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MULTI-BEAM

STEERING SYSTEMS FOR
SPACECRAFT MULTI-BEAM
LASER COMMUNICATION
TERMINALS

JOSHUA SPANDER

Multi-Beam Steering Systems for Spacecraft Multi-Beam Laser Communication Terminals

Multi-Beam Steering Systems for Spacecraft Multi-Beam Laser Communication Terminals

Dissertation

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at Delft University of Technology
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chair of the Board for Doctorates
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The best way to predict the future is to invent it.

Josh Lyman (*The West Wing*)

CONTENTS

Summary	xi
Samenvatting	xv
1. Introduction	1
1.1. Background and Motivation	2
1.1.1. The Rise in Data Demands and the RF Ceiling	3
1.1.2. The "Achilles' Heel(s)" of Laser Communication	4
1.2. Current State of Multi-Beam Laser Communication	5
1.2.1. Potential of Multi-Beam Terminals	6
1.2.2. Evolution of Multi-Beam Architectures for Space Applications	6
1.2.3. Scope and Identified Gaps	10
1.3. Thesis Goals and Outlines	11
1.3.1. Thesis Goal and Research Questions	11
1.3.2. Thesis Outline and Methodologies	12
1.3.3. Research Contributions	15
2. Multi-Beam Terminal Use Cases	23
2.1. Introduction	24
2.2. Methodology	26
2.2.1. Geometric Analysis	27
2.2.2. Potential User Population Densities	37
2.3. Results and Discussion	45
2.3.1. Results of the Geometric Analysis and Feasible Multi-Beam Terminal Altitude Ranges for Operations	46
2.3.2. Number of Potential Users in Field of View for Nadir Operations	51
2.3.3. Multi-Beam Performance Improvements in Space, Air, Ground and Sea Integrated Networks (SAGSINs)	56
2.4. Comparison of Multi-Beam Use Cases: Summary and Conclusion	58
2.4.1. Target Coverage and Spatial Resolution	58
2.4.2. Dwell Time, Angular Resolution and Field of View	58
2.4.3. Conclusion	59
3. Design of Multi-Beam Steering Systems	69
3.1. Introduction	70

3.2. Functions of Multi-Beam Laser Communication Terminals . .	74
3.2.1. Acquisition	74
3.2.2. Link Sustainment Functions	77
3.2.3. Link Termination Functions	79
3.2.4. Multi-Beam Terminal Functions	79
3.3. Design Options for Multi-Beam Steering Systems	83
3.3.1. Previous Multi-Beam Steering System Designs	84
3.3.2. Design Options and Recipe	89
3.3.3. Steering Mechanism Selection	91
3.3.4. Application on Example Use Cases	94
3.3.5. Transceiver Array Considerations	97
3.4. Conclusion	97
4. Hardware Setup	107
4.1. Introduction	108
4.2. Requirements	109
4.2.1. High Level Setup Requirements	110
4.2.2. Multi-beam Source Requirements	110
4.2.3. Image Detector Requirements	111
4.2.4. Spatial Light Modulator Requirements	111
4.3. Image Detector	112
4.3.1. Selection and Properties	112
4.3.2. Integration Approach	112
4.4. Spatial Light Modulator (SLM)	114
4.4.1. Selection and Properties	115
4.4.2. Interface and Data Handling	115
4.5. Multi-Beam Source	115
4.5.1. Design Selection	115
4.5.2. Generation	117
4.5.3. Actuation	118
4.6. Optical Integration and Overview of the Setup	120
4.6.1. Optical System	120
4.6.2. Setup Configurations	122
4.7. Summary and Conclusion	123
5. Multi-Beam Steering	129
5.1. Introduction	130
5.2. SLM Steering Performance using Phase Ramp (PR) Steering	131
5.2.1. Steering Regimes as a Result of Aliasing	133
5.2.2. SLM Angular Steering Resolution and Range	133
5.2.3. Diffraction Losses and Challenges for Tracking	136
5.2.4. Required Spatial Steering Resolution	141
5.2.5. Integration of Phase Ramp Steering in Multi-Beam Steering Systems	142
5.2.6. Summary of SLM Performance Using Phase Ramp Steering	146

5.3. Phase Ramp and Fresnel Lens (PRFL) Steering	146
5.3.1. PRFL and Tracking Performance	148
5.3.2. Experimental Demonstration of PRFL	151
5.3.3. Integration of PRFL into Multi-Beam Acquisition and Steering Systems	157
5.4. Discussion and Conclusion	160
6. Multi-Beam Tracking	167
6.1. Introduction	169
6.2. Method	171
6.2.1. Hardware Experiment	171
6.2.2. Tracking Image Modeling	172
6.2.3. Multi-Beam Tracking Algorithm	174
6.2.4. Analysis of Algorithm Limitations and Performance	189
6.3. Results and Discussion	192
6.4. Conclusion	196
7. Conclusion	203
7.1. Summary	204
7.2. Analysis and Discussion of Chapter Findings and Conclusions	205
7.3. Answers to the Research Questions	208
7.4. Innovations	212
7.5. Future Research	213
A. Appendix: Multi-Beam Terminal Use Cases	219
A.1. Field of View	219
A.2. Angular and Spatial Resolutions	219
B. Appendix: Design of Multi-Beam Steering Systems	223
C. Appendix: Hardware Setup	231
Curriculum Vitæ	233
List of Publications	235
Acknowledgements	237

SUMMARY

Laser communication is seen as the future of high-speed communication in space and a potential key technology for the future. This is due to low beam divergence, around three orders of magnitude less than that of for similarly sized microwave based radio frequency systems. This allows higher signal-to-noise ratios due to increased signal power transferred. Additionally, the reduced beam divergence implies no overlap with other optical links, eliminating cross interference. As a result, laser communication can leverage larger bandwidths. Nevertheless, low beam divergence has also meant that laser communication until now has been point-to-point, limiting scalability and reducing reliability. Multi-beam laser communication terminals (MBTs) offer point-to-multi-point laser communication, implying a scalable solution to bringing this technology into globally available networks.

However, research on MBTs remains limited compared to single-beam systems. Critically, no studies have addressed how use cases related variables (such as user type, application, or altitude) impact design parameters such as field of view (FoV), angular resolution, and beam count. Existing works on MBTs often discuss unique designs, with insight and overview of MBT design choices remaining underexplored. Among steering technologies, spatial light modulator (SLM)-based systems show significant promise, yet their implementation and associated system layouts remain underexplored. Furthermore, no known multi-beam tracking algorithms have been developed which can track large numbers of beams using image detectors within these types of steering systems.

The analysis indicated that the estimated number of terrestrial users per terminal increased disproportionately (quadratically and tangentially) with FoV, with the current optical technological restrictions being the largest limiting factor in wide FoV telescopes. Additionally, the density of counter terminals, orbital altitude and FoV dwell times were roughly linearly proportional. The number of potential users across all user types can be on the order of (tens, hundreds of) millions, however, competing technologies and adoption rates in combination with the aforementioned imply this number will initially be lower. It was estimated to be in the 10s-100s. Further analysis on inter-satellite communication in LEO constellations yielded a similar number, between 3-30, depending on the mission configuration and FoV. Lastly, analysis for space, air, ground and sea integrated networks (SAGSINs) found that increasing the number of beams eventually yields saturation in the number of beams used in ad-

dition to diminished returns of the added value of each beam. From this study, between 8-64 beams were found to be of use.

With this analysis as well as the available literature, the gaps in the multi-beam steering literature were identified. These focused primarily on the architecture, steering hardware implementation and multiple beam tracking.

To investigate potential designs of multi-beam terminals, first an overview of the per-beam and terminal level functions was created and contrasted with single beam terminals. It was found that multi-beam terminals require the same functions, with the additional functions of separation, labeling, classification and validation functions of the targets. Multi-beam terminals, in contrast with single beam terminals, also exist in a continuum, with multiple beams in various stages of acquisition, communication and termination at the same time. With these functions in mind, an extensive study was conducted comparing multi-beam designs with designs from the adjacent fields of single-beam terminals, 3D MEMS optical cross-connects, indoor LiFi terminals and fixed point-to-multi-point terminals. This yielded a design option tree which could be used as a recipe to determine the high level design of the terminal.

When applied to the aforementioned use cases, the design for the steering system was selected to be an SLM based steering system. This was due to its compact form factor and high degree of component sharing between all (incoming and outgoing) beams.

The use of SLMs for multiple beam steering was investigated and demonstrated. Beam steering using SLMs comes with inherent challenges related to diffraction and non-modulated beams (NMBs). These cause beam duplicates and increases tracking complexity taking up resources. A method using a composite steering phase screen consistent of a phase ramp and Fresnel lens (PRFL) was proposed and investigated. This method allows for direct hardware mitigation with little to no computational overhead. Additionally, this method of steering allows for dynamic allocation of individually tailored optical systems for each beam. As a result, the beams can be separated, conditioned and steered to their transceivers and the emitted beams to the counter terminals. This reduces the layout complexity and the number of components. The aliasing limitations associated with SLMs were found to provide a steering range and efficiency envelope, which helps define the steering system performance. Lastly, the SLM steering performance with regard to angular resolution was extensively modeled and an envelope was defined. Theory was compared to the hardware demonstrations, with the SLM used having a steering range of 2.25° and resolution of $1 \mu\text{rad}$.

As mentioned before, in contrast with single beam tracking, multiple beam tracking needs to detect, separate, label and classify beams from noise and other beams. Additionally, where single beam tracking can rely on region-of-interesting to reduce the computational load, multi-beam

tracking has to consider the whole FoV in order to acquire and track all the beams. When similar image processing techniques are employed, computational loads are experienced that scale with the number of pixels. An algorithm was proposed based on temporal tracking methods inspired by multiple target tracking. This method was found to be able to track 1000 beams with 99% precision at 1 ms per frame for a given noise level and size of the tracking window of each beam. This was demonstrated experimentally. Additionally, the performance envelope with respect to noise was analyzed and derived completely analytically.

SAMENVATTING

Lasercommunicatie wordt gezien als de toekomst van snelle communicatie in de ruimte en een potentiële sleuteltechnologie voor de toekomst. Dit komt door de lage bundeldivergentie, die ongeveer drie ordes van grootte lager is dan bij vergelijkbare op microgolven gebaseerde radiofrequentiesystemen. Hierdoor kunnen hogere signaal-ruisverhoudingen worden bereikt dankzij het toegenomen overgedragen signaalvermogen. Bovendien zorgt de lagere bundeldivergentie ervoor dat er geen overlap is met andere optische verbindingen, waardoor kruisinterferentie wordt geëlimineerd. Als gevolg hiervan kan lasercommunicatie gebruikmaken van grotere bandbreedtes. De lage bundeldivergentie heeft er echter ook toe geleid dat lasercommunicatie tot nu toe punt-naar-punt was, wat de schaalbaarheid beperkte en de betrouwbaarheid verminderde. Multi-beam lasercommunicatieterminals (MBT's) bieden punt-naar-multi-punt lasercommunicatie, wat een schaalbare oplossing biedt om deze technologie in wereldwijd beschikbare netwerken te integreren.

Onderzoek naar MBT's is echter nog beperkt in vergelijking met systemen met één bundel. Kritisch is dat er nog geen onderzoek is gedaan naar de invloed van gebruiksgerelateerde variabelen (zoals gebruikerstype, toepassing of hoogte) op ontwerpparameters zoals field of view (FoV), hoekresolutie en aantal bundels. Bestaand onderzoek naar MBT's bespreekt vaak unieke ontwerpen, maar inzicht in en overzicht van de ontwerpkeuzes voor MBT's blijven onderbelicht. Onder de stuurtechnologieën tonen systemen gebaseerd op spatial light modulators (SLM's) veelbelovende resultaten, maar de implementatie en bijbehorende systeemconfiguraties zijn nog onvoldoende onderzocht. Bovendien zijn er nog geen bekende multi-beam tracking-algoritmen ontwikkeld die grote aantallen bundels kunnen volgen met behulp van beelddetectoren binnen dit type stuursystemen.

Uit analyses die zijn uitgevoerd om het potentiële en geschatte aantal aardse gebruikers per terminal te bepalen, bleek dat dit aantal onevenredig (kwadratisch en tangentieel) afhankelijk is van het FoV, waarbij de huidige optische technologische beperkingen de grootste beperkende factor vormen voor telescopen met een breed FoV. Daarnaast waren de dichtheid van tegenterminals, de orbitale hoogte en de FoV-verblijftijden ruwweg lineair evenredig. Het aantal potentiële gebruikers van alle typen kan in de orde van (tientallen, honderden) miljoenen liggen, maar concurrerende technologieën en adoptiesnelheden in combinatie met de bovengenoemde factoren impliceren dat dit aantal aanvankelijk lager zal

liggen. Het werd geschat op enkele tientallen tot honderden. Verdere analyse van inter-satellietcommunicatie in LEO-constellaties leverde een vergelijkbaar aantal op, tussen de 3 en 30, afhankelijk van de missie-configuratie en het FoV. Ten slotte bleek uit analyse van geïntegreerde netwerken voor ruimte, lucht, land en zee (SAGSIN's) dat een toename van het aantal bundels uiteindelijk leidt tot verzadiging van het aantal gebruikte bundels, naast een afnemende meerwaarde van elke afzonderlijke bundel. Uit dit onderzoek bleek dat tussen de 8 en 64 bundels bruikbaar zijn.

Met deze analyse en de beschikbare literatuur werden de lacunes in de literatuur over multi-beam sturing geïdentificeerd. Deze lacunes richtten zich voornamelijk op de architectuur, de implementatie van de stuurhardware en het volgen van meerdere bundels.

Om potentiële ontwerpen van multi-beam terminals te onderzoeken, werd eerst een overzicht gemaakt van de functies op individuele bundel en terminalniveau en vergeleken met single-beam terminals. Hieruit bleek dat multi-beam terminals dezelfde functies vereisen, aangevuld met functies voor scheiding, labeling, classificatie en validatie van de doelen. Multi-beam terminals bestaan, in tegenstelling tot single beam terminals, ook in een continuüm, waarbij meerdere bundels zich tegelijkertijd in verschillende stadia van acquisitie, communicatie en beëindiging bevinden. Met deze functies in gedachten is een uitgebreide studie uitgevoerd waarin multi-beam ontwerpen werden vergeleken met ontwerpen uit aanverwante gebieden als single beam terminals, 3D MEMS optical cross connects, indoor LiFi terminals en vaste point-to-multi-point-terminals. Dit resulteerde in een ontwerpoptieboom die als leidraad kan dienen voor het bepalen van het ruwe ontwerp van de terminal.

Toegepast op de bovengenoemde gebruiksscenario's werd gekozen voor een SLM-gebaseerd stuursysteem. Deze keuze werd gemaakt vanwege de compacte vormfactor en de hoge mate van componentdeling tussen alle (inkomende en uitgaande) bundels.

Het gebruik van SLM's voor het sturen van meerdere bundels werd onderzocht en gedemonstreerd. Straalsturing met behulp van SLM's brengt inherente uitdagingen met zich mee met betrekking tot diffractie en niet-gemoduleerde bundels (NMB's). Deze veroorzaken straalduplicatie en verhogen de complexiteit van de tracking, waardoor ze meer middelen in beslag nemen. Er is een methode voorgesteld en onderzocht die gebruikmaakt van een samengesteld stuurfasescherm bestaande uit een faseramp en een Frensel lens (PRFL). Deze methode maakt directe hardwarematige mitigatie mogelijk met minimale tot geen rekenkundige overhead. Bovendien maakt deze stuurmethode dynamische toewijzing van individueel aangepaste optische systemen voor elke bundel mogelijk. Hierdoor kunnen de bundels worden gescheiden, geconditioneerd en naar hun zendontvangers worden gestuurd en de uitgezonden bundels naar de tegenterminal. Dit vermindert de complexiteit van de lay-out en

het aantal componenten. Van de aliasingbeperkingen die gepaard gaan met SLM werd vastgesteld dat ze een stuurbereik en efficiëntiebereik bieden, wat helpt bij het definiëren van de prestaties van het stuursysteem. Ten slotte werd de stuurprestatie van de SLM met betrekking tot de hoekresolutie uitgebreid gemodelleerd en een bereik gedefinieerd. De theorie werd vergeleken met de hardwaredemonstraties, waarbij de gebruikte SLM een stuurbereik van 2,25 graden en een resolutie van 1 μrad had.

Zoals eerder vermeld, vereist het volgen van meerdere lichtbundels, in tegenstelling tot het volgen van één lichtbundel, het detecteren, scheiden, labelen en classificeren van lichtbundels van ruis en andere lichtbundels. Bovendien, waar het volgen van één lichtbundel kan vertrouwen op region-of-interesting om de rekenlast te verminderen, moet bij het volgen van meerdere lichtbundels het hele FoV worden overwogen om alle lichtbundels te detecteren en te volgen. Wanneer vergelijkbare beeldverwerkingstechnieken worden gebruikt, treedt een rekenlast op die schaal met het aantal pixels. Er is een algoritme voorgesteld op basis van een temporele tracking methodes, geïnspireerd op het volgen van meerdere bundels. Uit experimenten is gebleken dat deze methode 1000 lichtbundels met 99% precisie kan volgen bij een frametijd van 1 ms, voor een gegeven ruisniveau en formaat van het trackingvenster van elke bundel. Daarnaast is de prestatiecurve ten opzichte van ruis geanalyseerd en volledig analytisch afgeleid.

1

INTRODUCTION

5, 4, 3, 2, 1! Thunderbirds are go!

Jeff Tracy (*Thunderbirds*)

Ever increasing data and connectivity demands require ever increasing data link capacities. Radio communication has been the go-to technology to fulfill wireless connectivity demand, however, interference has caused spectrum congestion. Laser communication promises high bandwidth and secure communication thanks to low beam divergence through optical wavelengths. However, the low beam divergence has also relegated laser communication to point-to-point applications, limiting scalability. Additionally, links using optical wavelengths can be easily blocked by obstacles such as clouds or loss of line of sight, making links fragile. To mitigate these challenges, multi-beam laser communication terminals (MBTs) offer point-to-multi-point optical communication through multiple beams from one terminal. This chapter will introduce the background of MBTs and identify the challenges and gaps. These will form the basis of goals and research questions. After this, an outline of this dissertation as well as the methodologies will be presented.

1 1.1. BACKGROUND AND MOTIVATION

The well known Moore's Law, first articulated by Gordon Moore in 1965, posits that the number of transistors on a microchip (and by extension computational power) doubles approximately every two years.[1, 2] In the same way, multiple laws for data connectivity and networks have been proposed. Nielsen's Law of Internet Bandwidth, for example, observes that user bandwidth demand grows by 50% annually, reflecting the insatiable appetite for data-intensive applications.[3] Edholm's Law further underscores this growth, in its turn observing that the bandwidth of telecommunication networks, including internet access, doubles every 18 months. Additionally, it states that data rates across various communication mediums converge toward this trend.[4] Hence, all forms of communication must relentlessly increase their communication capacity in the future in an effort to both grow and match other mediums. Motivation for more expansive, faster and reliable communication networks is strong. In fact, Metcalfe's Law highlights that the compounding economic value of networks scales with the square of the number of connected users, incentivizing further connectivity.[5]

These laws, and the fact that they more or less hold true to this day, highlight an important trajectory of the human species.[3, 4, 5] Namely, the trajectory of human progress has been inexorably tied to the digitization and interconnection of society over the current and preceding century. These trends will almost certainly accelerate into the future.[6, 7] This progress is in fact clear enough to make it quantifiable, as captured by these empirical laws.

However, this growth is not automatic. Maintaining these trends has been the result of strong sustained efforts by researchers and engineers around the world. These laws not only describe trends, they pose a challenge: how can the future demands for data bandwidth and connectivity be met?

Reaching users, especially remote users, through high bandwidth and ubiquitous global data coverage through traditional means has become increasingly difficult and in some cases impossible. Across various length scales, these technologies have or will reach their potential. This became the central motivator for the 5-year research program "Optical Wireless Superhighways: Free Photons (at Home and in Space)". Launched in 2022, funded by the Dutch Research Council (NWO) and supported by a consortium of knowledge institutes and companies, this project aims to research and develop technologies which make this possible.[8]

Central to global coverage and ubiquitous access are satellites (i.e. the longer length scales).[8] Numerous LEO constellations, such as Starlink, are being deployed and proposed from around the world which will provide global internet access.[9] These networks have multiple satellites, each capable of communicating with a section of Earth. Being in a constellation and capable of forwarding data between them, they provide

both a data relay network as well as global access points.[10] Nevertheless, here too traditional communication technologies are reaching limits.

1.1.1. THE RISE IN DATA DEMANDS AND THE RF CEILING

The exponential growth in global data traffic has pushed traditional Radio Frequency (RF) communication systems to their limits.[8] The RF spectrum, a finite and heavily regulated resource, is experiencing a "spectrum crunch" characterized by congestion, interference, and diminishing available bandwidth.[8, 11] This limitation is particularly acute in scenarios requiring high-throughput links, such as inter-satellite communication, backhaul for mobile networks, and deep-space data relay, where RF systems struggle to meet the escalating demand for data rate and latency performance.

Looking at the problem from a higher level, the theoretical channel capacity of a channel is given by the Shannon-Hartley theorem:

$$C = B \log_2 \left(1 + \frac{S}{N} \right) \quad (1.1)$$

Where C represents the channel capacity in bits/s, B the channel bandwidth in Hz, S the signal power in W and N the noise power in W. The drawback of RF technology stems from the large beam divergence causing reduced signal power received as well as interference with other RF transmitters. To limit interference, the frequency overlap is limited by allocating bandwidth slots. These slots limit the bandwidth.

