orbits.

4.1.2 Micro-Satellite (sub-100kg). Space-to-Space

Here we consider the space-to-space communications mode. As it was described above we fix the RAAN of the transmitting satellite, and vary the RAAN of the receiving satellite. In this mode we simulate the link that has the maximum duration of 5 min.

In the case of micro-satellite we are restricted by a 20 cm receiver diameter and 25 W for LCT input power.

The margins of the links as functions of time are presented in Figure 4.6. Table 4.3 contains the outputs of the integrated model for the different types of orbits.

We see that the areas of the solar arrays meet the $1m^2$ requirement and that the session durations equal to 300 s for all of the considered RAANs of the receiving satellite.

The results of the simulation suggest that the optical communications are feasible between all of the satellites from one constellation on 500 km LEO orbit. The weak dependence of the link margin on the inter-satellite distances corresponding to different RAANs allows us to
Figure 4.4: Data/Com Session versus Orbit for Micro-Satellite in Space-to-Ground Mode

Table 4.3: Integrated Model Outputs for Micro-Satellite in Space-to-Space Mode

<table>
<thead>
<tr>
<th>RAAN</th>
<th>Session Duration</th>
<th>Orbit Period</th>
<th>Duty Cycle</th>
<th>Eclipse Period</th>
<th>$A_{sa}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 rad</td>
<td>300 s</td>
<td>88.4 min</td>
<td>5.6 %</td>
<td>37.2 min</td>
<td>0.81 m²</td>
</tr>
<tr>
<td>0.5 rad</td>
<td>300 s</td>
<td>94.5 min</td>
<td>5.3 %</td>
<td>35.7 min</td>
<td>0.74 m²</td>
</tr>
<tr>
<td>1.0 rad</td>
<td>300 s</td>
<td>100.7 min</td>
<td>5.0 %</td>
<td>35.1 min</td>
<td>0.7 m²</td>
</tr>
<tr>
<td>1.5 rad</td>
<td>300 s</td>
<td>107.1 min</td>
<td>4.7 %</td>
<td>34.8 min</td>
<td>0.67 m²</td>
</tr>
<tr>
<td>2.0 rad</td>
<td>300 s</td>
<td>113.7 min</td>
<td>4.4 %</td>
<td>34.8 min</td>
<td>0.65 m²</td>
</tr>
<tr>
<td>2.5 rad</td>
<td>300 s</td>
<td>120.3 min</td>
<td>4.1 %</td>
<td>34.8 min</td>
<td>0.63 m²</td>
</tr>
<tr>
<td>3.0 rad</td>
<td>300 s</td>
<td>127.1 min</td>
<td>3.9 %</td>
<td>35.0 min</td>
<td>0.61 m²</td>
</tr>
</tbody>
</table>
Figure 4.5: Optimal Data Rate versus Orbit for Micro-Satellite in Space-to-Ground Mode
Figure 4.6: Communications Margins as Functions of Time for Micro-Satellite in Space-to-Space Mode
generalize the feasibility of 500 km orbit to all types of LEO orbits.

The performance of the optical links is presented in Figure 4.7 and Figure 4.8 in terms of $D_{com}$ and optimal data rate respectively.

Figure 4.7: Data/Com Session versus RAAN of the Receiving Platform for Micro-Satellite in Space-to-Space Mode

The plot highlights the strong dependence of $D_{com}$ on RAAN within one constellation. While 150 Gbits can be transmitted to the satellite on the same orbital plane, only 16.4 Gbits can be transmitted to the satellite on the farthest orbital plane.

4.1.3 Nano-Satellite (sub-10kg). Space-to-Ground

Here we consider the same satellite pass above the ground station lasting for 15 minutes as in the case of micro-satellite.

The constraints imposed on the ground receiver diameter and on the LCT input power are 1 m and 0.4 W, respectively. The area of the solar array is constrained by $0.05m^2$ The operating
Figure 4.8: Optimal Data Rate versus RAAN of the Receiving Platform for Micro-Satellite in Space-to-Space Mode
beam width for the case of nano-satellite is 0.7 deg for both of the downlink modes.

The feasibility is addressed in Figure 4.9 and in Table 4.4.

Figure 4.9: Link Margins as Functions of Time for Nano-Satellite in Space-to-Ground Mode

![Figure 4.9: Link Margins as Functions of Time for Nano-Satellite in Space-to-Ground Mode](image)

Table 4.4: Integrated Model Outputs for Nano-Satellite in Space-to-Ground Mode

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Session Duration</th>
<th>Orbit Period</th>
<th>Duty Cycle</th>
<th>Eclipse Period</th>
<th>A_{sa}</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 km</td>
<td>57.2 s</td>
<td>88.4 min</td>
<td>1 %</td>
<td>37.2 min</td>
<td>0.049 m²</td>
</tr>
<tr>
<td>500 km</td>
<td>135.4 s</td>
<td>94.5 min</td>
<td>2.4 %</td>
<td>35.7 min</td>
<td>0.045 m²</td>
</tr>
<tr>
<td>800 km</td>
<td>0 s</td>
<td>100.7 min</td>
<td>N/A</td>
<td>35.1 min</td>
<td>N/A</td>
</tr>
<tr>
<td>1100 km</td>
<td>0 s</td>
<td>107.1 min</td>
<td>N/A</td>
<td>34.8 min</td>
<td>N/A</td>
</tr>
<tr>
<td>1400 km</td>
<td>0 s</td>
<td>113.7 min</td>
<td>N/A</td>
<td>34.8 min</td>
<td>N/A</td>
</tr>
<tr>
<td>1700 km</td>
<td>0 s</td>
<td>120.3 min</td>
<td>N/A</td>
<td>34.8 min</td>
<td>N/A</td>
</tr>
<tr>
<td>2000 km</td>
<td>0 s</td>
<td>127.1 min</td>
<td>N/A</td>
<td>35.0 min</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The results imply that for the given $R_{ECC} = \frac{1}{2}$ (that is supposed to keep the acceptable
BER) and for the given atmospheric loss of 30 dB, the laser communications are feasible for two types of orbits, 200 km and 500 km. As it is shown in Table 4.4, proposed design meets the 0.05m² constraint on the area of the solar array for both of the feasible orbits. Since in the logarithmic form of the link budget equation, the atmospheric loss is simply added to the budget of the link, we can conclude that accounting for the good weather conditions and assuming 10 dB loss in the atmosphere, the optical link will be closed for all types of LEO orbits (see Figure 4.9).

Figure 4.10 introduces the performance of the links in terms of data that can be transmitted per communications session, $D_{com}$, while Figure 4.11 captures the optimal data rates for this case.

Figure 4.10: Data/Com Session versus Orbit for Nano-Satellite in Space-to-Ground Mode

While in the case of micro-satellite’s space-to-ground link the dependence on the orbit height is weak, here we observe a rapid decrease of $D_{com}$ with higher orbits.
Figure 4.11: Optimal Data Rates versus Orbit for Nano-Satellite in Space-to-Ground Mode
### 4.1.4 Nano-Satellite (sub-10kg). Space-to-Space

In this case the constraint imposed on the size of the receiver is 10 cm and the LCT input power constraint is 0.4 W. Here we use the orbital geometry introduced earlier for the case of micro-satellite.

The results of the simulation presented in Figure 4.12 suggest that under the taken assumptions on the acceptable link margin and BER, inter-satellite optical communications are feasible between nano-satellites on the same orbital plane. This case can be generalized to the random orbits of the same constellation, but with inter-satellite distances on the order of 1000 km (see Figure 4.2).

Figure 4.12: Link Margins as Functions of Time for Nano-Satellite in Space-to-Space Mode

![Link Margins](image)

Figure 4.13 introduces the performance metrics as a function of RAAN of the receiving satellite, while Figure 4.14 depicts the optimal data rates for this scenario. It is worth mentioning that even with the limited acceptable distances for space-to-space links between nano-satellites, this mode shows the better performance than space-to-ground mode for the same platform.
Figure 4.13: Data/Com Session versus RAAN of the Receiving Platform for Nano-Satellite in Space-to-Space Mode
Figure 4.14: Optimal Data Rate versus RAAN of the Receiving Platform for Nano-Satellite in Space-to-Space Mode
4.2 Benefits

In this section we estimate the benefits that can be brought by optical communications to the current practice of mission data downlink that relies on RF (radio frequency) part of the spectrum.

4.2.1 Space-to-Ground Mode

We compare the performance of optical and RF communications in terms of data that can be transmitted per session. Then, we determine how this metrics affect the duty cycle of the imaging instrument.

For comparison we use the baseline orbit of 500 km height. The number of accesses to the ground are estimated using STK [31]. We assume one ground station - Kiruna, Sweden [40] and consider the polar orbit with the inclination of 1.57 rad. According to the results of STK, the satellite on this orbit has 13 access to Kiruna per day.

The state-of-the-art RF transmitters are able to handle up to 2 Mbps for nano-satellite [6] and up to 100 Mbps for micro-satellite [5]. For the access durations we refer to the predictions of the integrated model for both optical and RF links.

As mentioned in chapter 3 we assume 20 Mbps for the data rate of micro-satellites’ imaging instrument and 5 Mbps for nano-satellite.

Tables 4.5 and 4.6 compare the performances of laser and RF links for micro- and nano-satellite respectively.

The results suggest that while optical communications can increase the duty cycle of the imaging instrument by more than twice for micro-satellite, RF fits better for nano-satellite providing the duty cycle of the instrument of almost three times higher compared to optics.

4.2.2 Space-to-Space Mode

Since to the authors’ best knowledge no noticeable inter-satellite demonstrations were conducted for small satellites, we can not compare the performance of optics and RF in space-to-space mode. Instead, we will compare the performance of optical inter-satellite link and optical space-to-ground link.

The number of accesses to the relay satellites significantly vary between different constella-
Table 4.5: Optical and RF Communications Performance Comparison for Micro-Satellite Optics

<table>
<thead>
<tr>
<th></th>
<th>Optics</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Period</td>
<td>94.5 min</td>
<td>94.5 min</td>
</tr>
<tr>
<td>Number of Accesses per Day</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Access Duration</td>
<td>352.2 s</td>
<td>352.2 s</td>
</tr>
<tr>
<td>$D_{com}$</td>
<td>88 Gbits</td>
<td>35.2 Gbits</td>
</tr>
<tr>
<td>Data/Day</td>
<td>1144 Gbits</td>
<td>457.6 Gbits</td>
</tr>
<tr>
<td>Number of Orbits per Day</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Amount of Data per Orbit</td>
<td>73.3 Gbits</td>
<td>30.1 Gbits</td>
</tr>
<tr>
<td>Instrument Data Rate</td>
<td>20 Mbps</td>
<td>20 Mbps</td>
</tr>
<tr>
<td>Instrument Active Time per Orbit</td>
<td>61 min</td>
<td>25 min</td>
</tr>
<tr>
<td>Instrument Duty Cycle</td>
<td>64.5 %</td>
<td>26.4 %</td>
</tr>
</tbody>
</table>

Table 4.6: Optical and RF Communications Performance Comparison for Nano-Satellite Optics

<table>
<thead>
<tr>
<th></th>
<th>Optics</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Period</td>
<td>94.5 min</td>
<td>94.5 min</td>
</tr>
<tr>
<td>Number of Accesses per Day</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Access Duration</td>
<td>135.4 s</td>
<td>135.4 s</td>
</tr>
<tr>
<td>$D_{com}$</td>
<td>90.9 Mbit</td>
<td>270.8 Mbits</td>
</tr>
<tr>
<td>Data/Day</td>
<td>1181.7 Mbit</td>
<td>3520.4 Mbits</td>
</tr>
<tr>
<td>Number of Orbits per Day</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Amount of Data per Orbit</td>
<td>77.7 Mbits</td>
<td>231.6 Mbits</td>
</tr>
<tr>
<td>Instrument Data Rate</td>
<td>5 Mbps</td>
<td>5 Mbps</td>
</tr>
<tr>
<td>Instrument Active Time per Orbit</td>
<td>15.5 s</td>
<td>46.3 s</td>
</tr>
<tr>
<td>Instrument Duty Cycle</td>
<td>0.27 %</td>
<td>0.81 %</td>
</tr>
</tbody>
</table>
tion designs. But we can assume at least one relay opportunity during the orbit. Therefore, for the given orbit we consider 16 accesses per day in space-to-space mode.

The results of the comparison are presented in Tables 4.7 and 4.8 for micro-satellite and nano-satellite respectively. Note that in the case of inter-satellite link between nano-satellites we assume that both platforms are close enough for the link to be closed (see Figure 4.13).

Table 4.7: Inter-Satellite and Space-to-Ground Optical Communications Performance Comparison for Micro-Satellite

<table>
<thead>
<tr>
<th></th>
<th>Space-to-Ground</th>
<th>Inter-Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Period</td>
<td>94.5 min</td>
<td>94.5 min</td>
</tr>
<tr>
<td>Number of Accesses per Day</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Access Duration</td>
<td>352.2 s</td>
<td>300 s</td>
</tr>
<tr>
<td>$D_{com}$</td>
<td>88 Gbits</td>
<td>112.5 Gbits</td>
</tr>
<tr>
<td>Data/Day</td>
<td>1144 Gbits</td>
<td>1800 Gbits</td>
</tr>
<tr>
<td>Number of Orbits per Day</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Amount of Data per Orbit</td>
<td>73.3 Gbits</td>
<td>118.4 Gbits</td>
</tr>
<tr>
<td>Instrument Data Rate</td>
<td>20 Mbps</td>
<td>20 Mbps</td>
</tr>
<tr>
<td>Instrument Active Time per Orbit</td>
<td>61 min</td>
<td>98.7 min</td>
</tr>
<tr>
<td><strong>Instrument Duty Cycle</strong></td>
<td><strong>64.5 %</strong></td>
<td><strong>100 % + Margin</strong></td>
</tr>
</tbody>
</table>

In both cases the results clearly identify the benefits of space-to-space optical links compared to space-to-ground links. Besides, inter-satellite laser communications can enable 100 % duty cycle of the instrument for micro-satellite.

4.3 Relaxed Regime. Technological Barriers

For feasible scenarios the sensitivity analysis will define the potential benefits that can be brought by the enhancement of small satellite capabilities in the future missions, while for infeasible scenarios it will define the technological barriers for using optical communications.
Table 4.8: Inter-Satellite and Space-to-Ground Optical Communications Performance Comparison for Nano-Satellite

<table>
<thead>
<tr>
<th></th>
<th>Space-to-Ground</th>
<th>Inter-Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit Period</td>
<td>94.5 min</td>
<td>94.5 min</td>
</tr>
<tr>
<td>Number of Accesses per Day</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Access Duration</td>
<td>135.4 s</td>
<td>300 s</td>
</tr>
<tr>
<td>$D_{com}$</td>
<td>90.9 Mbit</td>
<td>253.6 Mbits</td>
</tr>
<tr>
<td>Data/Day</td>
<td>1181.7 Mbit</td>
<td>4057.6 Mbits</td>
</tr>
<tr>
<td>Number of Orbits per Day</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>Amount of Data per Orbit</td>
<td>77.7 Mbits</td>
<td>266.9 Mbits</td>
</tr>
<tr>
<td>Instrument Data Rate</td>
<td>5 Mbps</td>
<td>5 Mbps</td>
</tr>
<tr>
<td>Instrument Active Time per Orbit</td>
<td>15.5 s</td>
<td>53.4 s</td>
</tr>
<tr>
<td><strong>Instrument Duty Cycle</strong></td>
<td><strong>0.27 %</strong></td>
<td><strong>0.94 %</strong></td>
</tr>
</tbody>
</table>

4.3.1 Power-Relaxed Regime

In the power subsystem model we account for the multijunction GaAs solar cell that nowadays shows the highest efficiency in space, 30 %. The theoretical efficiency limit of multijunction cell is 86.6 %. Therefore, we relax the input LCT power constraint by letting it to achieve the value that is twice bigger than the nominal value considered earlier. So that, for micro-satellite we have the range of 25 - 50 W and for nano-satellite we have 0.4 - 0.8 W. We augment the results of the simulations from the previous section by considering two additional LCT input power values from these ranges.

The sensitivity of both space-to-ground and inter-satellite link performances for micro-satellite are presented in Figures 4.15 and 4.16.

Figure 4.16 depicts that in the case of zero RAAN of the receiving platform, $D_{com}$ does not increase with the increasing input power. The reason for that is 150 Gbits is the maximum achievable $D_{com}$ for the given set of slot widths and modulation orders discussed in previous chapter.