In this context, Free Space Optical Communication (FSOC)/laser communication emerges as an attractive supplement to RF. Optical wavelengths are on the order of micrometers, compared with RF wavelengths in the centimeter-to-millimeter range. Beam divergence is proportional to the wavelength and inversely proportional to the aperture diameter, as shown in Equation (1.2).

$$\theta \propto \frac{\lambda}{D} \quad (1.2)$$

Reducing the wavelength by orders of magnitude therefore decreases beam divergence by orders of magnitude. This in turn implies more signal can be captured by the receiver, improving signal to noise ratio and thereby channel capacity. Moreover, the slow beam divergence also implies there is no longer any physical overlap with other beams. As a result, nearly limitless bandwidths, in combination with high frequency carrier, is available for communication, yielding even higher capacities. Additionally, lower beam divergence offers another practical benefit: the aperture size can be reduced yielding smaller and lower mass communication systems. Lastly, laser beams naturally provide security advan-

tages, as eavesdropping on a tightly bundled optical beam is exceedingly difficult without physical interception.[12]

FSOC therefore leverages larger bandwidths, improved signal reception, smaller and lighter systems as well as security advantages while consuming less power.[10, 13] These attributes make FSOC an attractive technology for addressing the bandwidth and security challenges of contemporary communication demands.

1.1.2. THE "ACHILLES' HEEL(S)" OF LASER COMMUNICATION

While the potential benefits of laser communication are difficult to overstate, it is also a double edged sword.

For one, unlike RF, optical wavelengths cannot penetrate most opaque obstacles. These obstacles can take the form of solid objects, such as physical obstruction from trees or limbs of spacecraft. However, these can also amount to clouds which cover almost 70% of the surface of Earth at any given moment.[14] This technology can also not communicate over the horizon. Additionally, signals with optical wavelengths interact with transparent media more than RF wavelengths. As a consequence, variations in density within the Earth's atmosphere due to turbulence can refract and diffract light, causing additional losses of power and scrambling of the phase front.

This places constraints on the availability and reliability of laser communication in operational scenarios, making the link more fragile. Additionally this poses risks to networks as these problems could sever interconnections causing multiple network components. These limitations can slow the adoption of laser communication and might require permanent RF fallback systems.

A significant benefit of laser communication is small beam divergence. When the beam divergence is reduced however, it increases the steering precision required to steer the beam. As a result the link is harder to maintain in the presence of jitter and atmospheric disturbances. Only in recent years has the pointing challenge been overcome for a single beam.

Limited beam divergence also makes acquisition a challenging process akin to finding a needle in a haystack. For successful acquisition to take place, a search pattern must be followed where both terminals are aligned. Then both systems must start aligning until the signal is stable and coupled reliably in the transceiver, all the while combating jitter and relative motion. This acquisition process takes long and makes hopping between counter terminals more economically and practically expensive within the context of providing reliable communication networks. In the context of obstructions and line of sight, hopping between counter terminals can be a frequent occurrence as well. This in turn yields less optimal links and a network that is more complicated and complex to handle.[15,

16, 17]

Lastly, due to small beam divergence, one beam can only be used to communicate from one terminal to another terminal. Hence, two communication terminals are needed for each active link. This poses a challenge in two ways.

The first hurdle is scalability, which might prevent inclusion into large scale networks. The need for two terminals per active link conjures an analogous image of requiring two telecommunication antennas for each mobile device. Coupled with obstructions and acquisition (potentially needing RF back-ups), these drawbacks can potentially make laser communication prohibitively expensive and unreliable for mass adoption despite its benefits.

Second, the direct added benefit of adding a link is simultaneously negated by the required addition of a terminal. Metcalfe's law states that the economic value of a network increases with the square of the number of connections. This is due to the number of connections within the network scales quadratically with the number of users. Indeed, with current single beam terminals (SBTs), each additional link comes with an additional terminal. As a result, the increased benefit of an additional link is in lockstep with the cost, potentially scaling quadratically with the number of users (due to each link needing an individual terminal). This might relegate SBTs to function as the backhaul for RF.

Multi-beam laser communication terminals (MBTs) might suggest a solution. When multiple links can be accommodated and acquired at the same time, the acquisition problem can be partially mitigated. Additionally, angular diversification in the emitted beams can imply easier obstacle avoidance and geographic diversity. Lastly, multi-beam terminals can potentially be made to scale more readily.

Nevertheless, on a per-link basis, the same challenges with MBTs as for SBTs remain. Additionally, there are a number of technological challenges related to MBTs that are yet to be overcome and demonstrated. Particularly large challenges are those associated with the wide field of view (FoV) optics and steering. Lastly, MBTs have not enjoyed the same level of attention as SBTs, implying that the technology readiness level (TRL) is also still too low for serious near future consideration.

This thesis will explore some of the benefits, design and technological challenges associated with MBTs in relation to multi-beam steering to contribute to the further body of knowledge on MBTs.

1.2. CURRENT STATE OF MULTI-BEAM LASER COMMUNICATION

Multi-beam laser communication terminals (MBTs) have not been as widely researched as single beam laser communication terminals (SBT). This

subchapter provides a short overview of the current state of MBT research and development.

1.2.1. POTENTIAL OF MULTI-BEAM TERMINALS

Optical communication networks yield lower latencies and higher capacities.[18] The network topology and construction are an important aspect of optical networks. The addition of optical communication and multi-path routing of data through a network has been shown to increase network performance.[15, 18]

Work by Ndongson et al. has shown that network topology changes within an SAGSIN or spatial FSOC networks occur frequently (compared to RF networks), with the average time between topology changes occurring within the first minute after the last topology change.[15] In the same study, topology changes were compared to an equivalent RF based network and RF was found to be around 4.5 times less numerous in the same time frame. Each one of these topology changes implies (multiple) acquisition(s), which is time spent not communicating.[16]

These topology changes can be explained by weather and line-of-sight phenomena. Variations can be expected on a range of larger and smaller time scales, implying optical networks are highly variable at timescales ranging from 1 ms to years.[17, 19] Despite this, the FSOC network capacity was still higher on average than the RF network.[15]

To date, there has been little work done on the potential impact of MBTs directly. This thesis will provide more analysis on this aspect. Nevertheless, a number of aspects of MBTs were noted and have been identified and compared. Multiple beams per terminal allows for parallel acquisition and communication, which yields higher data rate. Additionally, multiple links allow for continuous communication without interruption and hence improve reliability. Moving away from inter-nodal links within networks, MBTs also offer a scalable access point for end users directly. Later in this thesis we will elucidate more on this topic.

1.2.2. EVOLUTION OF MULTI-BEAM ARCHITECTURES FOR SPACE APPLICATIONS

As will be discussed later in this subsection, there have been numerous proposed MBT designs in the past. However, it can be of use for the reader to first describe some key elements and functions of the system on a higher level by taking an example of an MBT shown in Figure 1.1. The MBT functions can be broadly broken down into three main areas. [20]

First, the signal capture and transmission through free space. In Figure 1.1 this is performed by the telescope, which captures signal from incoming beams as well as emitting transmitted beams. Increasing the

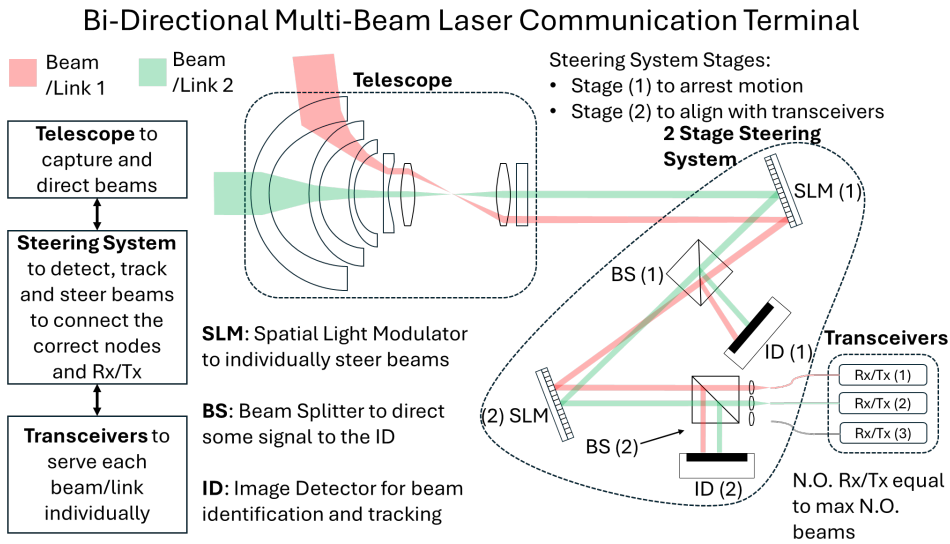


Figure 1.1.: Illustration of the optical path of a bi-directional multi-staged multi-beam laser communication system. Figure adapted from "Free-Space Multi-beam Optical Communication Terminal Design for Spacecraft" by J. Spaander on page 81 Figure 5.32[21, 22], reprinted and edited with permission.

FoV would allow for more beams at different angles to be accommodated. From the received signal perspective, this function captures sufficient signal power to achieve the desired data rate while simultaneously changing its form factor to one that is compatible with the rest of the MBT. From the transmission perspective, this the directing and shaping the beam to the correct diameters for propagation through free space.[20]

Second is steering multiple beams between the counter terminals and the transceivers. In Figure 1.1 this is performed by a two stage steering system utilizing a spatial light modulator (SLM). The steering system functions to map each counter terminal to a transceiver and compensate for beam wander (caused by relative motion) and jitter.[20]

Lastly, the transceivers encode and decode outgoing and incoming signals as well as serving amplification functions. This is the interface between the electrical and optical domains.[20]

Compared to SBTs, not much research has been performed on MBTs. Nevertheless, some alternate designs and concepts have been investigated.

The origins of multi-beam laser communication in research are difficult

to pin point. This is because it is difficult to identify an exact point at which MBTs can be distinguished from other devices with multiple optical channels. The first publications in this field that overlap significantly with MBTs as described in this thesis were patents. Sidorovich et al. published two patents in 2004 and 2006 on similar designs containing a wide field of view optical sphere used as a telescope and individual mirrors for the transmitters.[23, 24] Furthermore, Capots et al. in 2007 presented a different design based on mirror arrays and a mirror based telescope.[25] In the same year, Triebes et al. presented a patent utilizing multiple steering elements which actuated the position of transceivers and a shared telescope.[26] A common thread between the works from Sidorovich et al. 2004, Sidorovich 2006 and Capots et al. is the reliance on mirror arrays. This is contrasted with actuation of the fibers in Triebes et al.[23, 24, 25, 26] An important observation is that the design by Triebes et al. is smaller because the steering system is located after the telescope (from the received signal perspective) and a majority of (large) components (such as mirrors and beam splitters) are shared. Furthermore, the system layout and its associated complexities with regard to steering have not been detailed.

Perhaps the most prolific research group in both theoretical research as well as technological demonstration of MBTs is based in Changchun University of Science and Technology, China. In 2012, He et al. published an approach reliant on multiple large mirrors arranged in a parabolic shape.[27] The parabolic shape was used to achieve a wide field of view through reflections. It is also geometrically advantageous with regard to directing beams. The group improved upon this design as well as produced other designs in subsequent years. Huilin et al.'s work contains an overview of various multi-beam steering systems.[28] Multi-beam steering systems steer and direct each beam individually to their targets. Huilin et al. show that in their design, each link has an individual fine steering mirror (FSM) and optical system similar to an SBT.[28] This implies that the large mirror arrays are used as a lower size, weight and power (SWaP) alternative to mounting a number of SBTs on swivel mounts. Additionally, the paper shows initial experimental results of a mirror array. Further analyses were performed on the parabolic confocal reflection array by Zhang et al.[29] Subsequently outdoor ground-to-blimp tests were performed in 2021 by Wang et al. using a prototype of this system[30] and again indoors in 2023 by Wang et al.[31]

While this system may currently be the most developed MBT for spacecraft, it has some drawbacks. Namely, the size of the mirrors grows with the maximum FoV. Additionally, no components are shared between beams. This solution can, however, be effective for non-critical SWaP requirements.

As mentioned before, wide FoV telescopes might be a solution to reducing SWaP further. However, achieving wide FoVs is a challenge. Efforts

by the German aerospace center (DLR), presented by Poliak et al. in 2022 and 2024, in collaboration with ESA designed and built a wide FoV telescope for an MBT in GEO.[32, 33] In this case, the mission stipulates that the satellite must communicate simultaneously to static ground terminals geographically located around the Mediterranean Sea at the same time. Satellite itself being stationary with respect to the Earth (GEO orbit). The achieved FoV is around 4° . Additionally, 2.9° has also been presented.[34] Wider FoVs designs for different applications have been achieved, with a design proposed by Levenstein in 1989 for optical communications at significant mass above 150kg at 20° FoV, strongly limiting the applications to large platforms even when accounting for modern technological advancement.[35] This highlights a major limitation of paraxial optics; projecting a (hemi)spherical FoV onto a plane yields not only engineering challenges but also a mathematical impossibility to achieve distortion free projection. This is similar to the projection problems with maps of the Earth and maintaining relative shapes and scales of countries. Achieving diffraction limited systems with adequate telescope diameters requires additional (large) optical elements. This approach is in contrast to the non-paraxial optics proposed by Sidorovich et al. in 2004 and 2006 and Changchun between 2012 and 2023.[23, 24, 27, 28, 29, 30, 31] Furthermore, multi-telescope systems have been proposed, as mentioned earlier. Additionally, applying corrections through active optical elements, such as SLMs, can also increase the FoV.[36, 37]

Lastly, work at the Delft University of Technology (TU Delft) has explored various designs of MBTs in the past. This work began in 2021 with a master's thesis on the design of MBTs.[21] This has sparked subsequent investigation into MBTs with this PhD project as result.[38, 39] Contrary to the previously discussed work, particular focus was given to miniaturization of the multi-beam steering system through the use of SLMs and micro-mirror arrays (MMAs), as shown in Figure 1.1. Central to this design is that multiple beams share components without needing to rely on moving transceivers. This reduces complexity when compensating for beam motion while the steering system can simultaneously compensate for optical shortcomings. Furthermore, SLMs can also help increase the FoV.[36, 37] Nevertheless, this design was not detailed beyond high level design and relies on wide FoV optics. During this PhD project, the design, steering and tracking system has been further expanded upon and demonstrated within a lab setting.[20, 40, 41]

This thesis will analyze different use cases and design options for MBTs and multi-beam steering systems. Furthermore, the resulting selected design was further researched and demonstrated in the lab.

1.2.3. SCOPE AND IDENTIFIED GAPS

Having considered the advancements before this thesis, it is clear that the field of MBTs remains small and the current body of knowledge leaves much to be discovered. This is the case in every technical aspect of MBTs, from the telescope and steering system to the transceivers. Furthermore, this is also the case from a higher system level perspective, little is known about the SWaP of each design option as well as the use context in which these systems can/will operate. Each one of these topics would be more than adequate for a research project on its own. It is therefore needed to limit the scope of this thesis.

Within this context, the steering system was selected for further research. The reason for this lies in perhaps the most important benefit of MBTs over SBTs: scalability. While by no means straightforward or without research gaps, the other subsystems have clear scalability applications and either follow mature industrial roadmaps, like the transceivers, or established design practice, like the optics. The currently proposed steering systems have potential to improve upon multiple SBTs, however, form a scalability bottleneck. This is because previous MBT designs maintain separate optical paths, require individual steering mirrors and/or movable mounts. This not only has considerable drawbacks with regards to mass and volume, it also poses questions with regards to the number of moving components. Nevertheless, it is very important to make clear that the other subsystems would have made excellent topics, however, it was within this context that steering systems were selected.

Hence, to adequately limit the scope of this thesis, it was chosen to focus primarily on multi-beam steering systems. In particular, from [Section 1.2.1](#) and [Section 1.2.2](#) the following gaps were identified:

1. The impact on network performance of using MBTs compared to SBTs has not been systematically researched. Filling this gap would allow for better understanding as to the performance improvements when opting for MBTs.
2. While designs have been proposed, it is unknown what the impact of the use and use cases is on the design and capacity of MBTs. Filling this gap would improve understanding on the relation of different orbit regimes, user types and high level MBT requirements.
3. No overarching overview, analysis and comparison of the functions and design options of MBTs have been conducted in relation to their use cases and applications. Filling this gap would provide future researchers and designers with a framework to further develop MBT concepts. It would also shed light on high level design related SWaP and performance improvements.
4. Integration, operation and performance of key multi-beam steering technologies, such as SLMs, for multi-beam steering system

miniaturization has not been investigated. Exploration into this field would yield shortcomings and their associated solutions with regard applying these technologies. Furthermore, this would shed light onto how these technologies shape the steering system layout and design.

5. Tracking multiple individually randomly moving beams in the presence of noise and false beams has not been explored before, especially within the context of the use cases. Filling this gap would yield new theories with regard to tracking performance and computational loads as a function of noise and beam motion.

These gaps will form the basis for the thesis goals.

1.3. THESIS GOALS AND OUTLINES

Based on the limitations identified in [Section 1.2](#) from the current state-of-the-art, there remain gaps in the literature regarding the development of compact, multi-beam steering systems specifically tailored for the constraints of MBTs, as shown in [Section 1.2.3](#). While single beam solutions are well-documented, the requirements for simultaneous multi-point connectivity in a high-mobility environment introduce severe complexities. This thesis builds upon the concepts proposed in previous work.[\[20, 40, 41\]](#)

1.3.1. THESIS GOAL AND RESEARCH QUESTIONS

The primary objective of this thesis is to research and develop a comprehensive framework for a multi-beam steering system that allows multiple beams to share components simultaneously. Therefore, this thesis seeks to expand the understanding of multiple beam steering for space MBTs through the exploration, research and development of multi-beam steering system design and integration and aims to address the following research questions:

1. What is the relation between multi-beam terminals and their use cases?
 - a) How many beams would a multi-beam terminal be expected to handle for different use cases?
 - b) What is the relation between field of view requirements, orbit regime and user type?
 - c) How long is a counter terminal expected to dwell in the field of view?
 - d) How much could a multi-beam terminal impact a multi-domain integrated network?

2. What are the functions and design options for a space borne multi-beam steering system?
 - a) What are the functions of a multi-beam laser communication terminal?
 - b) How do the functions for a single beam laser communication terminal differ from those of a multi-beam laser communication terminal?
 - c) What are the design options for a multi-beam steering system?
 - d) How can a high level design for a multi-beam steering system be selected?
3. What are the characteristics of integrating an SLM based multi-beam steering system?
 - a) What are the operational drawbacks of SLMs and how can these be compensated?
 - b) What is the angular steering resolution performance envelope of an SLM within a multi-beam steering system?
 - c) What is the total angular steering range performance envelope of an SLM within a multi-beam steering system?
 - d) How can multiple beams be mapped from the counter terminals to the transceivers?
 - e) What is a viable SLM based multi-beam steering system layout?
 - f) Can steering and steering system layouts be validated in the lab?
4. How can multiple individually moving beams be tracked?
 - a) What are the limitations of single beam tracking methods when applied to multi-beam tracking?
 - b) How can multiple beam tracking performance in space match single beam tracking performance requirements?
 - c) How can the tracking performance envelope of this multiple beam tracking method be quantified with regard to noise and computational load?
 - d) Can the tracking principles and theory be demonstrated in the lab?

1.3.2. THESIS OUTLINE AND METHODOLOGIES

This thesis structure is shown in [Figure 1.2](#). Each chapter has a number of outcomes that inform subsequent chapters. These are summarized briefly in the figure and described in more detail here.

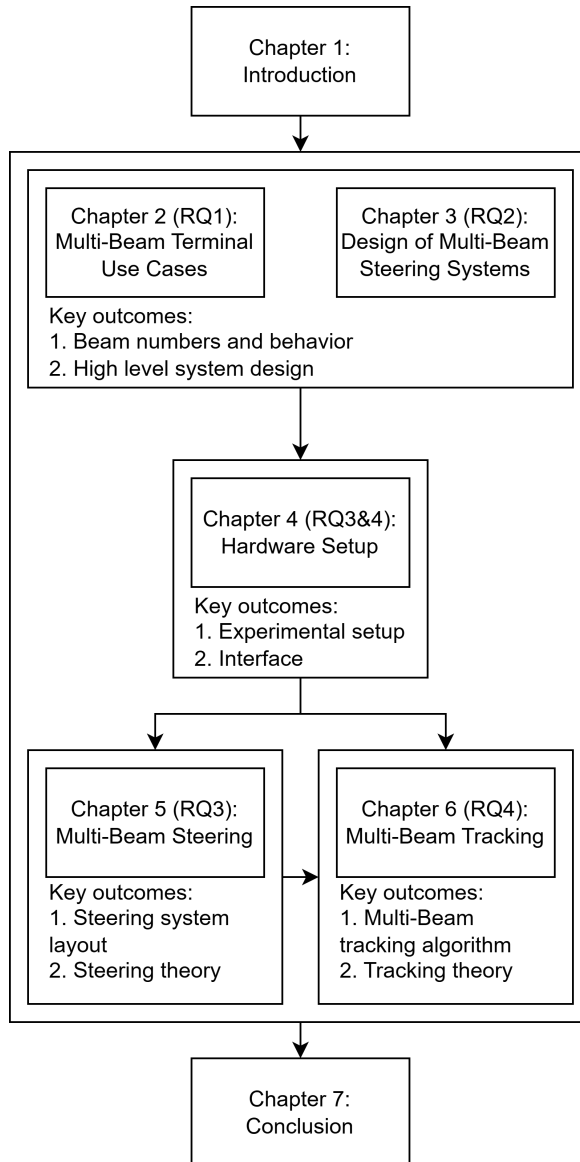


Figure 1.2.: Structure of the thesis and interactions of the chapters. Each chapter has the key outcomes as rough descriptions noted that are used in subsequent chapters.