Figures 4.17 and 4.18 present the same result, but for the case of nano-satellite.

First figure depicts the ”unlock” of one orbit per each step of power increase. The second figure suggests that the increase of the available power does not resolves the non-feasibility of
Figure 4.15: The Sensitivity of the Micro-Satellite Link Performance to the LCT Input Power in Space-to-Ground Mode
Figure 4.16: The Sensitivity of the Micro-Satellite Link Performance to the LCT Input Power in Space-to-Space Mode
Figure 4.17: The Sensitivity of the Nano-Satellite Link Performance to the LCT Input Power in Space-to-Ground Mode
Figure 4.18: The Sensitivity of the Nano-Satellite Link Performance to the LCT Input Power in Space-to-Space Mode
inter-satellite communications beyond 1000 km for nano-satellites.

Since the relaxation of input power constraint does not reveal the full potential of optical communications for nano-satellite in LEO, we treat the power issue as a fundamental technological barrier of using the technology on-board this platform. However, the optical links are still feasible for a wide range of LEO applications on nano-satellite platforms for both space-to-ground and space-to-space communications.

### 4.3.2 Pointing Accuracy-Relaxed Regime

While the power constraint is brought by fundamental limitations of solar cell efficiency and can be increased by the factor of two in the optimistic case compared to the state-of-the-art capabilities, the ADCS subsystem technology is constantly developing allowing to expect the one order of magnitude increase in performance. For example, if the closed-loop fine pointing control will be introduced to the LCT of small platforms [41]. Therefore, to check the sensitivity of the performance metrics to the pointing accuracy capabilities of the platform we will relax the current constraints for both platforms by letting them to be 10 times more precise.

Figures 4.19 and 4.20 present the results of sensitivity analysis for micro-satellite. By increasing the pointing accuracy by one order of magnitude, the link experiences the maximum achievable $D_{com}$ for all types of orbits in space-to-ground mode and all RAANs in space-to-space mode.

Figures 4.21 and 4.22 show the sensitivity of nano-satellite performance. An increase of nano-satellite’s pointing accuracy by one-order of magnitude does not bring the link performance to the limit of PPM as in the previous case. However, it provides the substantial increase of $D_{com}$ for the whole range of LEO orbits in space-to-ground mode and for the small differences of RAAN between the satellites’ orbits in space-to-space mode.

### 4.3.3 Receiver Size-Relaxed Regime

The size of the receiver aperture is another fundamental constraint of the system. It is especially the case when considering the space-to-space communications mode. The typical sizes of micro- and nano-satellites are $50\,cm \times 50\,cm \times 50\,cm$ and $30\,cm \times 10\,cm \times 10\,cm$ respectively. The dimensions of course vary, but these numbers can be used as a baseline. Therefore, in the space-to-space mode for the nominal values of the receiver aperture diameters we used 20 cm and 10
Figure 4.19: The Sensitivity of $D_{com}$ to the Pointing Accuracy of Micro-Satellite in Space-to-Ground Mode
Figure 4.20: The Sensitivity of $D_{com}$ to the Pointing Accuracy of Micro-Satellite in Space-to-Space Mode
Figure 4.21: The Sensitivity of $D_{com}$ to the Pointing Accuracy of Nano-Satellite in Space-to-Ground Mode
Figure 4.22: The Sensitivity of $D_{com}$ to the Pointing Accuracy of Nano-Satellite in Space-to-Space Mode
cm respectively. The nominal diameter of a ground-based receiver is assumed to be 1 m. This number represents the maximum diameter used so far for near-Earth optical communications (for example ESA optical ground station in Teide Observatory [32]).

For the size-relaxed regime, we let the diameters of the receivers to exceed the nominal values by the factor of two.

Figures 4.23, 4.24, 4.25 and 4.26 present the results of the sensitivity analysis. The influence of the receiver diameter to link performance is similar to the influence of LCT input power except for minor differences. Since the relaxation of the receiver size does not resolves the non-feasibility for all possible orbits and RAANs, we treat it as the second fundamental barrier for deploying the full potential of laser communications on nano-satellite platforms.

Figure 4.23: The Sensitivity of $D_{com}$ to the Diameter of the Receiver for Micro-Satellite in Space-to-Ground Mode

### 4.4 Discussion

First of all, the feasibility of laser communications within the framework of body pointing has been shown for both micro- and nano-satellite. But while for micro-satellite it is applicable for
Figure 4.24: The Sensitivity of $D_{com}$ to the Diameter of the Receiver for Micro-Satellite in Space-to-Space Mode
Figure 4.25: The Sensitivity of $D_{com}$ to the Diameter of the Receiver for Nano-Satellite in Space-to-Ground Mode
Figure 4.26: The Sensitivity of $D_{com}$ to the Diameter of the Receiver for Nano-Satellite in Space-to-Space Mode
all types of LEO orbits and inter-satellite distances, applications for nano-satellite are feasible for limited LEO orbits and inter-satellite distances.

Secondly, we have demonstrated that optical communications can increase the duty cycle of the micro-satellite’s instrument by more than twice in space-to-ground downlink mode compared to the current practice and even enable the duty cycle of 100% in space-to-space mode. However, it was identified that RF fits better for nano-satellite’s ground downlink, with optics slightly prevailing the RF performance only in inter-satellite communications.

Finally, it has been shown that the power and size budgets of nano-satellite represent the fundamental barriers that prevent the optical communications from being feasible for all types of possible near-Earth applications on these platforms.
Chapter 5

Limitations and Future Work

Studying the integrated system model we considered six disciplines, namely optical antenna performance; pointing loss; optical link budget; orbital mechanics; power generation and storage; tracking, telemetry and control.

Among the variety of signal modulations we only considered the Pulse Position Modulation (PPM) with direct detection scheme and investigated the near-Earth communications. Other modulation formats which allow to achieve higher data rate compared to PPM need to be considered.

For optical antenna modeling, we studied only the case of Cassegrain telescope. We also assumed that the receiver is situated in the far-field of the transmitter, possibly limiting the consideration of inter-satellite proximity operations.

Modeling the pointing loss we treated the satellite’s jitter as a random process, capturing the worst-case loss for the given error distribution. The time-domain simulation of the jitter that captures the design of the ADCS subsystem and model of the disturbance sources might be needed for some other applications, such as design of the pointing acquisition and tracking system.

In the link budget model we used the approximation to the actual PPM channel capacity that should be reviewed when the more accurate analysis of the optical communications channel is needed.

For orbital mechanics model we neglected the orbit-disturbing factors such as atmospheric drag or the Earth’s magnetic field. If the ADCS model is to be integrated in the analysis, the disturbing forces need to be added to the orbit propagator.
The power subsystem model is limited by accounting only for the power production and storage functions. The power distribution and control functions are omitted.

Finally, the model of TT&C subsystem was reduced to payload's concept of operations, and modeling of two communications interfaces: LEO relay satellite and ground station. For the LEO relay option we assumed that both of the communicating spacecrafts are the parts of a single satellite constellation. Opportunistic inter-satellite optical links represent a novel topic for the future work.

Another directions of future work are as follows. The first path is to integrate the lacking model of the atmosphere in order to characterize the dependence of the atmospheric loss on the seeing conditions and elevation angle of the satellite. The best practice for this task in academia is to use Modtran [18]. This will introduce the better precision to the current model and will enable to capture the more realistic benefits of optical communications compared to RF (throughout the work we assume that the space-to-ground link is always available with the fixed atmospheric loss, however that is not a case in the cloudy conditions when the loss is incompatible with optical communications). Besides, the bit error rate (BER) model need to be added to the integrated model. Along with the data that can be transmitted per communications session considered here as a single metrics of performance, the BER will introduce the second metrics adding a trade-off to the system.

The second path is to switch from feasibility study to the conceptual study of the particular micro-satellite mission. This demands the inclusion of the thermal, structure, avionics, propulsion, C&DH and cost models of the spacecraft. Besides, knowing the detailed concept of mission operation, the full time-domain modeling of the ADCS subsystem can be made. This will enhance the pointing loss model considered in this work.

As it was suggested in the Results and Case Studies chapter, increased pointing capabilities can significantly enhance the performance of optical communications for small platforms. But the challenge that comes in is a more stringent requirement for acquisition and tracking. This is especially a case for inter-satellite communications, when the typical link durations are 2 - 5 minutes. Therefore, another promising area for future research is the development of pointing acquisition and tracking (PAT) algorithm for optical communications applied to small satellites.