Chapter 2 will use analytical geometry to determine the relation between the use case related parameters such as orbit regimes, FoV, angular resolution and dwell time within the FoV. Then, through analysis of

literature and publicly available data, a set of different user types and scenarios are distilled. These are space-to-air, space-to-sea and space-to-land for LEO, high LEO, MEO and GEO orbit regimes. Additionally, inter-satellite communications for large LEO constellations such as Starlink are also analyzed. Lastly, the effect on the performance of sea, air, ground and space integrated networks (SAGSINs) is investigated through numerical modeling in collaboration with Schisin Ndongson.

Chapter 3 uses an extensive literature study on MBTs as well as SBTs, 3D MEMS optical cross connects (OXCs), LiFi terminals and inter building laser communication to determine multi-beam functions and design options. The results of the functions show all the functions of MBTs per beam in each stage of life (i.e. acquisition, link sustainment and termination) as well as the terminal operation as a whole. The results of these functions are then compared to SBTs to contrast and explore the differences. The design options are compared to the literature of all the aforementioned devices. These options are then presented as a "design recipe" through a design options tree where a designer or researcher can determine the high-level design of an MBT for a given use case or user scenario. Lastly, the various multi-beam steering technologies are compared through a trade-off. The most interesting design combinations were identified from the trade-off and design options tree, using input from **Chapter 2**. The selected design was a multi-staged SLM based multi-beam steering system, similar to the one shown in **Figure 1.1** and derived from the design of Spaander et al.[21]

With the known high level design, **Chapter 5** and **Chapter 6** will investigate steering and tracking, in part through the use of experiments and lab demonstrations with real hardware. This experimental setup is detailed in **Chapter 4**. Here, optical principles are used to achieve independently moving beams, optical projection and actuation of steering mechanisms are discussed and detailed. The performances are verified through calibration techniques.

Chapter 5 investigates the multi-beam steering system by determining the system layout and steering mechanism performance (in this case using SLMs). This is done by analyzing the imaging and diffraction challenges as well as determining the performance envelopes of SLMs within this system. This was done through using analytical diffraction theory as well as experimental and numerical verification and validation. The results are the SLM performance envelopes with regard to the efficiency, angular range and angular resolution as well as a steering layout and method which improves tracking, noise and cross talk performance.

Chapter 6 uses elements borrowed from SBT tracking and the adjacent fields of multiple target tracking as well as novel methods to identify, classify, label and track multiple beams. The algorithm layout was determined with computational load in mind while being able to track within the full FoV and maintaining tracking loop latency. The algorithm was

mathematically and analytically described and analyzed to determine the performance with respect to precision, computational load and latency performance. The algorithm is also experimentally verified and validated.

Finally, [Chapter 7](#) summarizes the results from the chapters and connects the key findings in the conclusion. Furthermore, the future research is recommended.

A brief summary of the chapters:

- **Chapter 2: Use Cases and Impact** establishes the operational context, detailing the specific performance indicators of MBTs and the potential impact of MBTs on global communications.
- **Chapter 3: Design of Terminals** focuses on the hardware synthesis, detailing the architecture of the proposed terminal steering system.
- **Chapter 4: Experimental Setup** describes the laboratory environment, the components used, and the methodology employed.
- **Chapter 5: Multi-Beam Steering** presents the core research on multi-beam generation and steering using SLMs, including the results of the initial steering demonstrations.
- **Chapter 6: Multi-Beam Tracking Algorithm** details the mathematical formulation and implementation of the tracking algorithm, including its performance against noise and target motion.
- **Chapter 7: Conclusion** summarizes the key findings of the research and proposes avenues for future work.

1.3.3. RESEARCH CONTRIBUTIONS

This thesis has four core contributions:

1. **Architectural Analysis and Design:** A systematic investigation into various multi-beam steering architectures will be conducted. The goal is to evaluate the trade-offs between complexity, size, capacity and steering to determine the design selection flow down as a tool for future designers.
2. **Multi-Beam Steering and Hardware Implementation and Analysis via Spatial Light Modulators (SLMs):** This work will investigate the efficacy of SLMs as the primary mechanism for multi-beam steering. By leveraging the phase-modulation capabilities of SLMs, this thesis aims to demonstrate the ability to generate and steer multiple independent beams simultaneously within a compact hardware footprint. Furthermore, the concept phase ramp Fresnel

lens (PRFL) steering is shown, where diffraction and non-modulated beams can be filtered. Furthermore, it is shown that PRFL can focus individual beams onto image detectors. The aim is to do so using real hardware in order to accurately determine the effects of multi-beam steering and how to mitigate drawbacks such as diffraction.

3. **Investigation and Analysis of a Multi-Beam Tracking Algorithm:** To address the challenges of platform instability, noise and dynamically moving counter terminals, a novel tracking algorithm will be developed and thoroughly analyzed. This algorithm is designed to maintain tracking of multiple simultaneously moving beams while compensating for platform jitter, noise and the relative motion of targets, ensuring link persistence under operational conditions. To do so, it uses temporal tracking techniques in order to reduce the computational load of image processing.
4. **Experimental Validation and Prototyping:** The theoretical and algorithmic contributions will be validated through a combination of simulations and the construction of an experimental testbed. This will provide empirical evidence of the system's efficacy.

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2

MULTI-BEAM TERMINAL USE CASES

Many of the truths we cling to depend greatly on your point of view.

Obi-Wan Kenobi (Star Wars)

Multi-beam laser communication terminals (MBTs) are being considered for point-to-multi-point applications. However, little is known about the relationship between use cases and parameters such as the number of potential users, field of view (FoV), angular resolution, altitude ranges and FoV dwell time. This chapter aims to quantify the spatial and temporal constraints governing laser communication terminal deployment across orbital regimes. It will do so by examining space-to-ground, sea, air as well as inter-satellite and cross domain integrated networks. A 3,000 km terrestrial cross-section of Europe is taken, where target types and population numbers are approximated. Target visibility is evaluated through a range of FoVs from 4° up to 80° and orbit altitudes from 400 km (LEO) up to 35,786 km (GEO). Results show dwell times scale with FoV and orbital altitude: higher orbits yield longer visibility windows due to slower relative velocities and wider footprints, whereas lower orbits compress them. However, maintaining ground resolution places limits on the altitude. These bounds define feasible operational limits for MBTs, directly informing mission-specific design. Furthermore, it was found that for most use cases with a 4° FoV, 10–1,000 targets remain visible across all orbital altitudes. Dwell times range from 1–265 s, establishing quantitative benchmarks for subsequent design chapters.

2.1. INTRODUCTION

Optical communication networks yield lower latencies and higher capacities.[1] The primary advantages of optical communication compared to more traditional radio frequency communications (RF) stem from the 3 orders of magnitude reduced wavelength. Reducing the wavelength yields reduced beam divergence which in turn allows for decreased aperture/antenna sizes, more secure communication due to reduced eavesdropping, increased received signal and elimination of interference which, in combination with higher carrier frequencies, allows for near unlimited bandwidths.

However, decreased beam divergence is a double edged sword. One crucial drawback is that this limits single beam laser communication terminals (SBTs) to point-to-point communication.[1, 2] This implies two terminals are required for each active link, which in turn limits scalability. Additionally, optical wavelengths are easily blocked by obstacles and require direct line of sight during operation. As a result, frequent changes in network topologies and counter terminals through time consuming acquisition processes are needed.[3, 4, 5, 6]

Multi-beam laser communication terminals (MBTs) offer the ability to communicate with multiple other terminals simultaneously.[2, 7] This offers back-up links and active re-routing possibilities. Additionally, as a result of beams sharing hardware, MBTs offer potentially improved scalability.[8, 9, 10] Work has been performed on various ways by which size, weight and power (SWaP) can be reduced through design (which will be discussed extensively in Chapter 3)[2, 9]. Additionally, the tracking and steering challenges are the main focus of this dissertation.

The design of such terminals, and in particular the steering system, will be discussed in the rest of this thesis. Nevertheless, despite their theoretical promise, technical challenges remain in all aspects of the terminal design. The most often cited points of concern are the wide field of view (FoV) optics and steering system, in particular with regards to their feasibility.[9, 11, 12]

The fundamental limitation of current optical terminal designs lies in their inability to efficiently capture, track, and maintain simultaneous links across a wide spatial footprint. Existing literature within the field of free space optical communication (FSOC) mainly focuses on SBTs. SBTs communicate with one counter terminal (in this text also referred to as target or user), therefore requiring a narrow FoV (on the order of micro- and milli-radians). Going to wider FoVs while maintaining similar performance poses technical challenges.[11, 12, 13]

Nevertheless, wide FoV optics do exist. Notably, recent work by the German aerospace center (DLR) has yielded a design with an FoV of 4° for multi-beam laser communication from geostationary orbit (GEO).[11, 12] Additionally, designs in adjacent fields, such as Earth observation, also contain examples of wide FoV telescopes.[13] Looking further afield,

common camera lenses such as rectilinear and fish-eye lenses offer a nearly spherical FoV.[2, 14, 15] However, these have been designed with consumer imaging in mind. It is therefore unknown if these meet the requirements set by FSOC. Additionally, similarly to the projection challenges in map making, it is impossible to project a spherical FoV onto a flat image plane without distortion.

A potential solution to this would be non-(para)axial optics. These have also been considered through optical elements as well as active compensation (for example, using spatial light modulators (SLMs)) for optical distortion on a per-link basis (see Chapter 5) in previous MBT designs.[9, 16, 17, 18, 19] While it might be possible to move towards non-(para)axial optics in future, steering on its own poses significant challenges. One of the primary challenges when increasing the FoV is maintaining (angular) steering resolution. As the FoV increases, not only does the steering actuation range need to increase, the angular resolution should remain similar to those required for SBTs or a more divergent beam accepted.

Overcoming these FoV related technical challenges is coupled with extensive research efforts and uncertainty with regard to the outcomes. As a result of this, one of the most common questions encountered during discussions with industry and other researchers during this PhD project is that of added value, feasibility and justification of MBTs.

This thesis seeks to answer some of these concerns in later chapters. In this chapter, the added value and justification will be examined. It is currently unclear from literature how MBT design parameters and requirements relate to the use case. In particular, as of writing, it is currently unknown what the relation is between FoV size and resolution with regards to mission parameters (orbit altitude, number of users and data rate requirements) and use cases (inter-satellite, space-to-ground, space-to-sea, space-to-air and multi-domain integrated networks such as space, air, ground and sea integrated networks (SAGSINs)). Additionally, the dwell time, defined as the amount of time in which a user is within the FoV, is considered. Due to acquisition and communication occurring within this time frame, this parameter is of interest to quantify within the context of comparatively long and complex acquisition processes for laser communication terminals.[4]

As mentioned, to the best of our knowledge, no prior work has quantitatively linked terminal FoV sizing and the resulting addressable user population. Consequently, this chapter bridges that gap by estimating the operational impact and network utility of multi-beam laser terminals across three main use case areas: nadir (communication to users in space and the air as well as on the ground and sea), inter-satellite within constellations and SAGSINs.

For the nadir use cases, a range of altitudes are characterized. In particular, four distinct orbital altitudes will serve as examples within the text: low Earth orbit (LEO) (500 km), high LEO (2,500 km), medium Earth

orbit (MEO) (10,000 km), and geostationary Earth orbit (GEO) (35,786 km). The analysis evaluates nadir-directed operations targeting platforms, including satellites, commercial aircraft, cruise ships, cargo vessels, railway networks, and terrestrial telecommunications masts. Specifically, it models: the aggregate number of potential user terminals within a defined FoV; their transit times across the coverage footprint, the total addressable user population and the aggregate downlink data rate requirements.

This chapter also briefly discusses the results of a collaboration analyzing Sea-Air-Ground-Space Integrated Networks (SAGSINs), quantifying the performance gains enabled by multi-beam capabilities across six key network dimensions: reliability, latency, throughput, operational flexibility, reduced (re-)acquisition costs, and network component consolidation.

To do so, first this chapter will discuss the used methodologies, beginning with the geometry relations. There, the relations between the FoV, angular resolution, altitude, relative velocities, dwell time and signal path lengths will be analyzed. Subsequently, publicly available data will be used to obtain spatial user densities which will be related to the FoV to determine user numbers of the aforementioned user types. Lastly, inter-satellite communication within constellations will be analyzed as well. The methodology for the SAGSIN analysis will be mentioned in the results and discussion section for brevity.

Following this, the results will be discussed. In particular, operational envelopes are defined based on use cases, and performance improvements to networks are detailed.

Lastly, the conclusions from this chapter will be discussed and reflected upon. In addition to allowing better trade-offs for MBT research, development and application, the insights herein directly inform the subsequent chapters. The expected number of simultaneous beams, the required field of view geometry, dwell time within the FoV, and the terminal beam acquisition as well as loss rate, serve as explicit inputs for the high level terminal architecture design. Subsequently, our research into multi-beam steering and tracking is informed by this chapter.

2.2. METHODOLOGY

This section will discuss the used methodologies for determining the relations between use cases and operational performance.

Starting with the geometric analysis of the problem. Here the relations between the FoV, altitude, relative velocities, dwell time and signal path lengths will be analyzed with the purpose of determining the behavior of their relationships. Here, mostly analytical mathematical derivations will be used.

Next, publicly available data is analyzed to obtain spatial user densities. These will be used to determine the number of users within the FoV broken down by types.

The methodology for the SAGSIN analysis will be mentioned in the results and discussion section for brevity.

2.2.1. GEOMETRIC ANALYSIS

The relation between FoV, altitude, relative velocities, dwell time and signal path lengths can be determined through geometric analysis. There are three main geometric relations of interest within this chapter.

Firstly, the relation of FoV, angular resolution and altitude with cross distance and area. Cross distance in this case being the diameter of the covered area on the surface covered by the FoV. It can be found by projecting the FoV onto the Earth's surface (i.e. determining the portion of the Earth's surface which is visible by the MBT). From the perspective of the terminal, Earth's surface is convex and therefore curves away around the periphery of the FoV. Understanding the geometric would make it possible to determine the number of users. In addition, this will allow for dwell time analysis discussed later on when combined with the relative velocities.

Also of interest are the approximations for nadir projections, in particular planar and concave surface approximations for Earth. These methods are simpler have been observed to aid in back-of-the-envelope calculations. Analysis into the accuracy of these approximations would aid in the understanding of the merit of these projections.

Secondly, the relation of dwell time with relative velocity and FoV. The covered area, target density distribution and FoV determine how much time a counter terminal can be expected to be (dwell) within the FoV. Only during the FoV dwell time can both acquisition and communication occur. Knowing its duration is therefore important to take into account during a trade-off.

Lastly, the relation between along and cross track visibility of counter terminals with respect to FoV within satellite constellations. This provides an indication of utility of using MBTs for inter-satellite communication within LEO constellations.

SPHERICAL CONVEX SURFACE PROJECTIONS OF FOV

From the perspective of an MBT pointing directly towards nadir, the Earth's surface is approximated as a spherical convex surface. Here, the FoV originating from the MBT is projected onto the surface to determine the area and cross distance. This will later be used to analyze communication to LEO, ground, sea and air targets/users.

Illustrated in [Figure 2.1](#) is a schematic representation of the FoV with a spherical convex plane representing Earth's surface. Here, z is the

distance from the terminal to the surface at the angle θ and z_0 is the altitude from the surface. θ denotes an FoV angle from the terminal with θ_{FoV} and θ_{pix} are the FoV of the terminal and center pixel respectively. The cross distance of the FoV projections are denoted as s , s_{FoV} and s_{pix} respectively. The cross distances cast an angle with respect to the center, denoted as γ , where γ_{FoV} and γ_{pix} are the cross distance angles for the FoV and pixels respectively.

Additionally, atmospheric turbulence places a constraint on the elevation angle. The elevation angle in this case is the angle with respect to the vertical from the surface. This is hence the path angle of a beam through the atmosphere. This makes the elevation angle, denoted here as α , an important metric to consider for later analysis.

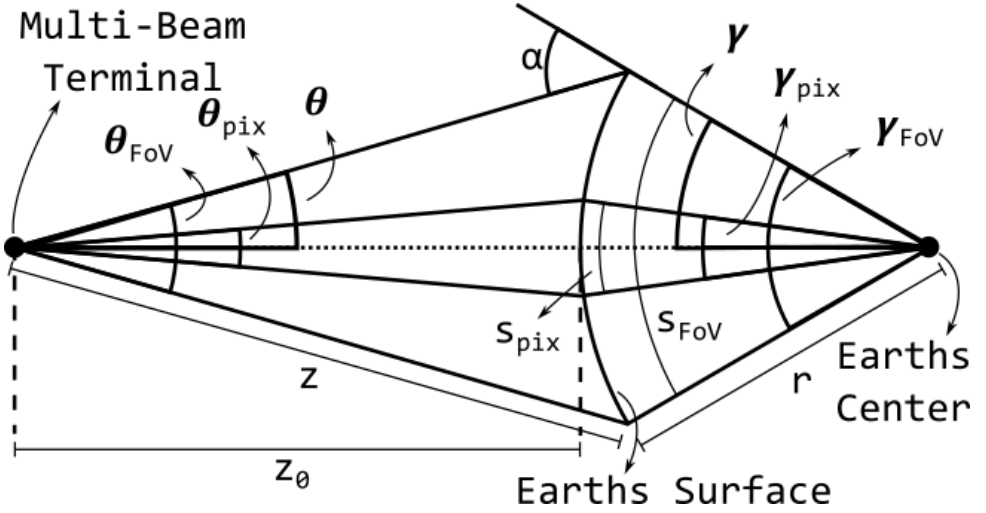


Figure 2.1.: Simplified convex projection of an MBT FoV directly nadir onto a sphere with radius r representing Earth surface.

The maximum elevation angle α is directly related to the FoV as shown in [Figure 2.2](#).

First, relating the elevation angle α with the angle from the terminal θ ,

$$(z + r) \sin \theta = r \sin \alpha \quad (2.1)$$

and re-arranging to find θ yields in,

$$\theta = \arcsin\left(\frac{r}{r+z} \sin \alpha\right), \alpha = \arcsin\left(\frac{r+z}{r} \sin \theta\right) \quad (2.2)$$

For the periphery, this implies,

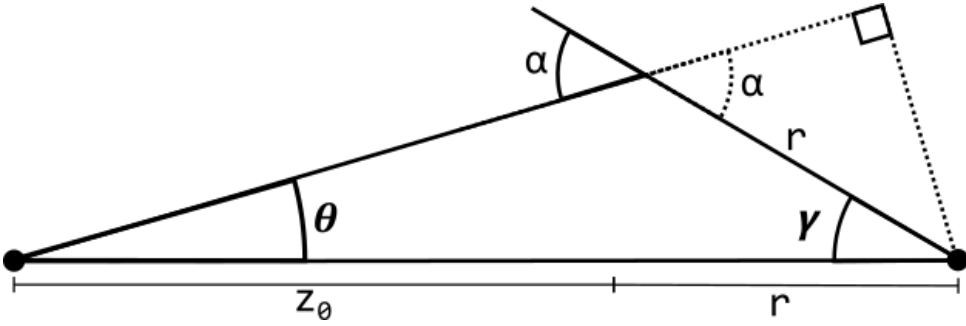


Figure 2.2.: Simplified from Figure 2.1, this figure shows the relation between elevation angle and the FoV.

$$\theta_{FoV} = 2 \arcsin\left(\frac{r}{r+d} \sin \alpha_{max}\right), \alpha_{max} = \arcsin\left(\frac{r+d}{r} \sin \theta_{FoV}\right) \quad (2.3)$$

These angles are also related to the cross distance angle γ through

$$\pi = \pi - \alpha + \theta + \gamma \rightarrow \alpha = \theta + \gamma \quad (2.4)$$

An increase in FoV yields a relatively larger increase in cross distance on the convex surface. This is due to the curvature of the surface away from the MBT. As a result, the ground resolution in the periphery is lower than in the center of the FoV. The peripheral case is illustrated in Figure 2.3. As a result, the peripheral pixel has a lower cross distance resolution compared to a pixel in the center of the FoV. The periphery is therefore the driver of resolution requirements.

This culminates in the limit case, where the FoV covers the maximum cross distance extent, as shown in Figure 2.4.

Where θ_{pixp} , γ_{pixp} and s_{pixp} are the angles and cross distances of a pixel in the peripheral respectively.

Determining the pixel cross section in the periphery is non-trivial. Instead, an approach was taken to relate the cross distance to the slope change of the convex surface in the periphery. First, it is assumed that the pixels and their FoV are small compared with the overall FoV. Second, it is assumed that for these small angular changes in FoV, the cross distance change is linear. Lastly, it is assumed that the pixels divide the FoV evenly (i.e. $\theta_{pixp} = \theta_{pix}$).

Using these assumptions, the cross distance in the periphery is,

$$s_{pixp} = r\gamma_{pixp} = r \left[\frac{\partial \gamma}{\partial \theta} \Big|_{\theta=\theta_{FoV}/2} \right] \theta_{pixp} \quad (2.5)$$

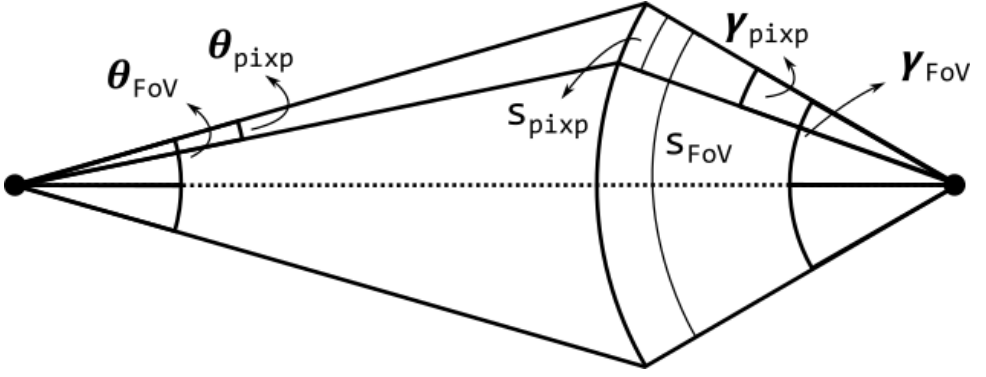


Figure 2.3.: The peripheral case for convex surface projection as simplified from Figure 2.1.

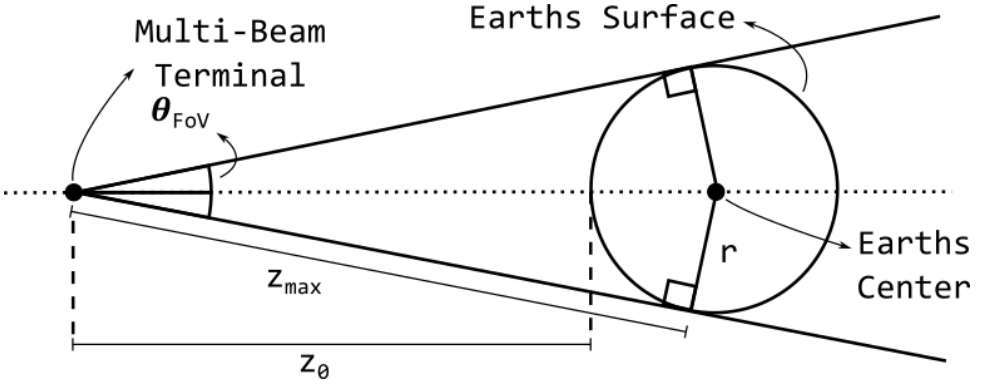


Figure 2.4.: The limit of the convex case.

Knowing the cross distances to the center of the sphere to be,

$$S_{FoV} = r\gamma_{FoV}, S_{pixp} = r\gamma_{pixp} \quad (2.6)$$

Defining the same distance of the projection onto the surface and relating to the angle θ :

$$z \sin(\theta) = r \sin(\gamma), \quad z = \sqrt{(z_0 + r(1 - \cos(\gamma)))^2 + (r \sin(\gamma))^2} \quad (2.7)$$

$$\theta = \arcsin\left(\frac{r \sin(\gamma)}{\sqrt{(z_0 + r(1 - \cos(\gamma)))^2 + (r \sin(\gamma))^2}}\right) = \arcsin\left(\frac{U}{V}\right) \quad (2.8)$$

This expression can be differentiated through differentiation by parts:

$$\frac{\partial \theta}{\partial \gamma} = \frac{\partial \arcsin(\frac{U}{V})}{\partial \gamma} = \frac{\partial \arcsin(\frac{U}{V})}{\partial \frac{U}{V}} \left(\frac{\partial U}{\partial \gamma} \frac{1}{V} + U \frac{\partial \frac{1}{V}}{\partial \gamma} \right) \quad (2.9)$$

$$\frac{\partial \arcsin(\frac{U}{V})}{\partial \frac{U}{V}} = \frac{1}{\sqrt{1 - (\frac{U}{V})^2}}, \quad \frac{\partial U}{\partial \gamma} = r \cos(\gamma) \quad (2.10)$$

$$V = \sqrt{(z_0 + r(1 - \cos(\gamma)))^2 + (r \sin(\gamma))^2} \quad (2.11)$$

$$= \sqrt{z_0^2 + 2z_0r + 2r^2 - 2d_0r \cos(\gamma) - 2r^2 \cos(\gamma)} \quad (2.12)$$

$$\frac{\partial \frac{1}{V}}{\partial \gamma} = \frac{1}{2} \frac{1}{(V^2)^{3/2}} (2z_0r \sin(\gamma) + 2r^2 \sin(\gamma)) \quad (2.13)$$

$$\frac{\partial \theta}{\partial \gamma} = \frac{1}{\sqrt{1 - (\frac{U}{V})^2}} \left(r \cos(\gamma) \frac{1}{V} + U \frac{1}{2} \frac{1}{(V^2)^{3/2}} (2z_0r \sin(\gamma) + 2r^2 \sin(\gamma)) \right) \quad (2.14)$$

This equation can then be applied to find the periphery pixel using Equation (2.5), and yields:

$$s_{pixp} = r\gamma_{pixp} = r \left[\frac{\partial \gamma}{\partial \theta} \Big|_{\theta=\theta_{FoV}/2} \right] \theta_{pixp} \quad (2.15)$$

$$= r \left(\frac{1}{\sqrt{1 - (\frac{U}{V})^2}} \left(r \cos(\gamma) \frac{1}{V} + U \frac{1}{2} \frac{1}{(V^2)^{3/2}} (2z_0r \sin(\gamma) + 2r^2 \sin(\gamma)) \right) \right)^{-1} \theta_{pixp} \quad (2.16)$$

In the limiting case shown in Figure 2.4, the expressions can be further simplified by using right-angled triangle identities:

$$z_{max} = (z_0 + r) \cos(\theta_{FoV}) \quad \text{and} \quad (z_0 + r)^2 = z_{max}^2 + r^2 \quad (2.17)$$

$$(z_0 + r)^2 = ((z_0 + r) \cos(\theta_{FoV}))^2 + r^2 \quad (2.18)$$

$$\theta_{FoV} = \arccos \left(\frac{\sqrt{(z_0 + r)^2 - r^2}}{z_0 + r} \right) \quad (2.19)$$

In the reverse case:

$$z \sin(\theta_{FoV}) = r \sin(\gamma_{FoV}) \rightarrow \gamma_{FoV} = \arcsin \left(\frac{z}{r} \sin \theta_{FoV} \right) \quad (2.20)$$

$$s_{FoV} = r\gamma_{FoV} = r \arcsin \left(\frac{z}{r} \sin \theta_{FoV} \right) \quad (2.21)$$

FLAT SURFACE PROJECTION

The flat surface projection can be useful in multiple aspects. It is sometimes used during back-of-the-envelope calculations and serves well for small angles (the size of this angle will be analyzed later in this chapter). In addition, this approach can be used for use cases that have targets arranged on a plane or a line, such as adjacent satellites in constellations. Lastly, the receivers in MBTs can be arranged on a plane, making this projection relevant for comparing target and receiver side steering performances.

Illustrated in Figure 2.5 is a schematic representation of the terminal FoV and a pixel projected onto a plane representing the Earth's surface in this case. Here, z is the distance from the terminal to the plane under the angle θ and z_0 is the altitude. θ denotes an FoV angle from the terminal with θ_{FoV} and θ_{pix} denoting the FoV of the terminal and pixel angles respectively. The cross distance of the FoV projections are denoted as s , s_{FoV} and s_{pix} respectively.

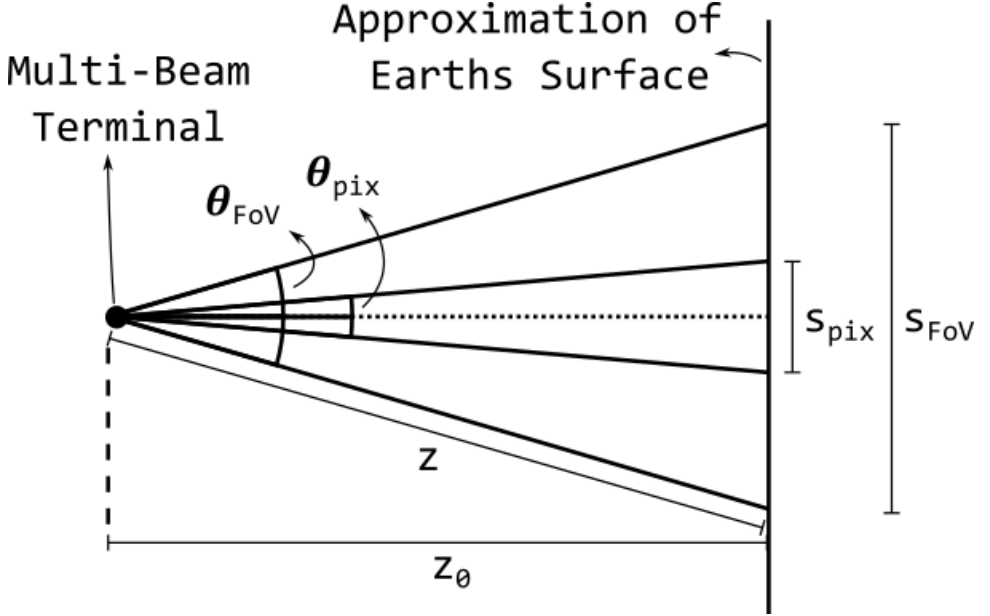


Figure 2.5.: Simplified flat surface projection definitions.

Assuming the FoV is evenly subdivided by pixels, the relation of the FoV with respect to the swath width is,

$$\theta_{FoV} = 2 \arctan\left(\frac{s_{FoV}}{2z}\right), s_{FoV} = 2z \arctan\left(\frac{\theta_{FoV}}{2}\right). \quad (2.22)$$

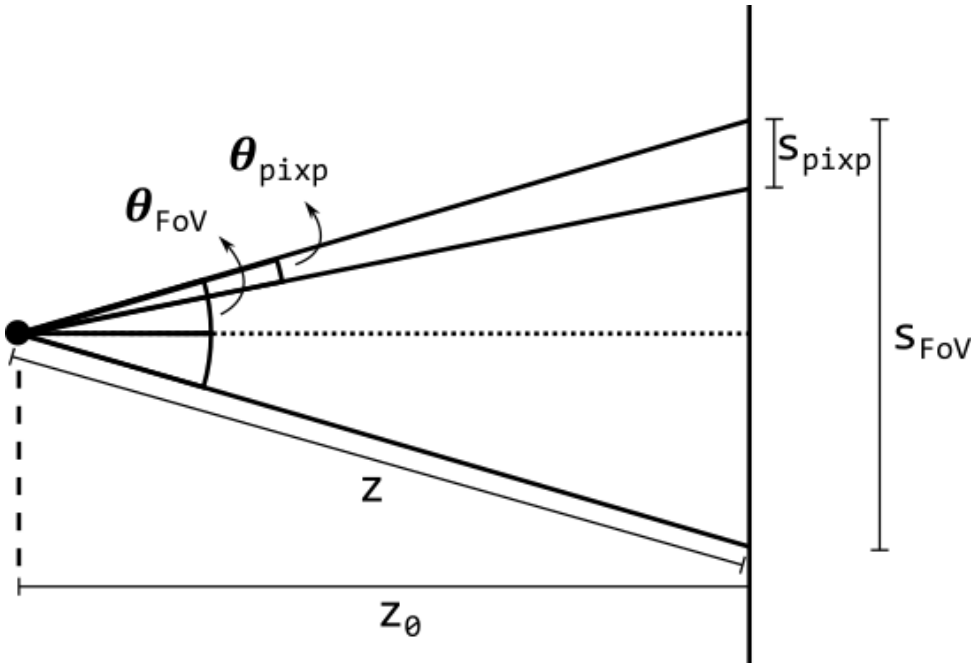


Figure 2.6.: Peripheral case for plane surface projection.

In the same way, the pixel cross distance is

$$s_{pix} = 2z \tan\left(\frac{\theta_{pix}}{2}\right) = 2z \tan\left(\frac{\theta_{FoV}}{2N_{pix}}\right). \quad (2.23)$$

In the periphery of the FoV, shown in Figure 2.6, a similar change in FoV yields a comparatively larger change in the cross distance compared to the center of the FoV. As a result, the resolution requirements would be driven by the periphery. The resolutions can be expressed as

$$s_{pixp} = z \left(\tan\left(\frac{\theta_{FoV}}{2}\right) - \tan\left(\frac{\theta_{FoV}}{2} - \theta_{pixp}\right) \right). \quad (2.24)$$

Re-arranging to make θ_{pix} the subject of the equation yields:

$$\theta_{pixp} = \frac{\theta_{FoV}}{2} - \arctan\left(\tan\left(\frac{\theta_{FoV}}{2}\right) - \frac{s_{pixp}}{z}\right) \quad (2.25)$$

CONCAVE SURFACE PROJECTION

The concave projection can be useful in small angle approximations, when targets/users are bound by a concave spherical surface as well

as when the target/users are angularly distributed within the FoV instead of on a defined surface. For example, in sea-air-ground-space integrated networks (SAGSINs), counter terminals can be at any distance at any time within the FoV. As a result, an angular density and a design distance can be selected and used for analysis instead. Additionally, under small enough angles it can be used as an approximation for Earth's surface. The size of this small angle will be determined later.

Illustrated in Figure 2.7 is a schematic representation of the FoV with a concave projected FoV. Here, z_0 is the distance from the terminal to the concave surface/plane, θ denotes an FoV angle from the terminal with θ_{FoV} and θ_{pix} are the FoV of the terminal and pixel respectively. The cross distance of the FoV projections are denoted as s , s_{FoV} and s_{pix} respectively.

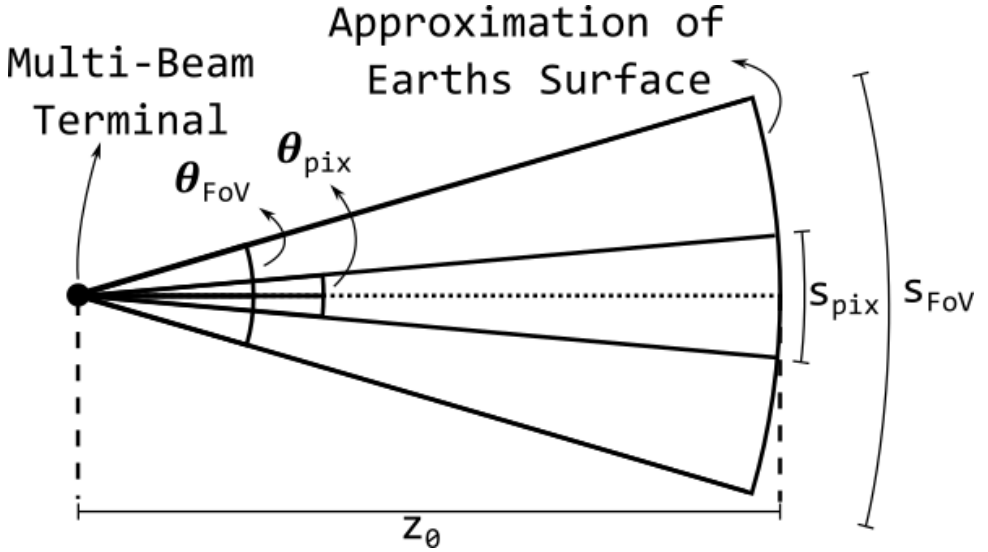


Figure 2.7.: Simplified concave projection of the terminal FoV at the radial center of a spherical surface with uniform radius z_0 .

Using arc formulas:

$$s_{FoV} = \theta_{FoV} z_0, s_{pix} = \theta_{pix} z_0 \quad (2.26)$$

The number of pixels can be related as follows:

$$N_{pix} = \frac{\theta_{FoV}}{\theta_{pix}} = \frac{s_{FoV}}{s_{pix}} \quad (2.27)$$

In this case, the peripheral resolution is no different from the central resolution.

RELATIVE VELOCITIES AND TIME IN FIELD OF VIEW

The relative velocities of the MBT FoV combined with the FoV can be used to determine the time spent within the FoV for an average target. This is an important parameter in determining the rate of acquisitions, time spent communicating and handovers. Here, an estimate is used to indicate a value for different orbit regimes and FoVs.

Assuming a uniform spatial density of targets with equal relative velocities, it can be assumed that targets enter the FoV at any random point and transit in a straight line. Assuming the FoV is circular, this is schematically shown in [Figure 2.8](#).

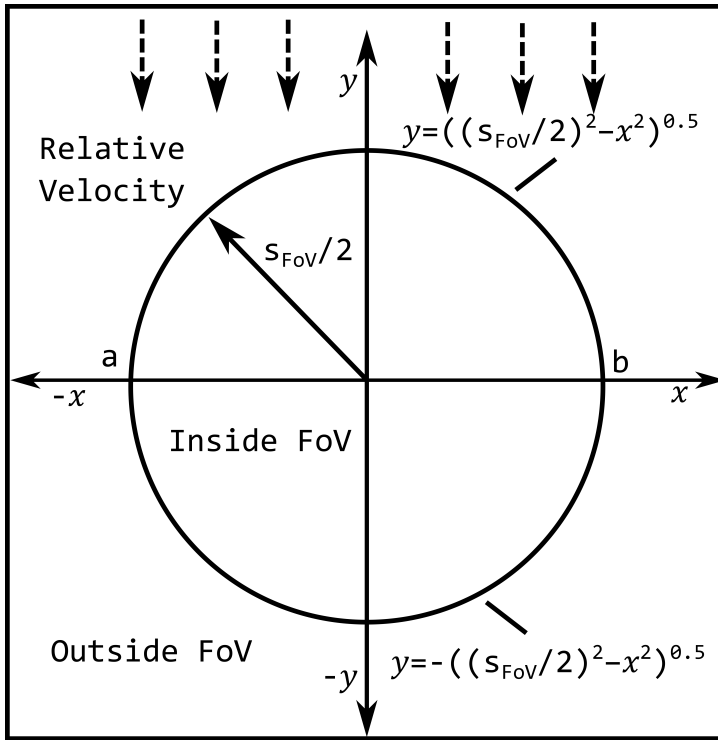


Figure 2.8.: Illustration of the field of view (FoV) moving relative to the targets/counter terminals. Assumed is a circular FoV.

Targets traveling to the far left or right of the FoV spend less time within the FoV than those with paths closer through the center. The average time spent in the FoV therefore depends on the average distance traveled through the FoV. The FoV can be expressed as two semi-circles on an $x-y$ plane,

$$y = \begin{cases} \sqrt{r^2 - x^2}, & \text{for } y \geq 0 \\ -\sqrt{r^2 - x^2}, & \text{for } y < 0 \end{cases} \quad (2.28)$$

with r being the radius of the FoV. The average distance traversed in the FoV as a function of the shape can be expressed as

$$y_{av} = \frac{\sum y(n)}{\sum n} = \frac{\sum y(x)dx}{\sum ndx} = \frac{1}{b-a} \int_a^b y(x)dx \quad (2.29)$$

with y_{av} the average distance, n the number of tracks, a and b being the limits of integration. Taking the limits of integration from [Figure 2.8](#) over both semi-circles yields

$$\begin{aligned} y_{av} &= \frac{2}{S_{FoV} - (-S_{FoV})} \int_{-S_{FoV}/2}^{S_{FoV}/2} \sqrt{(S_{FoV}/2)^2 - x^2} - (-\sqrt{(S_{FoV}/2)^2 - x^2}) dx \\ &= \frac{2}{S_{FoV}} \int_{-S_{FoV}/2}^{S_{FoV}/2} \sqrt{(S_{FoV}/2)^2 - x^2} dx \\ &= \frac{2}{S_{FoV}} \frac{\pi (S_{FoV}/2)^2}{2} \\ &= \frac{\pi}{4} S_{FoV}. \end{aligned} \quad (2.30)$$

The relative velocities between the projected FoV and the targets are estimated by subtracting the orbit velocity and adjusting for Earth's rotation for a particular latitude as follows:

$$V_{rel} = |\vec{V}_{orbit} + \vec{V}_{Earth} + \vec{V}_{target}| \quad (2.31)$$

where V_{rel} is the relative velocity of the FoV with respect to the targets, $\vec{V}_{orbit}$ is the orbit velocity, $\vec{V}_{Earth}$ is the velocity component due to Earth's rotation and $\vec{V}_{target}$ is the velocity of the target relative to Earth's surface. The orbits are assumed circular and the relative velocity is assumed to remain constant throughout the transit across the FoV. This is an approximation, it should be noted that particularly for larger FoVs and/or high latitudes this approximation is less accurate. More accurate models are recommended for future research. The orbital velocities were found using

$$|\vec{V}_{orbit}| = \sqrt{\frac{\mu}{r_{orbit}}} \quad (2.32)$$

where r_{orbit} is the radius of the orbit, μ the gravitational parameter and $\bar{V}_{orbit}$ the orbit velocity. Using Equation (2.30) and inserting the cross distance of the FoV, S_{FoV} , the dwell time t_D can be approximated as

$$t_D = \frac{\pi S_{FoV}}{4 V_{rel}} \quad (2.33)$$

The dwell time can also be related to the FoV and altitude directly through the cross distance. Inserting Equation (2.21) into Equation (2.33) yields:

$$t_D = \frac{\pi r}{4 V_{rel}} \arcsin\left(\frac{Z}{r} \sin \theta_{FoV}\right) \quad (2.34)$$

2.2.2. POTENTIAL USER POPULATION DENSITIES

The population density of potential users is a metric which can help determine the MBT design. It can yield a design range of users and also help determine data demands. Here, there are broadly three use cases discussed: terrestrial users for nadir operation, high-to-low orbit space-to-space communication and inter-satellite communication within a constellation.