The final direction for the future work implies the study of feasibility of gimbaled laser terminals and fine pointing control schemes on-board small platforms.
Chapter 6

Conclusion

The thesis has analyzed and characterized the performance of the novel strategy to implement laser communication terminals (LCTs) on micro- and nano-satellites. This strategy implies the reduction of LCT’s complexity and performing pointing by changing the attitude of the spacecraft.

To address the research questions stated in Chapter 1, we have developed the integrated spacecraft-payload mission analysis tool that considers six disciplines: optical link budget; optical antenna performance; pointing losses; power generation and storage; telemetry, tracking and control; and orbital mechanics. The integrated analysis tool was applied to space-to-ground and inter-satellite near-Earth communications.

We have proven the feasibility of optical communications for micro- and nano-satellites and for both space-to-ground and space-to-space links. We accessed the benefits of laser communications in terms of achievable data rates, the amount of data that can be transmitted per communication session and the influence of optical communication on the duty cycle of the satellite instrument.

The results of Chapter 4 suggest that in the case of micro-satellites laser communication shows better performance compared to RF (radio frequency) for both downlink modes. It was shown that the duty cycle of micro-satellite’s instrument can achieve up to 100 %, while RF enables a quarter less performance. For nano-satellites, RF is preferable for space-to-ground mode, with optical communications having better performance in space-to-space downlink mode.

The $D_{com}$-optimization tool described in Chapter 3 characterized the system level trade-off between the performance of optical channel and the link margin.
The sensitivity analysis conducted in Chapter 3 outlined that increasing pointing accuracy of the spacecraft can significantly enhance the performance of laser communication for both platforms. We also discovered that power and size budgets of nano-satellites represent the fundamental barriers for deploying the full potential of near-Earth optical communications for these platforms.

To the author’s best knowledge this work represents a first attempt to analyze the feasibility of optical communications for micro- and nano-satellites in the thorough range of near-Earth applications. The results obtained are the products of the integrated model that captures the first order impacts and gives the approximate assessment of the benefits of optical communication. While this approach is good to characterize the relative performance of different communication scenarios, future work outlined in Chapter 5 need to be conducted to better understand the challenges and benefits of optical communications for micro- and nano-satellites.
Appendix A

Code of the Integrated Model

A.1 Optical Antenna Model

clear all
clc

%System parameters
alpha = 1.12; % truncation
gamma = 0; % obscuration ratio
Dt = 0.1; % telescope diameter (meters)
lambda = 1.55E−6; % wavelength (meters)

% Spatial Distribution
v = [−5:0.01:5];
gt = zeros(1, size(v,2));

for i = 1:size(v, 2)
    fun = @(u) exp(-alpha^2*u).*besselj(0,3.14*v(i)*sqrt(u));
gt(i) = 10*log10(3.14^2*Dt^2/lambda^2)+10*log10(2*alpha^2*(abs(integral(fun, gamma^2, 1)))^2);
end
```matlab
plot(v, gt, 'b')

xlabel('Normalized Radial Angle, rad');
ylabel('Transmitter Gain, dB');

% FWHM beamwidth
Gt = max(gt);
Gfwhm = max(gt) - 3;
j = 1;

while gt(j) < Gfwhm
    Beamwidth = abs(v(j))*2*lambda/Dt; % beamwidth (radians)
j = j + 1;
end

BW = Beamwidth/pi*180 % beam width in degrees

A.2 Power Subsystem Model

% operating power of satellite's subsystems (Watts)
P_payload = 20;
P_thermal = 7;
P_adcs = 15;
P_power = 10.5;
P_coms_stat = 5; % input power of LCT in passive mode
P_cdh = 7;
P_coms = 25; % input power of LCT in active mode

% duty cycles of satellite subsystems at one orbit
D_payload = 1;
D_thermal = 1;
D_adcs = 1;
D_power = 1;
```
D_coms_stat = 1;
D_coms = 0.10;
D_cdh = 1;

Margin = 20; % in percent
P_average = (P_payload*D_payload + P_thermal*D_thermal + P_adcs*D_adcs + P_power*D_power + P_coms_stat*D_coms_stat + P_coms*D_coms + P_cdh*D_cdh)*(1 + Margin/100); % average power in orbit

Pd = P_average;
Pd = P_average;
Te = 35.0; % in minutes (from Orbital subsystem)
Td = 92.1; % in minutes (from Orbital subsystem)
T_lifetime = 5; % in years
Xe = 0.6; % for PPT power regulation
Xd = 0.8; % for PPT power regulation

% amount of power that must be produced by solar arrays
P_sa = (Pe*Te/Xe + Pd*Td/Xd)/Td;

% power output at the begining of life
Pi = 1367; % solar constant in Watts/m^2
eff = 0.3; % efficiency of gallium arsenide solar cell
P0 = Pi*eff; % power output of a single cell with sun light perpendicular to the solar array plane
tetta = 0.4; % sun angle in rad
Id = 0.77; % inherent degradation
P_BOL = P0*Id*cos(tetta);

% power output at the end of life
D = 0.0375; % degradation per year for gallium arsenaeide
\[
L_d = (1 - D)^\text{T\_lifetime}; \quad \% \text{life degradation}
\]
\[
P\_EOL = P\_BOL \times L_d;
\]

\[
\% \text{area of solar array needed}
\]
\[
A\_sa = P\_sa / P\_EOL; \quad \% \text{in m}^2
\]

\[
\% \text{power storage design}
\]
\[
N = 3; \quad \% \text{number of batteries}
\]
\[
n = 0.9; \quad \% \text{transmission efficiency}
\]
\[
DOD = 0.2; \quad \% \text{depth of discharge}
\]
\[
Cr = P_e \times (T_e / 60) / (DOD \times N \times n); \quad \% \text{battery capacity}
\]

### A.3 Orbit Propagator

\[
\%
\]
\[
\% \text{Constants}
\]
\[
\mu = 398345073E+06; \quad \% \text{gravitational constant}
\]

\[
\%
\]
\[
\% \text{Orbital parameters}
\]
\[
a = 7000000; \quad \% \text{semimajor axis in meters}
\]
\[
e = 0.000001; \quad \% \text{eccentricity (unitless)}
\]
\[
i = 1.57; \quad \% \text{inclination in radians}
\]
\[
Omega = 1; \quad \% \text{right ascension of ascending node in radians}
\]
\[
\omega = 0.5; \quad \% \text{argument of perigee in radians}
\]
\[
nu = 3.14; \quad \% \text{true anomaly in radians}
\]

\[
\%
\]
\[
\% \text{Communication window duration}
\]
\[
T = 900; \quad \% \text{in seconds}
\]

\[
\%
\]
\[
\% \text{Conversion from orbital parameters to initial conditions for equation of}
\]
\[
\%
\]
\[
\% \text{motion}
\]
\begin{verbatim}
syms x y z dx dy dz
S = solve(-mu/(2*a) == (dx^2 + dy^2 + dz^2)/2 - mu/(x^2 + y^2 + z^2)^(1/2), ... 
cos(i) == (x*dy - y*dx)/((y*dz - z*dy)^2 + (dx*z - x*dz)^2 + (x*dy - y*dx)^2)^(1/2), ...
cos(Omega) == -(dx*z - x*dz)/((dx*z - x*dz)^2 + (y*dz - z*dy)^2)^(1/2), ...
e == 1/mu*(((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * x - (x*dx + y*dy + z*dz)*dx)^2 + ...
(y*dz - z*dy)*(((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * y - (x*dx + y*dy + z*dz)*dy)^2 + ...
((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * z - (x*dx + y*dy + z*dz)*dz)^2)^(1/2), ...
cos(omega) == ((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * x - (x*dx + y*dy + z*dz)*dx + ...
((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * y - (x*dx + y*dy + z*dz)*dy)^2 + ...
((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * z - (x*dx + y*dy + z*dz)*dz)^2)^(1/2), ...
cos(nu) == (((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * x - (x*dx + y*dy + z*dz)*dx)*x + ...
((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * y - (x*dx + y*dy + z*dz)*dy)*y + ...
((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * z - (x*dx + y*dy + z*dz)*dz)*z)/((((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * x - (x*dx + y*dy + z*dz)*dx)^2 + (((dx^2 + dy^2 + dz^2) - mu/(x^2 + y^2 + z^2)^(1/2)) * y - (x*dx + y*dy + z*dz)*dx)^2)
\end{verbatim}
\( (x \cdot dx + y \cdot dy + z \cdot dz) \cdot dy \cdot dz + ((dx^2 + dy^2 + dz^2) - \mu/(x^2 + y^2 + z^2)^{(1/2)}) \cdot z - (x \cdot dx + y \cdot dy + z \cdot dz) \cdot dz \cdot dz \cdot (1/2) \cdot (x^2 + y^2 + z^2)^{(1/2)}) \);

\[
X = \text{double}(S.x);
Y = \text{double}(S.y);
Z = \text{double}(S.z);
dX = \text{double}(S.dx);
dY = \text{double}(S.dy);
dZ = \text{double}(S.dz);
\]