POPULATION DENSITY OF TERRESTRIAL TARGET/USER TYPES AND DATA RATE

To assess the number of potential users, first it is necessary to evaluate the number of the potential users by type. Five types were selected: commercial aircraft, cruise ships, cargo ships, trains and telecommunication towers. These were chosen to give a variety. A region analogous to Europe for ground based communications or the North Atlantic for air and sea based vehicles, each spanning a 3,000 km Earth-cross distance was selected.

Aircraft were chosen due to their mobility and remoteness, making data a high demand resource with their occupants. The number of passengers and crew an aircraft can carry varies. However, an average of 200 people was assumed. An estimate of the number of aircraft was difficult to find, however it is estimated around 100 aircraft can be airborne over Europe or the North Atlantic at any given time.[20, 21, 22]

In contrast, cruise ships carry more passengers but are less numerous. As a result, data demands will be higher per vehicle/link while at the same time the number of links are reduced due to their lower density. It was assumed that each ship on average can carry 3,000 people and that there are 10 cruise ships within the area of interest.[23, 24, 25, 26, 27]

Cargo ships are more numerous than cruise ships and hence have higher density. However, because they carry only a small crew (estimated at around 30), they require a lower data rate.[28, 29, 30]

Trains are also mobile. Some trains carry 3,000 or more passengers depending on the length of the train and the time of day. Nevertheless, 400 passengers is the assumed occupancy. It is important to note that in the case of trains, their proximity to land-based data services could be a substantial source of competition.[31, 32]

The last type considered is telecommunication towers. Although these are static and often used in situations with physical data infrastructure, supplementation and further expansion of the tower networks could be aided with data links from space. In this comparison, it is assumed that each person in Europe (450 million people) is on the network with four devices connected simultaneously to 600,000 telecommunication towers[33], yielding 3000 devices per tower on average.

Figure 2.9 shows an overview of the number of vehicles and communication towers. This visualization serves to quantify the number of each type for each target class, illustrating not just the number of physical nodes, but the aggregate number of end-users they serve. This establishes a baseline of high demand, suggesting that even a fraction of these targets could support a robust network.

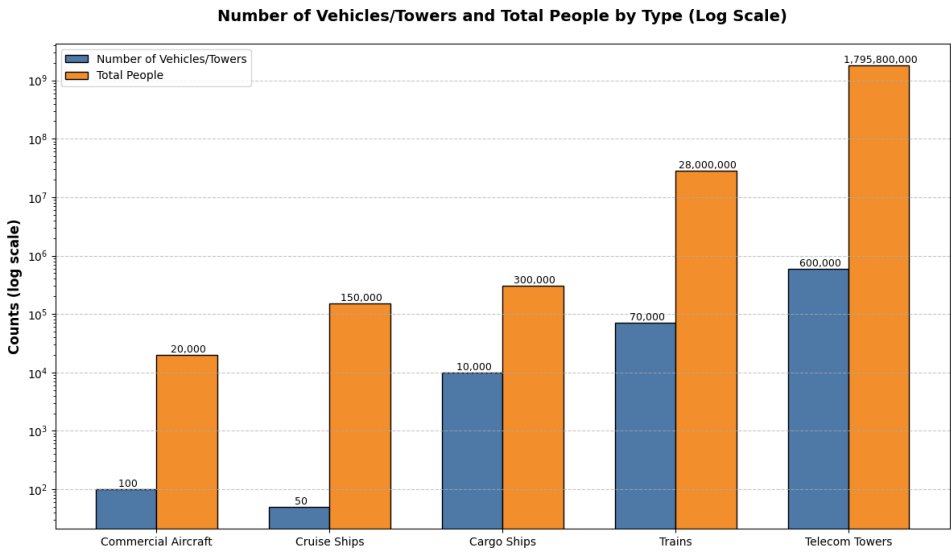


Figure 2.9.: Shown is a log plot of the number of each type of vehicle/tower and the total number of people that consume data.[20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33]

DATA RATES AND LINK BUDGET ESTIMATES

From Figure 2.9, an estimation can be made as to the data rate required for a link with one of these types. A use case scenario was envisaged where the average number of users were multiplied with a data rate of 10 Gb/hr (2.8 Mb/s). This data rate would allow simultaneous 4k video streaming together with a live video call. The results of this are shown in Figure 2.10.

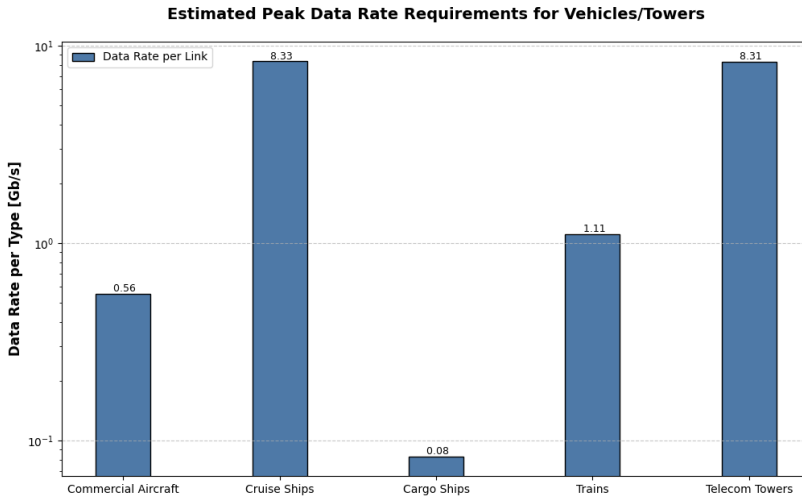


Figure 2.10.: Estimated data rate requirements based on the number of users per vehicle/tower (shown in Figure 2.9) multiplied with the data rate needed to stream video in 4k and maintain a video call (10 Gb/hr).

MBTs technology readiness levels (TRL) is as of writing are low and the specific future implementation of MBTs and SBTs at this scale is unclear. Additionally, the specifications of the counter terminals are also unknown. Furthermore, this thesis focuses on multi-beam steering systems, leaving crucial details such as telescope and transceiver design out of the scope. This makes accurate estimates on quality of service (QoS) and link budgets beyond the scope of the thesis.

Nevertheless, it can be useful to make a rough estimate in order to highlight the differences between orbit regimes per link. To estimate the link budget, a simplified model was used. The received optical power is computed as a power balance between the transmitted power and the cumulative gain and loss terms, expressed in decibels:

$$P_{Rx} [\text{dBm}] = P_{Tx} [\text{dBm}] + G_{Tx} + G_{Rx} + L_{tot}, \quad (2.35)$$

where all gain and loss terms below are in dB (losses are negative). The link margin follows as

$$M = P_{Rx} - P_{Rx,th}, \quad (2.36)$$

with $P_{Rx,th}$ the receiver power threshold, i.e. the minimum received optical power required for detection.

The transmitter antenna gain for a beam of full divergence angle θ_{div} is

$$G_{Tx} = 10 \log_{10} \left(\frac{8}{\theta_{div}^2} \right), \quad (2.37)$$

and the beam waist relates to the divergence as $w_0 = \lambda/(\pi\theta_{div})$, with λ the wavelength. Transmitter losses comprise the optical transmission t_{Tx} and a wavefront-error (WFE) loss

$$L_{WFE,Tx} = 10 \log_{10} \left(e^{-\sigma_{Tx}^2} \right), \quad \sigma_{Tx} = \frac{2\pi}{\lambda} \text{WFE}_{Tx}. \quad (2.38)$$

Free-space path loss over link length L and atmospheric transmission t_{atm} contribute

$$L_{FS} = 10 \log_{10} \left(\frac{\lambda}{4\pi L} \right)^2, \quad L_{atm} = 10 \log_{10}(t_{atm}). \quad (2.39)$$

A static pointing error θ_{PE} and a random pointing jitter with standard deviation θ_{PJ} cause losses

$$L_{PE} = 10 \log_{10} \left(e^{-2\theta_{PE}^2/\theta_{div}^2} \right), \quad (2.40)$$

$$L_{PJ} = 10 \log_{10} \left(p_{out}^{4\theta_{PJ}^2/\theta_{div}^2} \right) - 10 \log_{10} \left(\frac{\theta_{div}^2}{\theta_{div}^2 + 4\theta_{PJ}^2} \right), \quad (2.41)$$

where p_{out} is the allowed pointing-outage probability. Scintillation loss depends on the aperture-averaged scintillation index $\overline{\sigma_I^2} = A\sigma_I^2$, where the aperture averaging factor for receiver diameter d_{Rx} and speckle propagation length L_{AA} is

$$A = \left[1 + 1.07 \left(\frac{k d_{Rx}^2}{4L_{AA}} \right)^{7/6} \right]^{-1}, \quad k = \frac{2\pi}{\lambda}. \quad (2.42)$$

$$L_{sc} = (3.3 - 5.77 \sqrt{-\ln p_{out}}) \overline{\sigma_I^2}^{2/5} \quad (2.43)$$

Boresight (beam wander) loss with transmitter aperture D_0 and upper Fried parameter $r_{0,up}$ is

$$L_{BS} = 10 \log_{10} (1 + (D_0/r_{0,up})^2)^{-6/5}, \quad (2.44)$$

and the receiver WFE loss, dominated by turbulence-induced phase variance over Fried parameter r_0 , is

$$L_{WFE,Rx} = 10 \log_{10} (\eta_{nom} e^{-\sigma_{WFE}^2}), \quad (2.45)$$

$$\sigma_{WFE}^2 = \begin{cases} 0.134 (d_{Rx}/r_0)^{5/3} + (2\pi WFE_{Rx}/\lambda)^2 & \text{tip-tilt corrected,} \\ 1.0299 (d_{Rx}/r_0)^{5/3} + (2\pi WFE_{Rx}/\lambda)^2 & \text{uncorrected.} \end{cases} \quad (2.46)$$

with η_{nom} the nominal efficiency of the optics. The receiver aperture gain and optical transmission loss are

$$G_{Rx} = 10 \log_{10} \left(\frac{\pi d_{Rx}}{\lambda} \right)^2, \quad L_{Rx} = 10 \log_{10} (t_{Rx}). \quad (2.47)$$

The required transmit power follows from the receiver power threshold $P_{Rx,th}$ and the total link loss L_{tot} (sum of all terms above):

$$P_{Tx,req} = P_{Rx,th} \cdot 10^{-L_{tot}/10}. \quad (2.48)$$

In order to estimate a link budget, ball park values were taken that fell within the range of link budgets in literature. For the wavelength, 1550 nm has been selected. This is the most common wavelength used in optical communications and it benefits from mature telecom components. This wavelength has also been used in multiple link budgets found in literature.[34, 35, 36, 37, 38]

Aperture sizes in literature vary more widely. Aperture sizes of 0.2 to 0.4 m for the ground terminal and 0.1 to 0.15 m for the space segment are used in the up link budgets of Toyoshima et al.[35], while Saathof et al.[36] assume 0.3 m transmit and 0.4 m receive apertures. Considering the data rates involved and the current technological challenges facing wide FoV telescopes, a 0.1 m aperture was selected for the space segment. For the terrestrial and air segments, 0.25 m apertures were taken.

For on-off keying (OOK) at 10 Gbps, a receiver sensitivity of -35.5 dBm at a bit error rate of 10^{-12} is used by Liang et al.[37], whereas Saathof et al.[36] assume a threshold of -45.3 dBm at a pre-forward error correction (FEC) bit error rate of 10^{-3} . The receiver power threshold of -35.5 dBm was taken in order to be at the conservative end of this

range, in addition to the data rates being more similar compared to Liang et al.[37] Similarly, the fixed link margin of 6 dB used in this work lies between the respective 3 dB and 8 dB margins of Liang et al. and Saathof et al.[36, 37]

Atmospheric attenuation mentioned by Saathof et al.[36] and Liang et al.[37] were -0.4 dB and -0.48 dB respectively. The latter being at 40° elevation. Toyoshima et al. reports a -1.72 dB loss at 48° elevation. In addition, other sources use additional losses to encapsulate cloud losses and other atmospheric phenomena.[34, 36] An atmospheric transmission efficiency of 0.6 (-2.2 dB) is therefore selected to be on the more conservative side.

Based on measurements from SOTA (Small Optical Transponder) experiments, Toyoshima et al.[35] designed the atmospheric coherence length to be about 21.4 cm at 1550 nm using the standard Hufnagel-Valley (HV) profile (with $A = 1.7 \times 10^{-14} \text{ m}^{-2/3}$ and wind speed 21 m/s, the same daytime HV parameters adopted by Barrios et al.[34]), and yields $r_0 = 20$ cm used in this model. For the scintillation index, Saathof et al.[36] reports aperture-averaged downlink values of 0.001-0.037 and longitudinal uplink values up to 0.219 (best/median/worst turbulence conditions), which brackets the $\sigma_I^2 = 0.25$ used here.

The pointing and wavefront loss terms are expressed as Strehl-ratio-type factors, $\text{SR} \approx [1 + (d/r_0)^{5/3}]^{-6/5}$, following Stotts et al.[38] This was validated against in-field measurements, including the residual phase variance reduction achieved with tip-tilt and higher-order adaptive optics correction. The outage probability of $p_{\text{out}} = 0.001$ matches those mentioned by Toyoshima et al.[35] (fade and surge levels at $P < 10^{-3}$) and the scintillation loss calculation with log-normal statistics at outage 0.001 in Saathof et al.[36]

Beam divergences mentioned by Barrios et al.[34], range between 5.67 and 13.93 μrad . Liang et al.[37] mentions a beam divergence on the upper end of this range. Due to the influence of this parameter, it was decided to evaluate for both 5 and 15 μrad .

All these parameters have been summarized in Table 2.1. The link budget model was subsequently evaluated for multiple ranges based on the main altitudes considered in this chapter. The results of these evaluations can be found in Table 2.2.

Table 2.1.: Link budget parameters.

Parameter	Sat-to-Ground	Ground-to-Sat
Wavelength λ (nm)	1550	1550
Rx power threshold $P_{RX,th}$ (dBm)	-35.5	-35.5
Tx aperture D_0 (m)	0.10	0.25
Tx transmission t_{Tx}	0.60	0.60
Tx wavefront error WFE_{Tx} (nm)	0	0
Other transmission efficiencies t_{other}	1.00	1.00
Atmospheric transmission t_{atm}	0.60	0.60
Pointing outage probability p_{out}	0.001	0.001
Static pointing error θ_{PE} (μ rad)	0	0
Scintillation index σ_I^2	0.25	0.25
Upper Fried parameter $r_{0,up}$ (m)	10.0	10.0
Fried parameter r_0 (m)	0.20	0.20
Tip-tilt correction	on	on
Nominal efficiency η_{nom}	0.80	0.80
Speckle propagation length L_{AA} (km)	10	10
Rx aperture d_{Rx} (m)	0.25	0.10
Rx transmission t_{Rx}	0.60	0.60
Rx wavefront error WFE_{Rx} (nm)	0	0
Number of AO elements N_{AO}	0	0

It is clear from Table 2.2 that higher altitudes require higher transmit powers, even beyond 1 kW per beam in some GEO cases. From the perspective of the multi-beam steering system, it is important for the system to be able to handle such high optical intensities. Furthermore, when considering optical amplification, the thermal and power supply considerations for the spacecraft platform have strong influence on the spacecraft design as a whole. These factors in turn can limit the number of transmitted beams which can be accommodated or their associated performance. This is particularly true for GEO applications. At lower altitudes, optical power requirements decrease substantially.

Nevertheless, it must be highlighted that this exercise is highly dependent on the telescope and transmitter designs, in addition to the steering system. If the detector sensitivity is increased to that used by Saathof et al.[36] and aperture diameters are used as those presented by Levenstein et al., Saathof et al. and Liang et. al[39], these values can decrease substantially. Additionally, when multiple SBTs are used, the thermal and power loads are potentially more spread out across the system. However, remains at similar total levels for an equivalent number of beams. More study is needed to determine if the potential SWaP improvements of MBTs on the terminal level outweigh the SWaP changes on the spacecraft level as a whole.

Table 2.2.: Link budget summary for satellite-ground communication.

Scenario	Range	Divergence	Tx Power (6 dB Margin)	Min Tx Power
Sat-to-Ground	500 km	5 μ rad	0.008 85 W	0.002 22 W
	500 km	15 μ rad	0.0796 W	0.02 W
	1000 km	5 μ rad	0.0354 W	0.008 89 W
	1000 km	15 μ rad	0.319 W	0.08 W
	2500 km	5 μ rad	0.221 W	0.0556 W
	2500 km	15 μ rad	1.99 W	0.5 W
	5000 km	5 μ rad	0.885 W	0.222 W
	5000 km	15 μ rad	7.96 W	2 W
	10 000 km	5 μ rad	3.54 W	0.889 W
	10 000 km	15 μ rad	31.9 W	8 W
	35 786 km	5 μ rad	45.3 W	11.4 W
	35 786 km	15 μ rad	408 W	102 W
Ground-to-Sat	500 km	5 μ rad	0.0824 W	0.0207 W
	500 km	15 μ rad	0.741 W	0.186 W
	1000 km	5 μ rad	0.329 W	0.0828 W
	1000 km	15 μ rad	2.96 W	0.745 W
	2500 km	5 μ rad	2.06 W	0.517 W
	2500 km	15 μ rad	18.5 W	4.65 W
	5000 km	5 μ rad	8.24 W	2.07 W
	5000 km	15 μ rad	74.1 W	18.6 W
	10 000 km	5 μ rad	32.9 W	8.28 W
	10 000 km	15 μ rad	296 W	74.5 W
	35 786 km	5 μ rad	422 W	106 W
	35 786 km	15 μ rad	3.8×10^3 W	954 W

It can however, be safely concluded that when total optical power is the constraining factor, lower altitudes would be more favorable for the same number of beams.

POPULATION DENSITY OF CONSTELLATIONS FOR HIGH-TO-LOW ORBIT SPACE-TO-SPACE COMMUNICATION

For high to low orbit communication, where higher orbiting satellites are communicating with lower orbiting satellites directly below them, mega constellations are considered the users in this chapter. There are a number of mega constellations proposed similar to Starlink.[40, 41] Starlink is projected to have 10,000 satellites in LEO. The area of Europe is around 2% that of the Earth's surface.[40, 41] As a result, there are approximately 200 satellites which are in orbit over Europe at any given time.

POPULATION DENSITY OF CONSTELLATIONS FOR INTER-SATELLITE COMMUNICATIONS

Along track communication occurs when the satellite communicates to other satellites in front/behind it that are also in the same orbit plane. The number of satellites in the along track FoV depends on the FoV of the terminal and the population density of the orbits.

An illustration of the geometry is shown in Figure 2.11, where z_{max} is the distance from the center of the Earth to the satellite, r , the radius of the Earth, β_{FoV} the cross track angle of the FoV and θ_{FoV} the FoV.

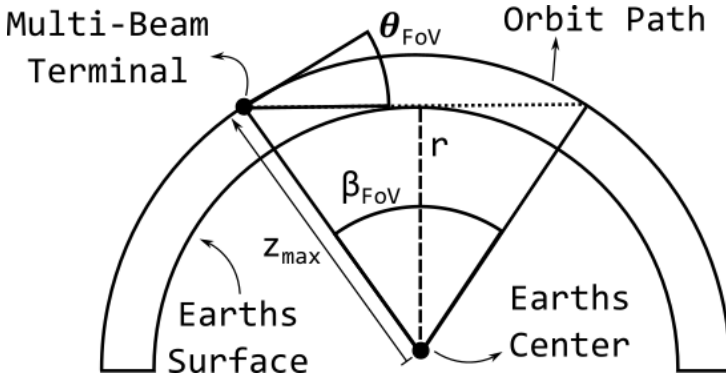


Figure 2.11.: Along track field of view (FoV) in relation to the Earth and minimum clearance altitude.

The relation between the field of view and the cross track angle is,

$$\theta_{FoV} = \frac{\pi}{2} - \frac{\pi - \beta_{FoV}}{2} = \frac{\beta_{FoV}}{2} \quad (2.49)$$

The largest usable FoV for along track communications before the Earth's horizon is blocked,

$$r = z_{max} \cos\left(\frac{\beta_{FoV}}{2}\right) = z_{max} \cos(\theta_{FoV}) \quad (2.50)$$

which determines the maximum FoV,

$$\theta_{FoVmax} = \arccos\left(\frac{r}{z_{max}}\right) \quad (2.51)$$

2.3. RESULTS AND DISCUSSION

This section presents and discusses the results obtained by applying the methodology described above. First the results of the geometric analysis will be presented, starting with the evaluation and comparison of the

projection methods. Here FoV as well as angular resolution are shown and compared for different orbit altitudes. After this the dwell time for different altitudes will be discussed. The combination of these geometric analyses together with an example will be used to define an operational altitude range where the MBTs can feasibly operate.

After the results of the geometric analysis, the number of potential users will be evaluated. This will be done using two examples using the state-of-the-art wide FoV telescope developed by DLR[11, 12] for laser communication with a FoV of 4° . These will also be evaluated at different altitudes. Additionally, this is compared to the limit case set by turbulence.

Subsequently, inter-satellite communication within the constellation will be briefly evaluated and discussed. Then the results of the SAGSIN networks will be briefly discussed.