\% true anomaly check
for \( j = 1: \text{size}(X, 1) \)
    if \( X(j, 1) \cdot dx(j, 1) + Y(j, 1) \cdot dy(j, 1) + Z(j, 1) \cdot dz(j, 1) < 0 \)
        \( X(j, 1) = \text{inf}; \)
        \( Y(j, 1) = \text{inf}; \)
        \( Z(j, 1) = \text{inf}; \)
        \( dX(j, 1) = \text{inf}; \)
        \( dY(j, 1) = \text{inf}; \)
        \( dZ(j, 1) = \text{inf}; \)
    end
end

\% right ascension of the ascending node check
for \( j = 1: \text{size}(X, 1) \)
    if \( Y(j, 1) \cdot dz(j, 1) - Z(j, 1) \cdot dy(j, 1) < 0 \)
        \( X(j, 1) = \text{inf}; \)
        \( Y(j, 1) = \text{inf}; \)
        \( Z(j, 1) = \text{inf}; \)
        \( dX(j, 1) = \text{inf}; \)
        \( dY(j, 1) = \text{inf}; \)
        \( dZ(j, 1) = \text{inf}; \)
end
% argument of perigee check

for j = 1:size(X, 1)
    if 1/mu*((dX(j, 1)^2 + dY(j, 1)^2 + dZ(j, 1)^2) - mu/(X(j, 1)^2 + Y(j, 1)^2 + Z(j, 1)^2)^(1/2)) * Z(j, 1) - (X(j, 1)*dX(j, 1) + Y(j, 1)*dY(j, 1) + Z(j, 1)*dZ(j, 1)) * dZ(j, 1)) < 0
        X(j, 1) = inf;
        Y(j, 1) = inf;
        Z(j, 1) = inf;
        dX(j, 1) = inf;
        dY(j, 1) = inf;
        dZ(j, 1) = inf;
    end
end

Init = zeros(1, 6);
Init(1, 1) = min(X);
Init(1, 2) = min(Y);
Init(1, 3) = min(Z);
Init(1, 4) = min(dX);
Init(1, 5) = min(dY);
Init(1, 6) = min(dZ);

% solving equation of motion

syms Rx(t) Ry(t) Rz(t)
[V, Y] = odeToVectorField(diff(Rx, 2) + mu*(Rx^2 + Ry^2 + Rz^2)^(3/2)*Rx == 0, diff(Ry, 2) + mu*(Rx^2 + Ry^2 + Rz^2)^(3/2)*Ry == 0, ...
    diff(Rz, 2) + mu*(Rx^2 + Ry^2 + Rz^2)^(3/2)*Rz == 0);
MFun = matlabFunction(V, 'vars', {'t', 'Y'});

options = odeset('RelTol', 1E-6);
sol = ode45(MFun, [0 T], [Init(1, 2) Init(1, 5) Init(1, 1) Init(1, 4) Init(1, 3) Init(1, 6)], options);
t = linspace(0, T, 5*T);
solution = deval(sol, t);

Rm = zeros(1, size(solution, 2));
for j = 1: size(solution, 2)
    Rm(1, j) = (solution(1, j)^2 + solution(3, j)^2 + solution(5, j)^2)^(1/2);
end

figure;
plot(t, Rm);
xlabel('Time, s');
ylabel('Distance, m');

V = zeros(1, size(solution, 2));
for j = 1: size(solution, 2)
    V(1, j) = (solution(2, j)^2 + solution(4, j)^2 + solution(6, j)^2)^(1/2);
end

figure;
plot(t, V);
xlabel('Time, s');
ylabel('Velocity, m/s');

T_orbit = 2*pi*(a^3/mu)^(1/2); % orbit period
T_eclipse = T_orbit*2*asin(6371000/a)/(2*pi); % eclipse duration
A.4 Pointing Loss Model

```matlab
function [ PL ] = PL_angle( Oa, lambda, Dt, alpha_t, gamma_t )

% PL_ANGLE Summary of this function goes here
% Detailed explanation goes here
Ga=2/alpha_t^2*(exp(-alpha_t^2)-exp(-gamma_t^2*alpha_t^2))^2; % on-axis gain
fun=@(u) exp(-alpha_t^2*u).*besselj(0,3.14*Dt/lambda*Oa*sqrt(u));
Go=(2*alpha_t^2*(abs(integral(fun, gamma_t^2, 1))))^2; % off-set gain
PL=10*log10(Go/Ga);

end

% System parameters
alpha =1.12; % truncation
gamma=0.3; % obscuration ratio
D=0.1; % telescope diameter (meters)
lambda=1550*10^(-9); % wavelength (meters)

% Spatial Distribution
v = [ -5:0.01:5];
gt = zeros(1, size(v,2));
for i = 1:size(v, 2)
    fun = @(u) exp(-alpha^2*u).*besselj(0,3.14*v(i)*sqrt(u));
gt(i) = 10*log10(3.14^2*D^2/lambda^2)+10*log10(2*alpha^2*(abs(integral(fun, gamma^2, 1))))^2);
end
```

worst case for circular orbits
figure
plot(v, gt, 'y')
xlabel('Normalized Radial Angle, rad');
ylabel('Transmitter Gain, dB');

% FWHM beamwidth
Gt = max(gt);
Gfwhm = max(gt) - 3;
j = 1;
while gt(j) < Gfwhm
    Beamwidth = abs(v(j))*2*lambda/D; % beamwidth (radians)
    j = j + 1;
end

% Pointing Loss
Oa = zeros(1, 10);
Go = zeros(1, 10);
PL = zeros(1, 10);

for l = 1:10
    Oa(l) = 10*l/100*Beamwidth; % off-axis angle as a fraction of beamwidth
    Ga = 2/alpha^2*(exp(-alpha^2) - exp(-gamma^2*alpha^2))^2; % on-axis gain
    fun = @(u) exp(-alpha^2*u).*besselj(0, 3.14*D/lambda*Oa(l)*sqrt(u));
    Go(l) = (2*alpha^2*(abs(integral(fun, gamma^2, 1)))^2); % off-axis gain
    PL(l) = 10*log10(Go(l)/Ga); % pointing loss
end
function [ fun ] = Rise_Density( x, mean, stdev )
    fun = x/stdev^2*exp(-1/(2*stdev^2)*(x^2+mean^2))*besseli(0, x*mean/stdev^2);
end

mean = 10*10^(-4);
stdev = 10*10^(-4);
x = [0:10^(-5):3*10^(-3)];
R = zeros(1, size(x,2));
for i = 1:size(x, 2)
    R(i) = Rise_Density(x(i), mean, stdev);
end

plot(x, R, 'r');
xlabel('Mispointing Angle, rad');
ylabel('Probability Density');

A.5 Link Budget Tool

clear all
clc

%Input Parameters
%Geometry/Atmosphere
R = 600000; %meters
lambda = 1.064E-06; %meters
Ib = 5; \text{W/m}^2 \text{sr um}

r0 = 0.1; \text{meters}

sigmaI = 0.02;

Nf = 16;

%Signaling

Ts = 1.0002e-09; \text{seconds}

M = 2048;

Recc = 0.5;

%Transmitter

Pt = 11.46; \text{dB-W}

Dt = 0.000074; \text{meters}

gamma_t = 0;

alpha_t = 1.12;

%Receiver

Dr = 0.3; \text{meters}

gamma_r = 0;

delta_lambda = 2E-4; \text{um}

%Photo-Detector Array

etta_det = -3.98; \text{dB}

delta_det = 1.5E-5; \text{meters}

ld = 1E+13; \text{e/s/m}^2

etta_j = 240E-12; \text{seconds}

omega_det = 1.778E-12; \text{sr}

att = 0.077;

%Received Power

Gt = Transmitter.Gain( Dt, lambda, alpha_t, gamma_t );
Gr = Receiver_Gain( Dr, lambda, gamma_r );
Ls = Space_Loss( lambda, R );
La = Atmospheric_Loss( );
etta_pt = Pointing_Loss( );
etta_t = Transmitter_Efficiency( );
etta_r = Receiver_Efficiency( );
Pr = Received_Power( Pt, Gt, Gr, Ls, La, etta_pt, etta_t, etta_r );

%Noise Power
Eph = Photon_Energy( lambda );
Pn = Noise_Power( Ib, delta_lambda, omega_det, Dr, att, Eph,
delta_det, ld );

%Required Power Lower Bound
run Required_Power_LB

%Required Power
run Required_Power

%Margin
Mar = Pr - RP;
if Mar>3
  disp('Link is closed with Margin(dB)');
disp(Mar);
disp('and Data Rate(bits/s)');
disp(Rb);
else
  disp('Link is not closed with Margin(dB)');
disp(Mar);
disp('and targeted Data Rate(bits/s)');
disp(Rb);
function [ La ] = Atmospheric_Loss( )

%ATMOSPHERIC LOSS Summary of this function goes here
% Detailed explanation goes here
La = -30;
end

function [ Cppm ] = Channel_Capacity( RPLB, Pn, M, Ts, Eph )

%CHANNEL CAPACITY Summary of this function goes here
% Detailed explanation goes here
Cppm = 1/(log(2)∗Eph)∗(RPLB^2/(RPLB/log(M)+2∗Pn/(M–1)+RPLB^2*M*Ts/((log(M)*Eph)))
end

function [ Rb ] = Data_Rate( Recc, M, Ts )

%DATA RATE Summary of this function goes here
% Detailed explanation goes here
Rb = Recc*log2(M)/(M*Ts);
end

function [ Pn ] = Noise_Power( Ib, delta_lambda, omega_det, Dr, att, Eph, delta_det, ld )

%NOISE POWER Summary of this function goes here
% Detailed explanation goes here
Pn = ( Ib*delta_lambda*omega_det*(pi*Dr^2/4)*att+delta_det^2*ld*Eph);
end
function [ Eph ] = Photon_Energy( lambda )
%PHOTON_ENERGY Summary of this function goes here
% Detailed explanation goes here
Eph = 6.626E−34*299792458/lambda;
end

function [ etta_pt ] = Pointing_Loss( )
%POINTING_LOSS Summary of this function goes here
% Detailed explanation goes here
etta_pt = -3.5558;
end

function [ Pr ] = Received_Power( Pt, Gt, Gr, Ls, La, etta_pt, etta_t, etta_r )
%RECEIVED_POWER Summary of this function goes here
% Detailed explanation goes here
Pr = Pt + Gt + Gr + Ls + La + etta_pt + etta_t + etta_r;
end

function [ etta_r ] = Receiver_Efficiency( )
%RECEIVER_EFFICIENCY Summary of this function goes here
% Detailed explanation goes here
etta_r = -4;
end

function [ Gr ] = Receiver_Gain( Dr, lambda, gamma_r )
% RECEIVER_GAIN Summary of this function goes here
% Detailed explanation goes here

Gr = 10 * log10 (( pi * Dr / lambda )^2 * (1 - gamma_r^2)) ;

end

Lb = -0.19;

psi = ( etta_j / Ts ) *(1 + tanh ( Recc - 0.5 )) / 1.25 * log2 ( M ) ;

Lj = -10 * log10 ( 5 * psi^2 + 2 * psi + 1 ) ;

Lf = - Recc * sigmaI^2 * 10 / log ( 10 ) ;

Lt = -0.07;

etta_imp = -1.5;

etta_code = -1;

etta_int = - 16 * sigmaI / sqrt ( Nf ) ;

RP = RPLB - Lb - Lj - Lf - Lt - etta_det - etta_imp - etta_code - etta_int ;

Rb = Data_Rate ( Recc , M , Ts ) ;

A = Rb * log ( 2 ) * M * Ts * ( M - 1 ) - log ( M ) * ( M - 1 ) ;

B = Rb * log ( 2 ) * ( M - 1 ) * Eph ;

C = 2 * Pn * log ( M ) * Eph * Rb * log ( 2 ) ;

PR1 = ( - B + sqrt ( B^2 - 4 * A * C ) ) / ( 2 * A ) ;

PR2 = ( - B - sqrt ( B^2 - 4 * A * C ) ) / ( 2 * A ) ;

if PR1 < 0 && PR2 < 0
    disp ( ' Not feasible to handle targeted data rate ' ) ;
end

if PR1 > 0 && PR2 > 0
    RPLB = 10 * log10 ( min ( PR1 , PR2 ) ) ;
end
if PR1 > 0 && PR2 < 0
    RPLB = 10 * log10(PR1);
end

if PR1 < 0 && PR2 > 0
    RPLB = 10 * log10(PR2);
end

function [ Ls ] = Space_Loss( lambda, R )
%SPACE_LOSS Summary of this function goes here
% Detailed explanation goes here
Ls = 10 * log10((lambda/(4*pi*R)^2);
end

function [ ettat ] = Transmitter_Efficiency( )
%TRANSMITTER_EFFICIENCY Summary of this function goes here
% Detailed explanation goes here
ettat = -1.6;
end

function [ Gt ] = Transmitter_Gain( Dt, lambda, alpha_t, gamma_t )
%TRANSMITTER_GAIN Summary of this function goes here
% Detailed explanation goes here
Gt = 10 * log10((pi*Dt/lambda)^2*2/alpha_t^2*(exp(-alpha_t^2)-exp(-alpha_t^2*gamma_t^2))^2);
end
A.6 Data Rate Maximization Tool

clear all
clc

%Signaling
M_array = [ 2 4 8 16 32 64 128 256 512 1024 2048 ];
Tmin = 0.5E−09; %seconds
Ts_array = [ Tmin 1.26∗Tmin 1.26^2∗Tmin 1.26^3∗Tmin 1.26^4∗Tmin
1.26^5∗Tmin 1.26^6∗Tmin 1.26^7∗Tmin 1.26^8∗Tmin 1.26^9∗Tmin
1.26^10∗Tmin ]; %seconds

i = 1;
j = 1;
Rb_array = zeros(size(M_array, 2), size(Ts_array, 2));
Margin = zeros(size(M_array, 2), size(Ts_array, 2));

for i = 1:size(M_array, 2)
    for j = 1:size(Ts_array, 2)
        run Link_Budget_Tool_1;
        if Mar > 3
            Rb_array(i, j) = Rb;
            Margin(i, j) = Mar;
        else
            Rb_array(i, j) = 0; % if link is not closed there is no
            Margin(i, j) = inf; % we make--up infinite margin for this
            case in order to eliminate it when building paretto
            front
        end
    end
end
end

Rb_max = max(max(Rb_array));

Rb_paretto = max(Rb_array);
Margin_paretto = min(Margin);
figure
scatter(Margin_paretto, Rb_paretto);
xlabel('Margin, dB');
ylabel('Data Rate, b/s');

% calculation of number of photons incident to the detector
inds = find(Rb_array == Rb_max);
[row, col] = ind2sub(size(Rb_array), inds);
i = row;
j = col;
run Link_Budget_Tool_1;
N_photons = 10^(Pr/10)/Eph*Ts % number of photons received per pulse

Rb_max % output of maximum data rate
M_optimal = M_array(i)
Ts_optimal = Ts_array(j)

% Input Parameters
% Geometry/Atmosphere
R = 600000; %meters
lambda = 1.55E−06; %meters
Ib = 5; %W/m^2 sr um
r0 = 0.1; %meters
sigmaI = 0.02;
Nf = 16;
%Signaling
Ts = Ts_array(j); %seconds
M = M_array(i);
Recc = 0.5;

%Transmitter
Pt = 10*log10(0.4*0.3); %dB-W
Dt = 0.00015; %meters
gamma_t = 0;
alpha_t = 1.12;

%Receiver
Dr = 1; %meters
gamma_r = 0;
delta_lambda = 2E-4; %um

%Photo-Detector Array
etta_det = -3.98; %dB
delta_det = 1.5E-5; %meters
ld = 1E+13; %e/s/m^2
etta_j = 240E-12; %seconds
omega_det = 1.78E-12; %sr
att = 0.077;