2.3.1. RESULTS OF THE GEOMETRIC ANALYSIS AND FEASIBLE MULTI-BEAM TERMINAL ALTITUDE RANGES FOR OPERATIONS

The relations discussed in [Section 2.2.1](#) will be evaluated and discussed here.

FIELD OF VIEW

Taking the projection relations previously discussed in [Section 2.2.1](#), the relation between the FoV and the cross distance (the diameter of the area on Earth seen by the MBT i.e. projected by the FoV) on Earth can be evaluated using the convex projection and approximated by the plane and concave projections. These methods were investigated for LEO, 2,500 km, MEO and GEO. [Figure 2.12](#) shows the results up to a cross distance of 10,000 km. In [Chapter A Section A.1](#) the results are shown for up to 1 km in [Figure A.1](#), and up to 100 km in [Figure A.2](#).

Regarding the FoV size with respect to the cross distance: it can be observed that for short distances, increasing the FoV linearly increases the cross distance. This also implies that for the center of the FoV, any of the projection methods can be used. The resulting covered area increases quadratically. In contrast, at larger FoVs the cross distance increases disproportionally. The disproportionality is due to the spherical convex surface of Earth from the perspective of the MBT curving away from the terminal, see [Figure 2.1](#). This implies that increasing the FoV yields disproportionately larger areas being served.

Furthermore, serving the same area can be achieved with a smaller FoV from higher altitudes. Moreover, the linear region persists longer for the same cross distance at higher altitudes compared to low altitudes. Considering the technological challenges regarding the development and production of wide FoV telescopes, as discussed in [Section 2.1](#), choosing higher orbits could be beneficial from purely an FoV perspective.

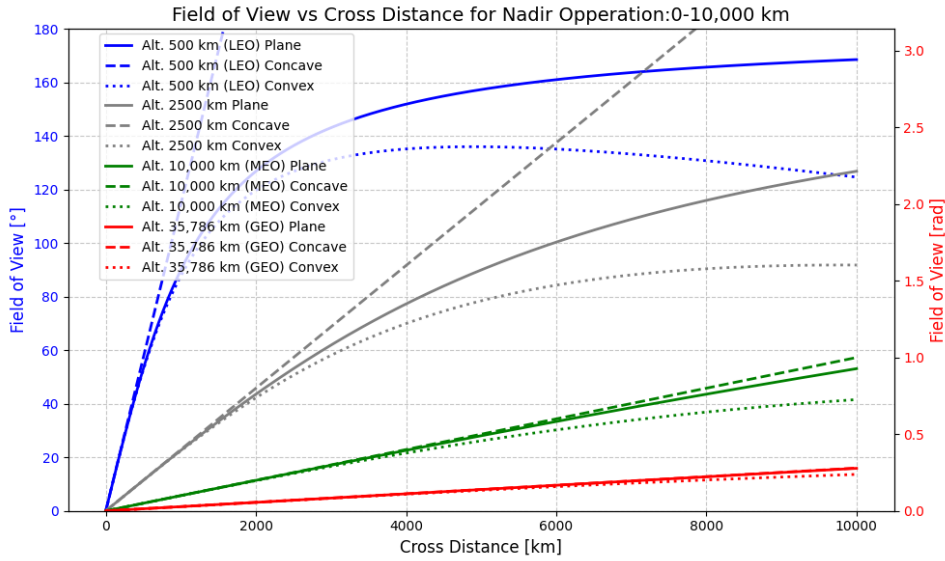


Figure 2.12.: Field of view as a function of the cross distance of the projected field of view with different methods for cross distances between 0 and 10,000 km. For the 500 km altitude case the FoV decreases after 5000 km cross distance due to the mathematical relations and has no real-world significance.

Then with regard to approximations of the convex projection: observed is that there is close adherence between projection methods for small distances. These then diverge for larger distances. Additionally, the level of divergence depends on altitude of the orbit, clearly showing that approximations hold for larger cross distances when applied to higher altitudes. Depending on the level of accuracy needed during analysis, care needs to be taken with regard to the FoV, cross distance and altitude in the periphery of the FoV.

ANGULAR AND CROSS DISTANCE RESOLUTION

The relation between the angular and cross distance resolutions is shown in Figure 2.13 for 3000 km cross distance. Additionally, for 300 km and 30 km, these relations are shown in Figure A.4 and Figure A.3 in Chapter A Section A.2.

Remembering that the concave method can also be used to estimate the center of the FoV, it shows that the angular resolution in the center remains unchanged. The angular resolution in the periphery on the other

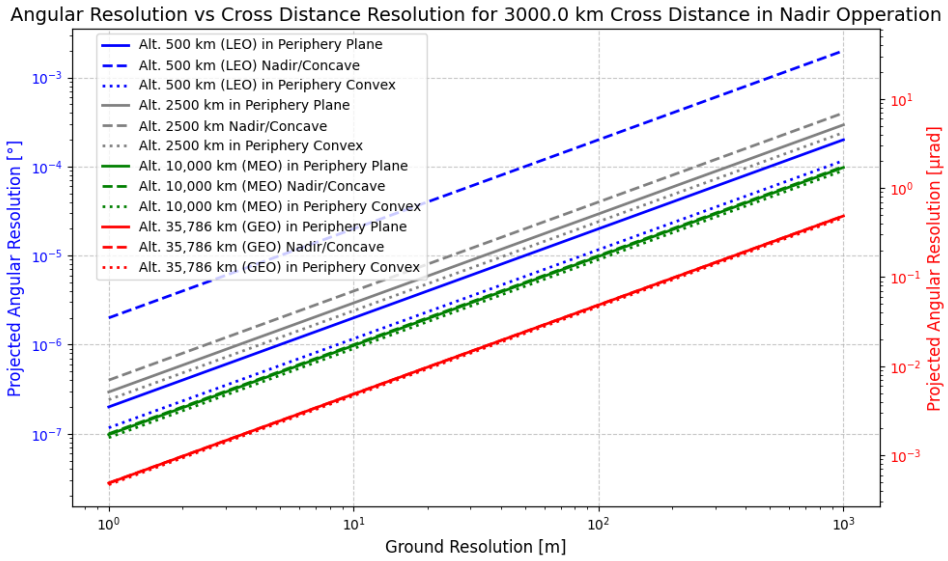


Figure 2.13.: Angular resolution as a function of ground resolution with 3000 km cross distance.

hand does change significantly due to the curvature of Earth playing a larger role for longer cross distances. Care should be taken when using approximations of the resolutions required in the periphery. These approximations diverge from the convex projection for lower altitudes and larger cross distances.

Considering the relation of resolution with altitude, lower altitudes are preferable over higher altitudes purely from a resolution perspective.

TARGET DWELL TIME IN FIELD OF VIEW

Figure 2.14 shows the FoV as a function of the average time a target spends within the FoV (i.e. dwell time). In this time, acquisition and communication occur.

Clearly indicated is that increasing the dwell time requires increasing the FoV or increasing the altitude. This is because the cross distance increases and relative velocities decreases as a result the FoV takes longer to traverse. Not shown in the plot is that the dwell time across the FoV is not uniform due to the convex nature of Earth's surface. As a result, targets dwell longer in the periphery and increasing the FoV disproportionately increases dwell time.

In addition to this, for the same acquisition time, shorter dwell times directly reduce the time spent on communication. The acquisition delay

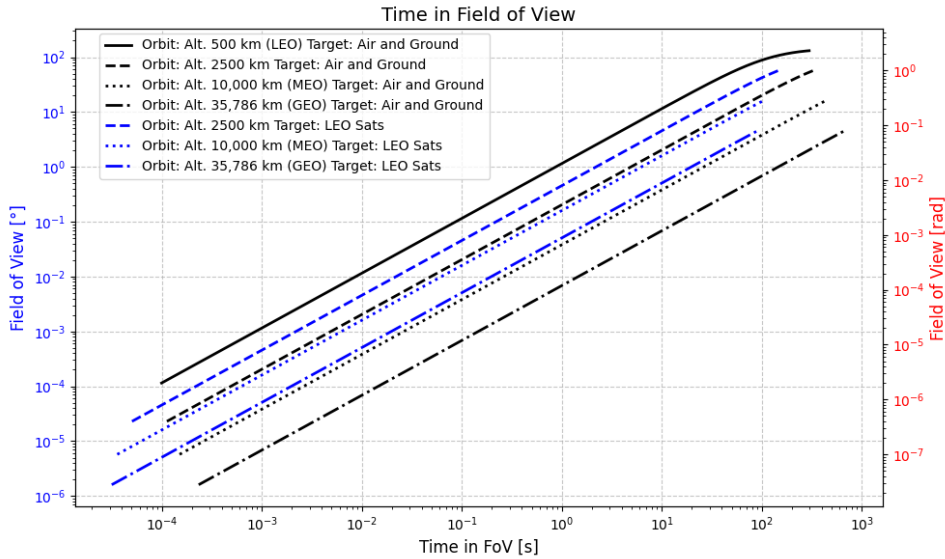


Figure 2.14.: Time in field of view (FoV) as a function of FoV. Shown are various altitudes and target types. Increasing the FoV and/or the orbit altitude implies targets remain in the FoV for longer.

for multi-beam terminals are unknown as these have not been produced yet. For single beam terminals however, reported acquisition times vary from 0.5 s to 25 s. [42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61] However, in CCSDS, SDA and ESTOL, acquisition times are listed between 30-90s.[62, 63, 64] Shorter acquisition times might be possible with more pre-knowledge. Considering this large range of acquisition times, a wide range of dwell times have been provided.

When taking 4° and 12° FoVs as examples, for static terrestrial targets the results are shown in Figure 2.15.

Purely from the perspective of dwell time, increasing FoV and altitude would be beneficial for the communication duration.

FEASIBLE ALTITUDE RANGES

Until now, the FoV, dwell time and resolution have been discussed in isolation. However, when considering them together, it can be seen that these quantities have opposing directions of optimization when designing an MBT and deciding the altitude. Increasing the FoV is challenging and hence purely from an FoV perspective, increasing the altitude is beneficial. For resolutions, smaller FoVs are also beneficial due to the pe-

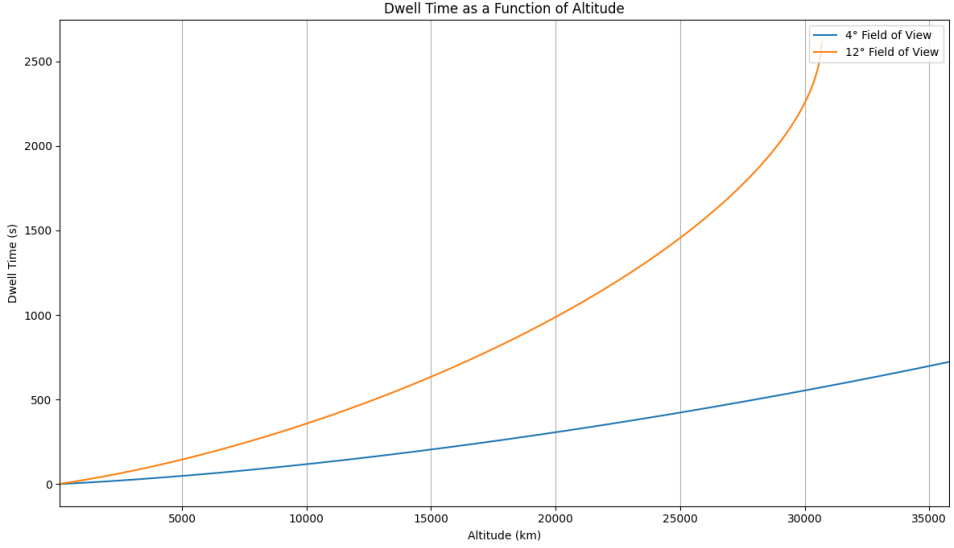


Figure 2.15.: Dwell time comparisons between 4° and 12° as a function of altitude.

ripheral of the FoV disproportionately requiring higher angular resolutions. However, in stark contrast, lower altitudes are more beneficial for ground resolution. Lastly, dwell times would improve when increasing both the FoV and altitude.

When constraints are placed, the combination of these three parameters define an altitude range where it is feasible to operate an MBT. To demonstrate this, an example is used here.

To show the influence of FoV, two different systems are considered: one with a telescope aperture diameter of 25 cm and an FoV of 4° similar to the telescope proposed by DLR[11, 12] and another telescope aperture diameter of 25 cm and an FoV of 12°. Next, the ground resolution is set to 100 m. When using the diffraction limit as the resolution limit, then

$$\epsilon = 1.225 \frac{\lambda}{D} \quad (2.52)$$

can be used. Where ϵ is the resolution, λ the wavelength and D the aperture diameter. Choosing 1550 nm as the wavelength, this would result in a resolution of 7.5 μ rad. This then gives a maximum altitude of 13,300 km.

Suppose hypothetically a minimum dwell time is needed of 10 seconds for acquisition and communication, then the minimum allowable altitude allowed would be 1309 km and 450 km for 4° and 12° FoV respectively.

The feasible altitude ranges for the 4° FoV case is hence between 1309 km and 13,300 km while for the 12° case this would be between 450 km and 13,300 km. This is visually shown in [Figure 2.16](#).

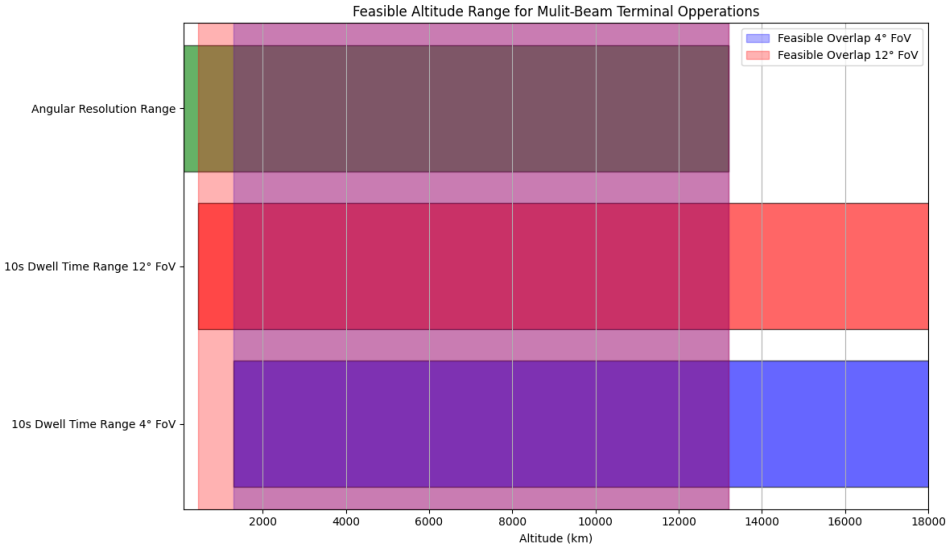


Figure 2.16.: Feasible altitude ranges for 4° and 12° field of view (FoV) and 100 m diffraction ground resolution of a 25 cm aperture telescope using 1550 nm wavelength.

Suppose hypothetically a minimum dwell time is increased to 240 seconds for acquisition and communication, then the minimum allowable altitude allowed would now be 16,800 km and 7410 km for 4° and 12° FoV respectively. The feasible altitude range for the 12° case would be between 7410 km and 13,300 km. However, in this case there is no feasible range for a 4° FoV telescope, implying this telescope can no longer be used. This is visually shown in [Figure 2.17](#).

2.3.2. NUMBER OF POTENTIAL USERS IN FIELD OF VIEW FOR NADIR OPERATIONS

In [Section 2.2.2](#) the population sizes of different user types were determined. Now, this will be combined with the geometric relationship between orbit, surface and FoV explored before. The number of potential users that fall within the FoV will now be discussed.

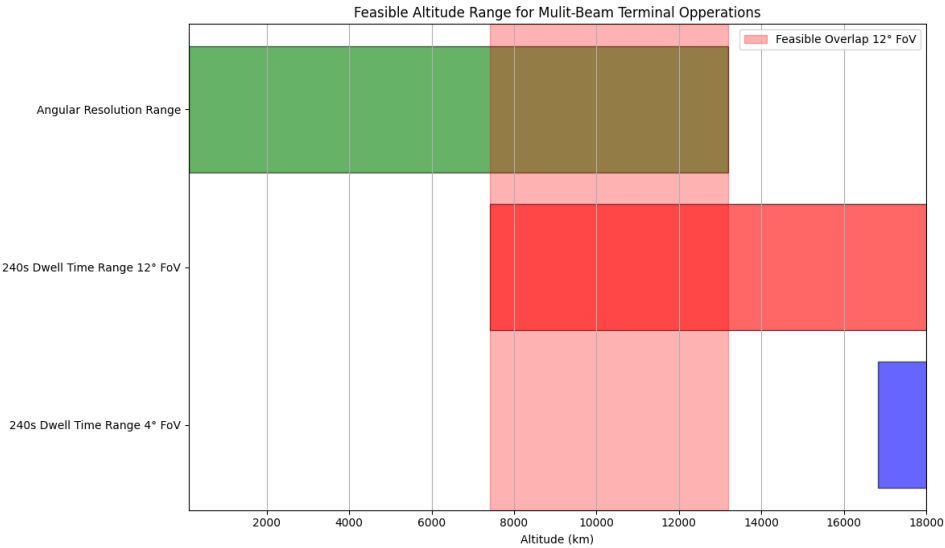


Figure 2.17.: Feasible altitude ranges for 4° and 12° field of view (FoV) and 100 m diffraction ground resolution of a 25 cm aperture telescope using 1550 nm wavelength.

USER NUMBERS FOR DIFFERENT FIELD OF VIEWS

Aside from market forces and adoption rates, the number of users are constrained by the physics of satellite-to-ground communication. Here, two will now be discussed: atmospheric turbulence and FoV. Important to note is that the values presented are all linearly interpolated from the numbers in [Figure 2.9](#) through the projected area. This is not realistic, since the densities expected in Europe cannot be propagated to other land and sea masses nor are they uniform in reality. However, making distinction between each geographic area goes beyond the scope of this chapter. Instead, a uniform density is used to approximate the values.

Atmospheric turbulence imposes a practical limit on the elevation angles at which stable links can be maintained. This limitation might be less strict for aircraft due to their altitude being above the majority of the atmospheric mass, however, to limit the scope, this effect was omitted. [Figure 2.18](#) illustrates the maximum expected number of vehicles and towers visible from different orbital regimes if their elevation angle (i.e. the propagation angle through the atmosphere) was limited to 45° (see [Section 2.2.1](#) for more details). This figure also shows the maximum FoV useful to scan the accessible sky volume, providing an upper bound on FoV.

This plot shows that when limited to atmospheric turbulence and not

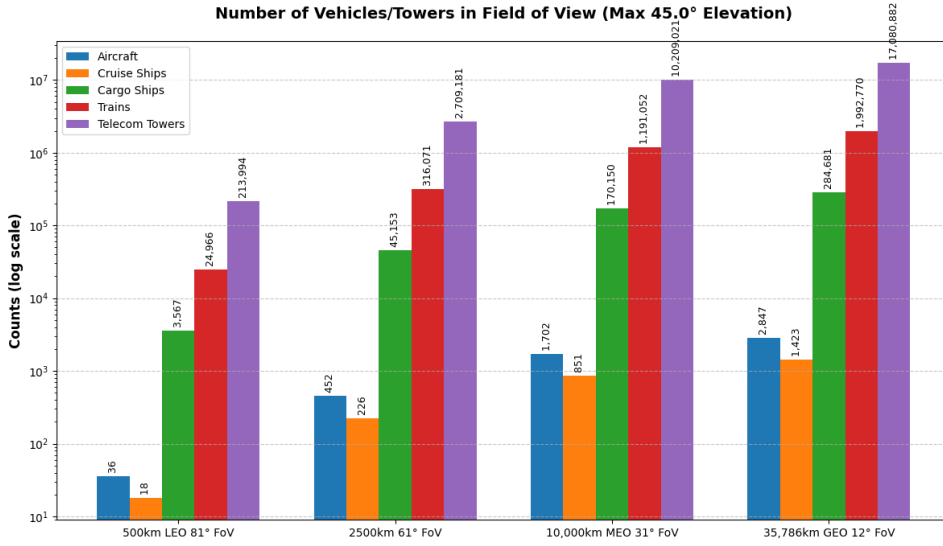


Figure 2.18.: Estimated number of targets within the field of view (FoV) of a terminal that can view the MBT from the surface of the Earth with at most an elevation angle of 45 degrees.

by FoV, the number of vehicles and towers increases with the altitude (as a result of larger coverage area) while simultaneously the useful FoV decreases.

Figure 2.19 overlays the FoV of the widest FoV telescope currently demonstrated for laser communications (4°) onto the target distribution.[11, 12] By mapping this specific FoV onto the target population, we can determine the expected number of accessible targets for each type. This comparison highlights the trade-off between the vast number of available targets and the practical limitations of current wide-angle optical systems, guiding the design of the next generation of high-throughput terminals.

Comparing Figure 2.18 and Figure 2.19 firstly shows that the limiting factor is the FoV. In fact, for lower orbit altitudes, some target types such as aircraft are not available in meaningful quantities to justify multi-beam terminals. Increasing the FoV would be the obvious technological challenge to overcome to help obtain more counter terminals. This can be achieved on the telescope side either through optical design of the telescope or through utilizing multiple telescopes. On the steering system side large FoVs have to be accommodated through increased angular steering range and resolution.