%Received Power
Gt = Transmitter_Gain(Dt, lambda, alpha_t, gamma_t);
Gr = Receiver_Gain(Dr, lambda, gamma_r);
Ls = Space_Loss(lambda, R);
La = Atmospheric_Loss();
etta_pt = Pointing_Loss();
etta_t = Transmitter_Efficiency();
\[ \text{etta}_r = \text{Receiver\_Efficiency}(\quad) ; \]
\[ \text{Pr} = \text{Received\_Power}(\text{Pt, Gt, Gr, Ls, La, etta}_pt, \text{etta}_t, \text{etta}_r) ; \]

\%Noise Power

\[ \text{Eph} = \text{Photon\_Energy}(\text{lambda}) ; \]
\[ \text{Pn} = \text{Noise\_Power}(\text{Ib, delta\_lambda, omega\_det, Dr, att, Eph, delta\_det, ld}) ; \]

\%Required Power Lower Bound

run Required\_Power\_LB

\%Required Power

run Required\_Power

\%Margin

\[ \text{Mar} = \text{Pr} - \text{RP} ; \]
\[ \text{if} \text{Mar}>3 \]
\[ \text{disp(’Link is closed with Margin(dB)’)} ; \]
\[ \text{disp(Mar)} ; \]
\[ \text{disp(’and Data Rate(bits/s)’)} \]
\[ \text{disp(Rb)} ; \]
\[ \text{else} \]
\[ \text{disp(’Link is not closed with Margin(dB)’)} ; \]
\[ \text{disp(Mar)} ; \]
\[ \text{disp(’and targeted Data Rate(bits/s)’)} \]
\[ \text{disp(Rb)} ; \]
\[ \text{end} \]

**A.7 Integrated** \(D_{com}\)-Maximization Tool

**A.7.1 Space-to-Ground**
P_input_array = [25];
Orbit = [200 500 800 1100 1400 1700 2000];

load('200 km. Orbit.mat')
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 1) = Data_max;
Rb_OPT(1, 1) = Rb_optimal;
M_OPT(1, 1) = M_optimal;
Ts_OPT(1, 1) = Ts_optimal;
delta_T_OPT(1, 1) = delta_T_optimal;

load('500 km. Orbit.mat')
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 2) = Data_max;
Rb_OPT(1, 2) = Rb_optimal;
M_OPT(1, 2) = M_optimal;
Ts_OPT(1, 2) = Ts_optimal;
delta_T_OPT(1, 2) = delta_T_optimal;

load('800 km. Orbit.mat')
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end

DATA_OPT(1, 3) = Data_max;
Rb_OPT(1, 3) = Rb_optimal;
M_OPT(1, 3) = M_optimal;
Ts_OPT(1, 3) = Ts_optimal;
delta_T_OPT(1, 3) = delta_T_optimal;

load('1100 km. Orbit.mat')
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end

DATA_OPT(1, 4) = Data_max;
Rb_OPT(1, 4) = Rb_optimal;
M_OPT(1, 4) = M_optimal;
Ts_OPT(1, 4) = Ts_optimal;
delta_T_OPT(1, 4) = delta_T_optimal;

load('1400 km. Orbit.mat')
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end

DATA_OPT(1, 5) = Data_max;
Rb_OPT(1, 5) = Rb_optimal;
M_OPT(1, 5) = M_optimal;
Ts_OPT(1, 5) = Ts_optimal;
delta_T_OPT(1, 5) = delta_T_optimal;
load ('1700 km. Orbit.mat')
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 6) = Data_max;
Rb_OPT(1, 6) = Rb_optimal;
M_OPT(1, 6) = M_optimal;
Ts_OPT(1, 6) = Ts_optimal;
delta_T_OPT(1, 6) = delta_T_optimal;

load ('2000 km. Orbit.mat')
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 7) = Data_max;
Rb_OPT(1, 7) = Rb_optimal;
M_OPT(1, 7) = M_optimal;
Ts_OPT(1, 7) = Ts_optimal;
delta_T_OPT(1, 7) = delta_T_optimal;

plot(Orbit, DATA_OPT/1000000000)
xlabel('Orbit, km')
ylabel('Data, Gbits')

%Signaling
M_array = [ 2 4 8 16 32 64 128 256 512 1024 2048 ];
Tmin = 0.5E−9; %seconds
Ts\_array = [ \text{Tmin} 1.26^1 \text{Tmin} 1.26^2 \text{Tmin} 1.26^3 \text{Tmin} 1.26^4 \text{Tmin} 1.26^5 \text{Tmin} 1.26^6 \text{Tmin} 1.26^7 \text{Tmin} 1.26^8 \text{Tmin} 1.26^9 \text{Tmin} 1.26^{10} \text{Tmin} ] \; \% \text{seconds}

Rb\_array = \text{zeros(size(M\_array, 2), size(Ts\_array, 2))};
Margin = \text{zeros(size(M\_array, 2), size(Ts\_array, 2))};
Data\_array = \text{zeros(size(M\_array, 2), size(Ts\_array, 2))};

\text{for i = 1:size(M\_array, 2)}
\quad \text{for j = 1:size(Ts\_array, 2)}
\quad \quad \text{run Orbit\_LBT\_interface}
\quad \quad \text{Data\_array(i, j) = Rb*delta\_T};
\quad \text{end}
\text{end}

\% Find maximum data and optimal M, Ts
Data\_max(1, b) = \text{max(max(Data\_array))}; \% maximum data that can be transmitted for a given orbit and power

\% calculation of number of photons incident to the detector
inds = \text{find(Data\_array == Data\_max(1, b))};
[row, col] = \text{ind2sub(size(Data\_array), inds)};
i = row;
j = col;
\text{if size(i, 1) ~= 1}
\quad \text{if size(i, 1) ~= 2}
\quad \quad i = i(11, 1);
\quad \quad j = j(11, 1);
\quad \text{end}
\quad i = i(1, 1);
\quad j = j(1, 1);
M_optimal(1, b) = M_array(i);
Ts_optimal(1, b) = Ts_array(j);
Rb_optimal(1, b) = Data_Rate( Recc, M_optimal(1, b), Ts_optimal(1, b)));
delta_T_optimal(1, b) = Data_max(1, b)/Rb_optimal(1, b);
T = 900;

Rm = zeros(1, size(solution, 2));
for e = 1: size(solution, 2)
    Rm(1, e) = (solution(1, e)^2 + solution(3, e)^2 + solution(5, e)^2)^(1/2);
end

k = 6371000/Rm(1, 1);
l = 6371000/Rm(1, size(Rm, 2));
Xa = k*solution(3, 1);
Ya = k*solution(1, 1);
Za = k*solution(5, 1);
Xb = l*solution(3, size(Rm, 2));
Yb = l*solution(1, size(Rm, 2));
Zb = l*solution(5, size(Rm, 2));

alph = acos((Xa*Xb + Ya*Yb +Za*Zb)/(6371000)^2);
syms Xgs Ygs Zgs
Gs = solve ( Xa*Xgs + Ya*Ygs +Za*Zgs == (6371000)^2*cos(alph/2), Xb*Xgs + Yb*Ygs +Zb*Zgs == (6371000)^2*cos(alph/2), ...
    Xgs^2 + Ygs^2 + Zgs^2 == (6371000)^2);
Xgs = real(double(Gs.Xgs(1)));
Ygs = real(double(Gs.Ygs(1)));  
Zgs = real(double(Gs.Zgs(1)));  

Margin = zeros(1, size(solution, 2));  
RR = zeros(1, size(solution, 2));  
for q = 1:size(solution, 2)  
    RR(1, q) = ((solution(1, q) - Ygs)^2 + (solution(3, q) - Xgs)^2) + (solution(5, q) - Zgs)^2)^0.5;  
    R = (RR(1, q));  
    run MAIN_Link_Budget_Tool;  
    Margin(1, q) = Mar;  
end  

t = linspace(0, T, T/3);  
Crit_mar = 3; % critical margin is 3 dB  
g = 1;  
TTT = 0;  
for f = 1:size(Margin, 2)  
    if Margin(1, f) >= Crit_mar  
        TTT(1, g) = t(1, f);  
        g = g+1;  
    end  
end  

delta_T = max(TTT) - min(TTT); % duration of a possible link  

%Input Parameters  
  %Geometry/Atmosphere  
  lambda = 1.55E-06; %meters  
  Ib = 5; %W/m^2 sr um
r0 = 0.1; %meters
sigmaI = 0.02;
Nf = 16;