Should the FoV not increase, there is likely little gain in choosing MBTs

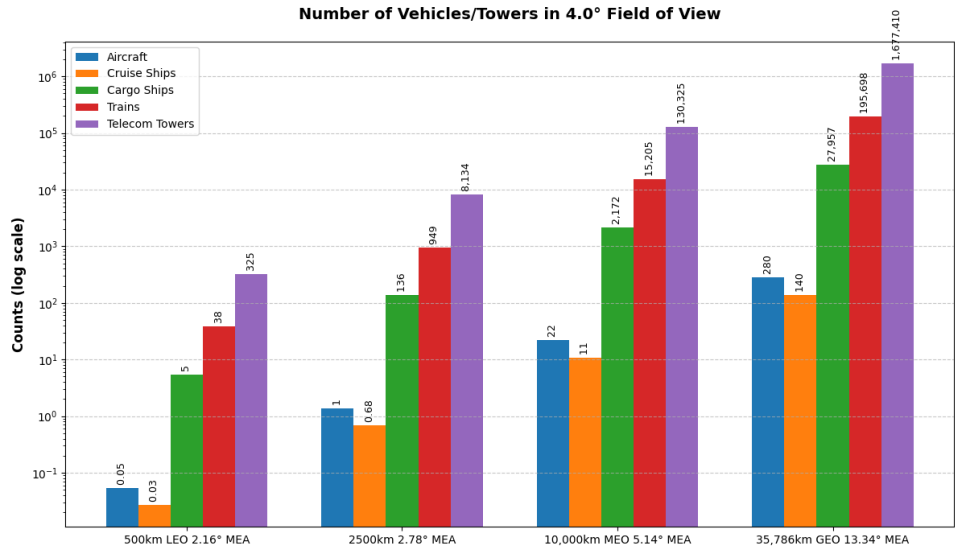


Figure 2.19.: Estimated number of targets of each type within a 4 degree field of view (FoV). In addition, the maximum elevation angle (MEA) is indicated.

over SBTs. While it is currently unknown where the break even point is with respect to the number of links when choosing a single multi-beam terminal over multiple single beam terminals, it is unlikely to be the case for 1-2 beams. As a result, for lower altitudes, types are likely limited to users such as trains and towers. Only in MEO and GEO does the prospect of using MBTs for aircraft become more interesting.

Increasing the FoV to 12°, potentially also achievable through multiple telescopes, yields a more interesting option for 2,500 km altitude orbits as shown in Figure 2.20. As can be seen in Figure 2.18, this is around the maximum elevation angle limit for GEO.

ALONG TRACK CONSTELLATION INTER-SATELLITE COMMUNICATION

From Section 2.2.2 it was found that a mega constellation such as Starlink could contain 10,000 evenly spaced satellites within the constellation (i.e. 100 satellites in 100 orbits). The along track density is hence 2.3e-3 satellites per meter (i.e. roughly one satellite every 500 km). Using the relations found in Section 2.2.1 for the along track FoV and taking these values yields the results shown in Table 2.3.

The relative positions of the satellites between planes changes over time. To approximate the spatial distribution, it is assumed that the

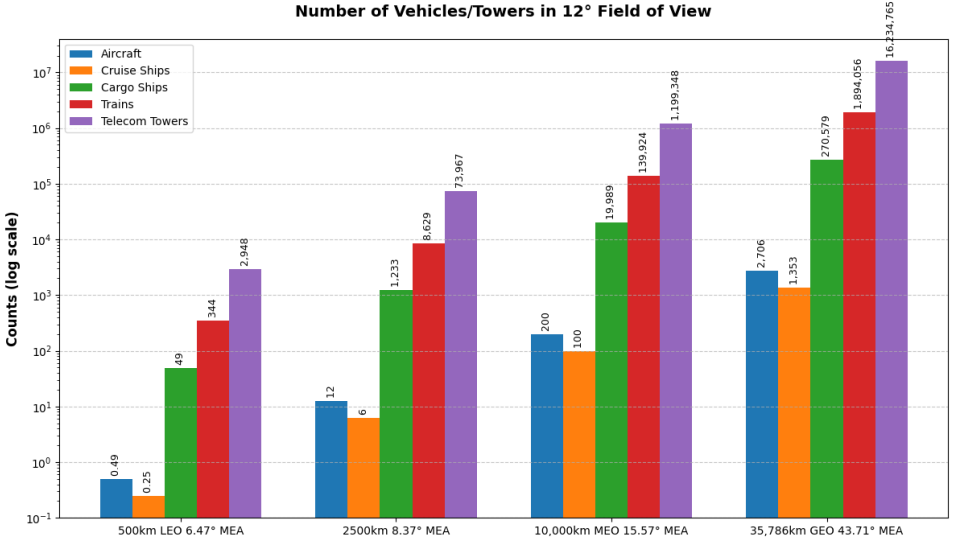


Figure 2.20.: Estimated number of targets of each type within a 12 degree field of view (FoV). In addition, the maximum elevation angle (MEA) is indicated.

FoV (°)	Number of Satellites
4	2-3
12	6-7
max FoV: 20.8	11-12

Table 2.3.: Number of satellites within a field of view (FoV) along track for a 500 km altitude LEO constellation with 10,000 satellites in 100 orbits. The lowest allowable propagation altitude in this case was set to 50 km above the surface of the Earth.

satellites are organized within a grid. Applying the same method for communication between orbit planes yields [Table 2.4](#).

FoV (°)	Satellites (incl. Along Track)	Satellites (excl. Along Track)
4	2-3	0
12	6-7	0
20.8	≈ 17	6
45	≈ 25	14
90	≈ 29	18

Table 2.4.: Number of inter-orbit and along track satellites in view.

2.3.3. MULTI-BEAM PERFORMANCE IMPROVEMENTS IN SPACE, AIR, GROUND AND SEA INTEGRATED NETWORKS (SAGSINS)

Sea-air-ground-space integrated networks (SAGSINs) are networks that span four domains. The topology of optical SAGSINs can change relatively quickly due to obstructions (such as weather) and line of sight (such as when a vehicle rotates and the terminal is no longer within the FoV). In a study by Ndongson et al. the majority of topology changes occur within 45 seconds after the previous topology was established.[3] When considering that SBTs can only establish one link at a time together with the complexity and duration of re-acquisition. The implication is that the reliability is lower and outage times are proportionally larger compared to radio communication alternatives. The ability of multi-beam terminals to acquire and maintain links in parallel has the potential to improve reliability and acquisition limitations.

In collaboration with the FREE program, the added utility was assessed of multi-beam terminals in these networks. One of the networks investigated was a 100-node SAGSIN over Western Europe with a mixture of domains and an FoV was set to 45°. From the investigations, improvements in network performance were witnessed with asymptotic trends when increasing the number of beams.[65]

Performance Parameter	Value for SBTs	Value for MBTs	Number of Beams at Saturation
Median number of components	1	1	1
Upper quartile number of components	2	1	1
Median Number of links	75	600	16
Median end-to-end latency	55 ms	30 ms	4
Upper quartile end-to-end latency	65 ms	30 ms	4
Allocated capacity	0.98 Gbps	1.1 Gbps	4
Network capacity	1000 Gbps	4800 Gbps	32

Table 2.5.: Comparison between performance parameters for SAGSINs when using MBTs over SBTs.

One of the results of this investigation was the number of instances in which a certain number of beams were used. This is summarized in Table 2.6.[65]

Table 2.6.: Mean percentage of terminals in various beam-count categories, with the corresponding average number of terminals in parentheses. Reproduced with permission.

Scenario	0	1	2	3-4	5-8	9-16	17-32	33-64
1 beam	46.7% (183)	53.3% (209)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
2 beams	44.0% (173)	12.6% (49)	43.3% (170)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
4 beams	43.2% (169)	11.0% (43)	8.2% (32)	37.6% (147)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)
8 beams	42.7% (168)	10.5% (41)	7.6% (30)	11.6% (45)	27.6% (108)	0.0% (0)	0.0% (0)	0.0% (0)
16 beams	42.5% (167)	10.3% (41)	7.4% (29)	11.2% (44)	15.5% (61)	13.2% (52)	0.0% (0)	0.0% (0)
32 beams	42.4% (166)	10.3% (40)	7.3% (29)	11.1% (44)	15.4% (60)	11.8% (46)	1.7% (6)	0.0% (0)
64 beams	42.4% (166)	10.3% (40)	7.3% (29)	11.1% (44)	15.4% (60)	11.8% (46)	1.6% (6)	0.0% (0)

In summary, the results show that the node geometry of the network can also limit the number of usable beams. Although terminals may support up to 64 beams, they are typically exposed to only a limited set of feasible line-of-sight neighbors, leading to significant under-utilization of beam resources. As a result, increasing the beam count beyond 8–16 beams yields diminishing returns, with network performance ultimately constrained by topology rather than hardware capability.

2.4. COMPARISON OF MULTI-BEAM USE CASES:

SUMMARY AND CONCLUSION

In the previous sections, numerous parameters were evaluated across different orbital regimes and use cases. To facilitate a comprehensive comparison, Table 2.7, Table 2.8, Table 2.9, and Table 2.10 consolidate the key metrics for LEO, 2500 km, MEO, and GEO altitudes respectively. These summaries reveal distinct trade-offs regarding target coverage, ground resolution, dwell time, latency, and inter-satellite link requirements.

2.4.1. TARGET COVERAGE AND SPATIAL RESOLUTION

As orbital altitude increases, the instantaneous coverage area expands significantly, leading to a rise in the number of targets observable. For example, at a 4° FoV, the number of visible communication towers grows from only 325 in LEO to over 1.68 million in GEO. Similarly, cargo ships increase from 5 in LEO to 28,000 in GEO. This makes higher orbits (MEO and GEO) suitable for wide-area coverage and higher number of targets.

However, this coverage gain imposes constraints on the required angular resolution. To maintain a constant ground spot size of 100 m, the required resolution scales inversely with altitude. While LEO and 2500 km regimes can operate with resolutions between 200 μrad and 100 μrad , the MEO regime requires approximately 10 μrad . Most critically, GEO demands a resolution of 2.8 μrad (1.6×10^{-4} degrees), which represents a substantial challenge.

2.4.2. DWELL TIME, ANGULAR RESOLUTION AND FIELD OF VIEW

The dwell time, angular resolution and cross distance are strongly dependent on orbital altitude and FoV. As discussed, a combination of these parameters yields an altitude range for feasible MBT operation. LEO offers short dwell times ranging from 1.1 s to 27 s, suitable only when acquisition is fast enough and data rates are high enough or FoV is increased. In contrast, MEO and GEO regimes provide dwell times exceeding 80 s, with GEO reaching up to 265 s at larger FoVs. This extended dwell time

is advantageous for tracking persistent or slow-moving targets. Correspondingly, the cross-distance (swath width) increases from roughly 35-864 km in LEO to 2,520-8,400 km in GEO, further confirming the broad coverage capability of higher orbits. However, the upper bounds are determined by the angular resolution, making increases in altitude beyond MEO potentially challenging.

2.4.3. CONCLUSION

The range of feasible orbital regimes depends heavily on the available technology and is constrained by the FoV, angular resolution and dwell times. LEO is superior for low-latency communication and systems constrained by resolution hardware, offering minimal latency and the most manageable resolution requirements. 2500 km offers a potentially more balanced intermediate solution depending on the limits to acquisition and handovers. MEO and GEO regimes excel in wide-area coverage with smaller FoVs and long dwell times, capturing orders of magnitude more targets in the process. However, they impose stringent resolution demands and higher latencies.

Nevertheless, if a small portion of the types discussed accommodates a link and small 4° FoVs are selected, then an order of magnitude design envelope of 10-1000 targets can be expected. This includes other satellites. For nadir and high-to-low orbit communications, the transit times expected to range from 20-265s aside from LEO. These numbers will be taken as inspiration for the following chapters.

Aspect\FoV	4°	12°	45°	80°
Nadir				
# Aircraft	0.05	0.49	7	36
# Cruise ships	0.03	0.25	3	18
# Cargo ships	5	49	773	3570
# Trains	38	344	5410	25000
# Communication towers	325	2948	46400	214000
Dwell time [s]	1.1	3.3	13	27
Cross Distance [km]	35	105	417	864
Req. res. (100 [m] spot) [μ rad]	200	200	170	107
[deg]	0.011	0.011	0.0096	0.0061
Inter-satellite				
# along track	2-3	6-7	11-12*	11-12*
# inter-orbit	0	0	14	18
# total	2-3	6-7	≈25	≈29

Table 2.7.: Summary for LEO. *Note that the maximum useful FoV in the along track case is 20.8°.

Aspect \ FoV	4°	12°	45°	60°
Nadir				
# Aircraft	1	12	205	452
# Cruise ships	0.68	6	102	226
# Cargo ships	136	1233	20500	45100
# Trains	949	8629	143000	316000
# Communication towers	8134	73967	1230000	2710000
# Inter-satellite nadir	6	72	1230	2712
Dwell time [s]	5.5	17	68	99
Cross Distance [km]	174	525	2160	3140
Req. res. (100 [m] spot) [μ rad]	40	40	30	23
[deg]	0.0023	0.0023	0.0017	0.0013

Table 2.8.: Summary for 2500 km altitude.

Aspect \ FoV	4°	12°	30°
Nadir			
# Aircraft	22	200	1700
# Cruise ships	11	100	851
# Cargo ships	2172	19989	170000
# Trains	15205	139924	1200000
# Communication towers	130325	1199348	10200000
# Inter-satellite nadir	132	1200	10200
Dwell time [s]	22	67	187
Cross Distance [km]	695	2130	5930
Req. res. (100 [m] spot) [μ rad]	10	9.5	6.8
[deg]	5.7E-4	5.4E-4	3.9E-4

Table 2.9.: Summary for MEO.

Aspect \ FoV	4°	12°
Nadir		
# Aircraft	280	2710
# Cruise ships	140	1350
# Cargo ships	28000	270000
# Trains	196000	1890000
# Communication towers	1680000	16200000
# Inter-satellite nadir	1680	16300
Dwell time [s]	80	265
Cross Distance [km]	2520	8400
Req. res. (100 [m] spot) [μ rad]	2.8	2.8
[deg]	1.6E-4	1.6E-4

Table 2.10.: Summary for GEO.

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3

DESIGN OF MULTI-BEAM STEERING SYSTEMS

Decisions are made by those who show up.

Jed Bartlett (*The West Wing*)

Traditional laser communication terminals are limited to point-to-point links, restricting scalability. Multi-beam laser communication terminals offer a promising alternative, through the design of an effective beam steering system remains a key challenge. This chapter addresses the design of multi-beam steering systems, reviewing existing space borne technologies and insights from related fields. It identifies key system functions, evaluates design options, and presents a design options tree as a framework. Case studies for high and low target densities show that micro-mirror arrays and spatial light modulators offer significant advantages. This study offers a comprehensive framework for designing multi-beam steering systems for space-based laser communication terminals.

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3.1. INTRODUCTION

Ever increasing demand for unfettered high speed global access to data has lead to data and network providers to seek ways to meet this demand. However, in order to affordably connect the most remote and difficult to reach customers, a new approach is needed.[2] Furthermore, constructing physical infrastructure can be costly, inflexible and vulnerable to outages.[3, 4, 5, 6, 7, 8, 9] A strong contender is providing wireless networks from space. Numerous large satellite constellations are currently being designed or are under construction, primarily using radio communication. The problem with this approach, however, is radio frequency congestion.[2, 7, 10]

A promising alternative technology already in use to speed-up data transmission is laser communication. Due to micro-meter wavelengths instead of millimeter radio wavelengths, the beam divergence can be reduced by at least 3 orders of magnitude for a given aperture size. As a result, the transmission losses are heavily reduced and crosstalk as well as interference between users eliminated, making available a comparatively large bandwidth at high signal to noise ratios (SNR). This allows for higher capacity data links at lower SWaP, making laser communications an attractive technology for space based communications.[7, 8]

As a result, although not yet equally as established as radio communications, laser communications is seeing increased use in space. For example, bringing laser communication to consumers on the ground, air and sea is also gaining interest.[3, 4, 5, 6, 11, 12, 13] Furthermore, small satellites (from nano to mini ranges) are becoming increasingly numerous in various applications.[7, 14] Laser communication promises miniaturized high-capacity communication for small satellites.[7, 8] In this vein, large constellations of satellites heavily rely on small satellites (up to 500 kg) to bring internet connection to consumers from space, and require increased capacity between satellites to facilitate this.[7, 10, 14, 15] Furthermore, large capacity feeder links and data relay applications are also looking towards laser communications to supplement the download of data between space and ground.[5, 16, 17, 18]

These trends indicate a direction of space-based laser communications to be used in all aspects of communications, especially in networks. The domains that consider laser communication span a wide range of locations, from LEO to GEO and large networks to single links. Of particular interest in this work are applications where laser communication is expected to serve numerous clients. Specifically in the area of space-to-space and space-to-Earth communications, with the former focusing on inter-satellite data relay/forwarding applications and the latter on providing data services to numerous users on Earth. Chapter 2 investigated the number of users and data rates for a number of use cases and determined that each satellite could serve 10s to 1000s of users across domains. Additionally, the data demands per link can amount to multi-

ple gigabits per second.

Nonetheless, low beam divergence simultaneously also makes laser communication by nature point-to-point communication. Although this might be sufficient for some applications, it might hold back integration of laser communication into point-to-multi-point applications.[19, 20]

There are three overlapping potential areas identified where laser communication for space applications currently encounter challenges: link switching and reliability, routing of data and nodal networks, and scalability in terms of Size, Weight and Power (SWaP) when expanding to multiple links per satellite.

Link switching, for example, occurs when a link is established with a transceiver different from the one currently active. Switching links are inevitable when targets and transceivers are moving into or out of each other's view. As a result of low beam divergence and optical wavelengths, moving in and out of view completely interrupts data flow for a significant portion of time until the next link is finally established.[11, 12, 21, 22, 23] This makes the (re-)acquisition phase inherently expensive from an operational and network perspective, as it requires peer discovery through a thorough search of the field of regard (FoR).[11, 24] When optimizing link selection and network topologies through mathematical cost functions, a large cost is attributed to termination and (re-)acquisition processes for establishing a new link.[11, 12, 22, 23, 24, 25] As a result, the decision to switch to more optimal links is postponed, thereby making the link configuration sub-optimal and decreasing attractiveness of using laser communication. While these processes are being optimized, the drawbacks of link switching remain.[11, 22, 23, 25]

Connecting points to multiple other points through links naturally creates nodal networks. In such a network, each node is connected to multiple other nodes. This not only allows for redundancy and flexibility in routing options but also increased volumes of data transmitted through multiple links. Furthermore, these network architectures are common and moving to such a network type would improve compatibility with existing network architectures and routing algorithms, further improving performance[10, 19, 20, 21, 26, 27, 28, 29, 30]. The drawback of laser communication being point-to-point by nature is that it connects two nodes rather than connecting one node to multiple nodes. Proposed laser communication networks rely on multiple laser communication terminals per spacecraft to create these networks as a result.[19, 20, 27, 28, 31, 32, 33]

Considering the scalability of such a solution, while increasing the number of terminals would work to make spacecraft point-to-multi-point, it does not reduce the SWaP per beam. The result is limited scalability of laser communication in such applications. This is in stark contrast to modern radio communication systems, with its the ability to perform communications over multiple links at once[19, 20, 27, 28, 31, 32, 33].

As a result, combining multiple beams into a single multi-beam terminal (MBT) would overcome the three challenging areas mentioned above. This would allow establishment of links to multiple unique targets while sharing components, making it more SWaP-friendly per beam and therefore more scalable.[27, 31, 32, 33] Multiple links to multiple targets, such as shown in Figure 3.1, would also create a nodal network and provide multiple routing options. Another benefit is that each terminal has a set of existing optimized links, allowing interruption of multiple links at once while not losing connection to the wider network which improves reliability. The terminal would also be able to acquire new links in parallel to maintaining existing links, in turn cutting the cost of (re-)acquisition.

Some work on space MBTs for space applications has been done. This work will be investigated in greater detail in Section 3.3.1. However, the available literature on MBTs is sparse. Nevertheless, some work has been done on the design of multi-beam steering systems, proposing systems from antenna and mirror arrays on overview chapters.[27, 33] Work has been done on FSM array designs, which use multiple FSMs to steer multiple beams.[34, 35] Furthermore, a design has been proposed where transceivers are selected to spatially serve an area.[36] However, these systems are not described in detail beyond their patents.

More detailed work has been done on the use of liquid lenses to create multi-user laser communication. Such a system uses a wide beam steering concept and quickly jumps between targets to establish and maintain multiple links at once.[37] While this concept is interesting, the time division of a single beam yields decreased data rates and total communication time share (as a result of time lost hopping between counter terminals). Other work has also proposed sustained multiple beams in multistage steering systems that combine multiple steering mechanisms. This would improve the flexibility and scalability of such a terminal.[31] The system which has been furthest developed, is One-Point to Multi-Point laser communication system (OPMP), which has been designed, prototyped and tested experimentally.[19, 20, 28, 38] This design features large mirror arrays arranged in a parabolic configuration to allow for a large field of service.

As can be seen, the literature on space borne MBTs is limited and MBTs as a technology is therefore still in its infancy.[19, 20, 27] The existing work also consists of a diversity of different design choices resulting in stark differences between designs. As a result, there is currently a framework lacking through which MBTs can be designed. In particular designed, prototyped and tested experimentally steering portion. Such a framework could be created by analyzing the use cases, adjacent fields, added value and important functions of MBTs. This would help to create an overview of possible design options and layouts for the multi-beam steering system.