%Signaling
Ts = Ts_array(j); %seconds
M = M_array(i);
Recc = 0.5;

%Transmitter
Dt = 0.0015; %meters
gamma_t = 0;
alpha_t = 1.12;

%Receiver
Dr = 1; %meters
gamma_r = 0;
delta_lambda = 2E-4; %um

%Photo-Detector Array
etta_det = -3.98; %dB
delta_det = 1.5E-5; %meters
ld = 1E+13; %e/s/m^2
etta_j = 240E-12; %seconds
omega_det = 1.778E-12; %sr
att = 0.077;

%Received Power
Gt = Transmitter_Gain(Dt, lambda, alpha_t, gamma_t);
Gr = Receiver_Gain(Dr, lambda, gamma_r);
Ls = Space_Loss(lambda, R);
La = Atmospheric_Loss( );
etta_pt = Pointing_Loss( );
etta_t = Transmitter_Efficiency( );
etta_r = Receiver_Efficiency( );
Pr = Received_Power( Pt, Gt, Gr, Ls, La, etta_pt, etta_t, etta_r );

%Noise Power
Eph = Photon_Energy( lambda );
Pn = Noise_Power( Ib, delta_lambda, omega_det, Dr, att, Eph, delta_det, ld );

%Required Power Lower Bound
run Required_Power_LB

%Required Power
run Required_Power

%Margin
Mar = Pr − RP;

A.7.2 Space-to-Space
DATA_OPT(1, 1) = Data_max;
Rb_OPT(1, 1) = Rb_optimal;
M_OPT(1, 1) = M_optimal;
Ts_OPT(1, 1) = Ts_optimal;
delta_T_OPT(1, 1) = delta_T_optimal;

load('500 km. Orbit2. 0.5.mat');
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(0.3*P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 2) = Data_max;
Rb_OPT(1, 2) = Rb_optimal;
M_OPT(1, 2) = M_optimal;
Ts_OPT(1, 2) = Ts_optimal;
delta_T_OPT(1, 2) = delta_T_optimal;

load('500 km. Orbit2. 1.0.mat');
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(0.3*P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 3) = Data_max;
Rb_OPT(1, 3) = Rb_optimal;
M_OPT(1, 3) = M_optimal;
Ts_OPT(1, 3) = Ts_optimal;
delta_T_OPT(1, 3) = delta_T_optimal;

load('500 km. Orbit2. 1.5.mat');
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(0.3*P_input_array(b)*0.3);
run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 4) = Data_max;
Rb_OPT(1, 4) = Rb_optimal;
M_OPT(1, 4) = M_optimal;
Ts_OPT(1, 4) = Ts_optimal;
delta_T_OPT(1, 4) = delta_T_optimal;
load('500 km. Orbit2_2.0.mat');
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(0.3*P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 5) = Data_max;
Rb_OPT(1, 5) = Rb_optimal;
M_OPT(1, 5) = M_optimal;
Ts_OPT(1, 5) = Ts_optimal;
delta_T_OPT(1, 5) = delta_T_optimal;
load('500 km. Orbit2_2.5.mat');
for b = 1:size(P_input_array, 2)
    Pt = 10*log10(0.3*P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 6) = Data_max;
Rb_OPT(1, 6) = Rb_optimal;
M_OPT(1, 6) = M_optimal;
Ts_OPT(1, 6) = Ts_optimal;
delta_T_OPT(1, 6) = delta_T_optimal;
load('500 km. Orbit2_3.0.mat');
for b = 1: size(P_input_array, 2)
    Pt = 10*log10(0.3*P_input_array(b)*0.3);
    run MAIN_MAIN_Data_Maximization_Tool
end
DATA_OPT(1, 7) = Data_max;
Rb_OPT(1, 7) = Rb_optimal;
M_OPT(1, 7) = M_optimal;
Ts_OPT(1, 7) = Ts_optimal;
delta_T_OPT(1, 7) = delta_T_optimal;

plot(RAAN, DATA_OPT/1000000000)
xlabel('RAAN of the Receiving Satellite, rad')
ylabel('Data, Gbits')

%Msignaling
M_array = [ 2 4 8 16 32 64 128 256 512 1024 2048 ];
Tmin = 0.5E−9; %seconds
Ts_array = [ Tmin 1.26*Tmin 1.26^2*Tmin 1.26^3*Tmin 1.26^4*Tmin 
            1.26^5*Tmin 1.26^6*Tmin 1.26^7*Tmin 1.26^8*Tmin 1.26^9*Tmin 
            1.26^10*Tmin ]; %seconds

Rb_array = zeros(size(M_array, 2), size(Ts_array, 2));
Margin = zeros(size(M_array, 2), size(Ts_array, 2));
Data_array = zeros(size(M_array, 2), size(Ts_array, 2));

for i = 1: size(M_array, 2)
    for j = 1: size(Ts_array, 2)
        run Orbit1_Orbit2_LBT_interface
        Data_array(i, j) = Rb*delta_T;
    end
end
% Find maximum data and optimal M, Ts
Data_max(1, b) = max(max(Data_array)); % maximum data that can be transmitted for a given orbit and power

% calculation of number of photons incident to the detector
inds = find(Data_array == Data_max(1, b));
[row, col] = ind2sub(size(Data_array), inds);
i = row;
j = col;
if size(i, 1) ~= 1
    if size(i, 1) ~= 2
        i = i(1, 1);
        j = j(1, 1);
    end
    i = i(1, 1);
    j = j(1, 1);
end

M_optimal(1, b) = M_array(i);
Ts_optimal(1, b) = Ts_array(j);
Rb_optimal(1, b) = Data_Rate(Recc, M_optimal(1, b), Ts_optimal(1, b));
delta_T_optimal(1, b) = Data_max(1, b)/Rb_optimal(1, b);
T = 300;

Margin = zeros(1, size(solution1, 2));
for q = 1:size(solution1, 2)
    R = ((solution1(1, q) - solution2(1, q))^2 + (solution1(3, q) - solution2(3, q))^2 + (solution1(5, q) - solution2(5, q))^2)
\[ V \left( \frac{1}{2} \right) \]
run MAIN_Link_Budget_Tool;
Margin(1, q) = Mar;
end

t = linspace(0, T, T/3);
Crit_mar = 3; % critical margin is 3 dB

g = 1;
TTT = 0;
for f = 1: size(Margin, 2)
    if Margin(1, f) >= Crit_mar
        TTT(1, g) = t(1, f);
        g = g+1;
    end
end
delta_T = max(TTT) - min(TTT); % duration of a possible link

%Input Parameters
%Geometry/Atmosphere
lambda = 1.55E−06; %meters
Ib = 5; %W/m^2 sr um
r0 = 0.1; %meters
sigmaI = 0.02;
Nf = 16;

%Signalization
Ts = Ts_array(j); %seconds
M = M_array(i);
Recc = 0.5;
%Transmitter
Dt = 0.0015; %meters
gamma_t = 0;
alpha_t = 1.12;

%Receiver
Dr = 0.2; %meters
gamma_r = 0;
delta_lambda = 2E-4; %um

%Photo-Detector Array
etta_det = -3.98; %dB
delta_det = 1.5E-5; %meters
ld = 1E+13; %e/s/m^2
etta_j = 240E-12; %seconds
omega_det = 1.778E-12; %sr
att = 0.077;

%Received Power
Gt = Transmitter.Gain( Dt, lambda, alpha_t, gamma_t );
Gr = Receiver.Gain( Dr, lambda, gamma_r );
Ls = Space.Loss( lambda, R );
La = Atmospheric.Loss( );
etta_pt = Pointing.Loss( );
etta_t = Transmitter.Efficiency( );
etta_r = Receiver.Efficiency( );
Pr = Received.Power( Pt, Gt, Gr, Ls, La, etta_pt, etta_t, etta_r );

%Noise Power
Eph = Photon.Energy( lambda );
\texttt{Pn = Noise\_Power(Ib, delta\_lambda, omega\_det, Dr, att, Eph, delta\_det, ld);}

\%Required Power Lower Bound
\texttt{run Required\_Power\_LB}

\%Required Power
\texttt{run Required\_Power}

\%Margin
\texttt{Mar = Pr – RP;}
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