This chapter proposes a function flow diagram and design option tree

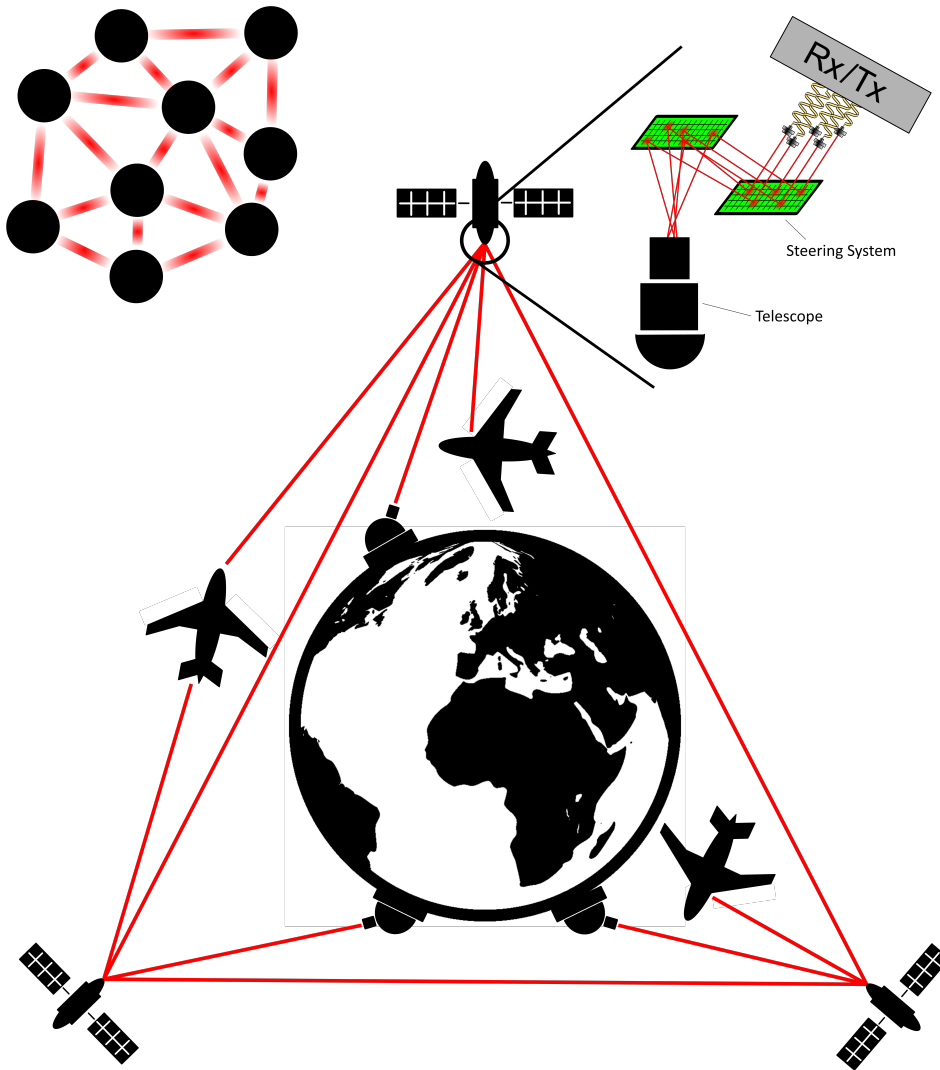


Figure 3.1.: Illustration of multi-beam laser communication terminals in space providing data connection services to a variety of users in a nodal network type fashion.

for MBTs to help answer the question:

How can multi-beam steering systems be designed?

This question will be answered in two parts by answering the following:

1) What are the functions that an MBT steering system needs to fulfill?

2) What are the design options and how can we select between them?

Subsequently, the results from these sections will be applied to some selected use cases and the outcomes will be discussed.

3.2. FUNCTIONS OF MULTI-BEAM LASER COMMUNICATION TERMINALS

3

This section will discuss the functions of a multi-beam laser communication terminal (MBT) steering system. Taking a page from single beam laser communication terminals, the function flow of MBTs is split into three parts: 1) Acquisition. 2) Link sustainment. 3) Link termination. Considering that MBTs have multiple links, the functions can be viewed from both a per-link perspective, as well as the functions of the terminal as a whole. All of these perspectives will be discussed in their own subsections, starting with acquisition.

3.2.1. ACQUISITION

Here acquisition is understood as the process of establishing a link. This includes the time from initiation, coarse alignment, fine alignment until the establishment of a stable link over which data can be transmitted. Due to the low beam divergences used in laser communication, finding the target can be difficult and time consuming.[11, 12, 21, 22, 23] In a literature search, no proposed acquisition schemes for MBTs have been found by the author. Hence the functions here are extrapolated from three adjacent areas: 1) single beam laser communication terminals (SBTs) 2) multi-beam radio communication 3) multiple target tracking.

Considering SBTs first, a challenge that MBTs share with SBTs is that the narrow beam width creates a problem in determining the location of the other terminal, especially without prior knowledge. This is overcome through search patterns. These search patterns can be initiated by either party and often are shaped as a spiral.[39] Each terminal monitors its Field of Regard (FoR) for a signal from the other. This pattern is then expanded until such a signal is received. The target is then tracked and steered to until pointing errors have been reduced such that communication becomes possible. This is often achieved through both coarse as well as fine steering. Once the signal is coupled into the transceiver, communication can begin and the acquisition phase is over.[39, 40, 41, 42, 43, 44]

The main take-aways from SBTs are that the narrow beam divergence is overcome through following a search pattern and monitoring of the FoR for return signals, in the same way as SBTs. However, when investigated, the single beam acquisition process differs in two main ways from multi-beam acquisition. The first is the size, orientation and use of the FoR

and the need to accommodate multiple beams in multiple stages at the same time. The second is the need to filter out noise and false targets. To determine these functions, the fields of radio and multiple target tracking were used.

The initiation of acquisition can come from either terminal at each end. One potential difference the FoR makes between SBT and MBTs would be the coarse alignment phase where terminal FoRs are aligned. In a narrow FoR scenarios, both terminals need to actively search by moving the FoR in order to avoid missing. The narrowness of the FoR makes it that the counter terminal is likely not within the FoR to begin with. For both terminals, prior knowledge with respect to the counter terminal location and acquisition initiation time is either required or can play a large role in the acquisition duration. For wide FoRs, this initial pointing of the non-initiating terminal is less crucial, potentially only requiring prior knowledge from the initiator side with regards to the correct direction for initial beam pointing. In wide enough FoRs, such that the counter terminal is within the FoR already, an MBT could conceivably listen for an initiation attempt from either MBT or SBT counter terminals. Furthermore, in order to initiate in the same scenario, the MBT would start steering a beam in a search pattern into a pre-determined FoR location. The coarse alignment of telescope FoRs would therefore be unnecessary from the wide FoR MBT side as this step was completed by default due to the counter terminal already existing within the wide FoR.

Nevertheless, in both terminals, active monitoring of the FoR is required after the acquisition phase has been initiated.

To communicate with multiple spatially distributed targets in a reliable manner without favoring one link over another requires an FoR unbiased to one particular link. As a result, the orientation of the terminal and by extension, the FoR cannot be easily adjusted. The FoR tracking sensor of an MBT will track a larger FoR larger compared to that of an SBTs. The identified literature on proposed MBT designs also have this in common.

Multi-beam radio communication, such as that found for 5G and 4G, acquire spatially through detection on an antenna array with a wide FoR. These can be full 360° in all directions. This is done without adjusting the orientation of the array itself. The FoR plane is therefore spatially sampled by transmitters and receivers. Transmitters are then selected to optimally serve the new target while maintaining the existing links.[45, 46, 47, 48, 49]

For radio communications, techniques to sub-divide the plane and strategically subdivide (tile) the FoR are directly transferable to MBTs which tile the plane and steer beams using transmitter selection.[50] For MBTs which require steering, these methods are still useful when utilizing the FoR for steering and receiving purposes. Missing however, is a method by which multiple targets can be correctly identified and tracked in the presence of noise.

In [Chapter 5](#) and [Chapter 6](#) the steering and tracking will be discussed. Briefly however, there is a need to filter the sensor data and subsequently validate as well as identify the target. In multiple target tracking, the sensor readout and data processing are separated from the data analysis to assess likelihood of correct target identification. During this process the potential new target is tracked and evaluated through a probabilistic approach. In the meantime, each existing target is also tracked simultaneously without interruption.[51, 52] Each MBT which requires target tracking for both active steering and transmitter selection.

Having considered the literature, these concepts can now be adapted to MBTs. From the perspective of one beam within the MBT, the functions have been illustrated in a function flow diagram shown in [Figure 3.2](#). Looking from the terminal perspective, when considering multiple beams, the multiple target tracking algorithm will be able to assess all existing and potential new beams in the FoR at once. The same is true for the steering algorithm which will consider the placement of any newly acquired beams to allocate receivers and transmitters as required. The operation of an MBT, in contrast with an SBT, exists on a continuum. Multiple links can be undergoing acquisition, communication and termination at the same time. This will be discussed in [Section 3.2.4](#).

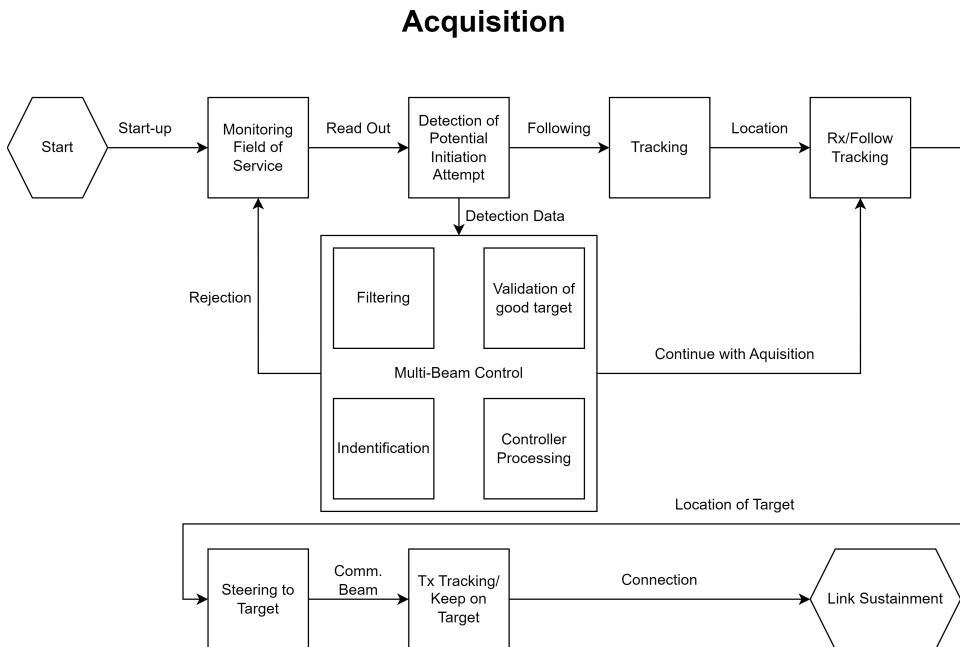


Figure 3.2.: Function flow diagram of multi-beam acquisition.

Following acquisition, the processes needed to sustain a link are initiated.

3.2.2. LINK SUSTAINMENT FUNCTIONS

Here, link sustainment is understood as the process by which a link is maintained such that data can be transmitted. From the perspective of the terminal when considering one beam, sustainment chronologically occurs after acquisition. However, from the broader terminal perspective, it is a portion of the link life cycle where there is a continuous stream of multiple links entering, existing and leaving simultaneously.

As with SBTs, phenomena such as jitter and target motion need to be compensated. SBTs do so through tracking the beam and correcting for errors. The movement of a target produces a wandering motion from the perspective of the terminal. This motion is compensated through coarse pointing systems (motorized mounts for example) or body pointing (rotation of the satellite). For MBTs however, as discussed in [Section 3.2.1](#), the FoR must accommodate multiple targets and as a result will not be re-orientable to a more favorable position for a single link at the expense of other links. As a result, the FoR will be larger to accommodate this wander and spatial distribution of targets.

For radio systems which tile the FoR with beams, due to more divergent preformed beams and static antennas, tend to hand over the target to the next beam or slew a beam.[[45](#), [46](#), [47](#), [48](#), [49](#)] This process can be referred to as pre-coding. In the case of MBTs where transmitters and receivers are selected as a form of steering, this approach would be similar.

With respect to multiple target tracking, the main functions of filtering and target identification remain relevant. One key component is to identify and label each individual beam in order to distinguish it from other beams. Temporally maintaining the correct label to each beam from one instant of time to the next is crucial. This is particularly important when beams are in the proximity to other beams as these are regions where confusion can most likely occur.[[51](#), [52](#)] However, there are numerous and diverse methods through which this can be achieved, and this is beyond the scope of this chapter and will be discussed in [Chapter 6](#).

The transmitted beams and the received beams can be considered separate, unless the terminal is designed such that the control of one directly controls the other. The function flow for link sustainment from the perspective of a terminal of one beam is shown in [Figure 3.3](#).

The functions and their order are similar to that of an SBT. However, considering the details of each function more closely, the implementation can take inspiration from radio and multiple target tracking.

Link Sustainment

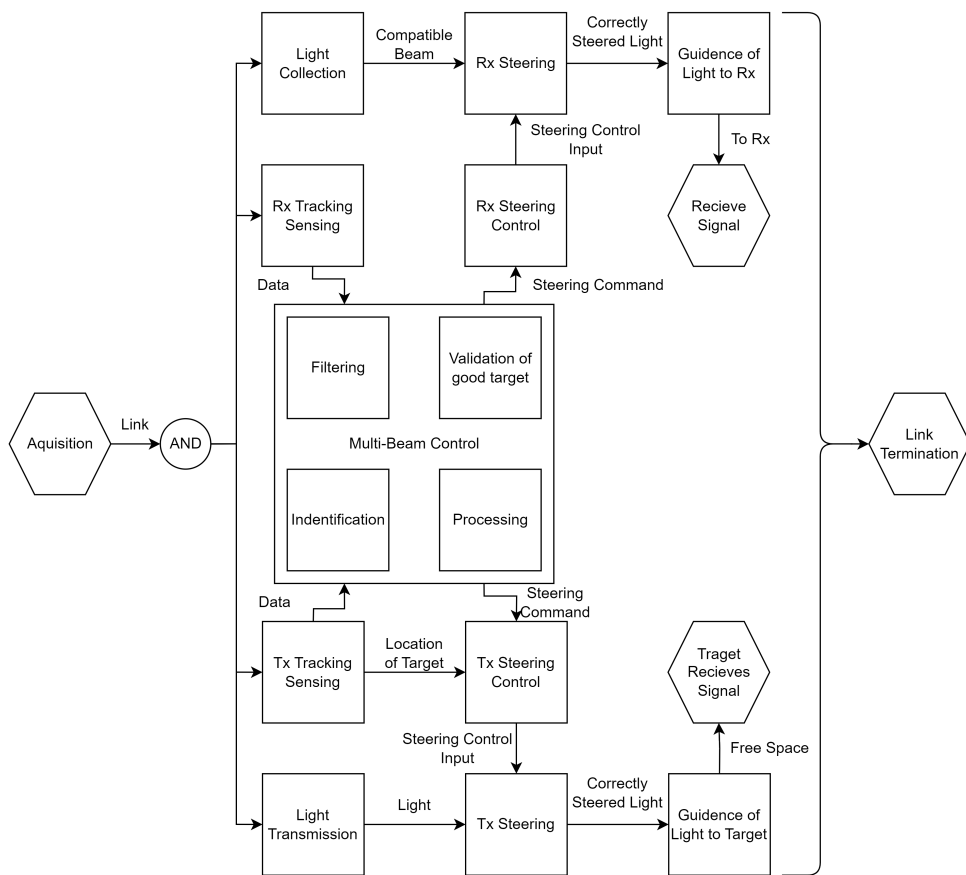


Figure 3.3.: Function flow diagram of multi-beam link sustainment.

3.2.3. LINK TERMINATION FUNCTIONS

When the link either is lost, a hand-off needs to occur or when the communication has ended, the link can be ended through a termination process.

In the case of multi-beam radio communications as well as multiple target tracking, multiple targets are tracked. To do so a form of register is maintained of the known targets and their location.[51, 52] Such data needs to be updated. In the case of abrupt loss of contact an analysis needs to be performed to ensure that the beam has indeed been lost. This is illustrated in Figure 3.4. This process is of primary importance for the software and operations. Nevertheless, a termination process also offers the ability to re-direct resources.

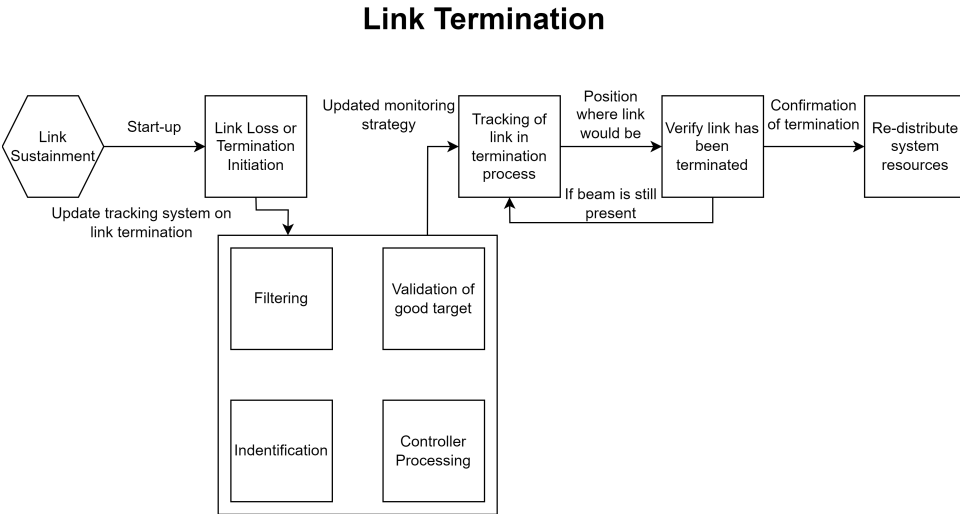


Figure 3.4.: Function flow diagram of link termination.

3.2.4. MULTI-BEAM TERMINAL FUNCTIONS

So far, the functions have been viewed from the perspective of the terminal on the life cycle of one beam. From a broader perspective, the terminal is handling multiple beams in various stages at once. In contrast to SBTs, MBTs operate on a continuum of link acquisition, sustainment and subsequent termination, as shown in Figure 3.5. From a high level perspective, these functions need to happen in a parallel and coordinated fashion to achieve high quality and reliable links. Furthermore, it is important from an MBT perspective that different targets are kept separate from each other, in particular for control. This is done through

filtering and correct identification as part of multiple target tracking in combination with a steering strategy shown in [Figure 3.6](#).

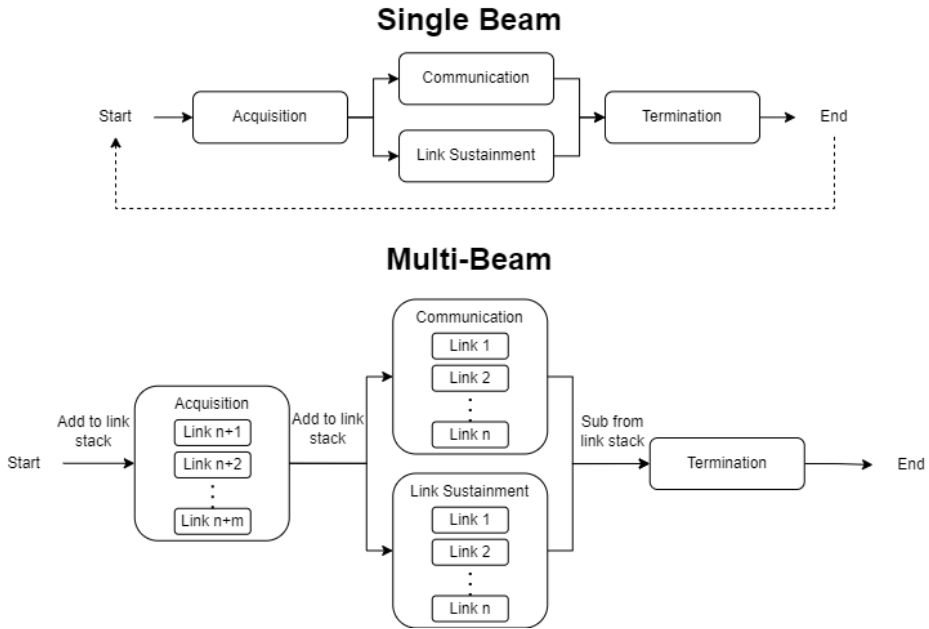


Figure 3.5.: Phases of beams from perspective of single and multi-beam terminals.

Higher level multi-beam specific functions for the controller are depicted in [Figure 3.7](#). In contrast with single beam tracking, multi-beam tracking cannot rely only on broad image processing techniques such as center of gravity and peak intensity tracking. This is because these methods analyze the sensor output data globally. In contrast, multiple beams exist in multiple places on the sensor. As a result, local tracking has to be performed. In addition, beams must be separated from noise, individually identified, verified and associated/labeled correctly. As will be seen in [Chapter 6](#), multi-beam tracking takes lessons from multi-target tracking. As a result, this function flow is heavily inspired by multiple target tracking.

An additional difference between multi-beam and single beam tracking is resource utilization and allocation. Instead of there being a transceiver and steering system per beam/link/counter terminal, the utilization of which is fully dedicated to the active link, multi-beam terminals have multiple links to contend with. The allocation of beams to transceivers and steering mechanisms requires a strategy to ensure appropriate re-

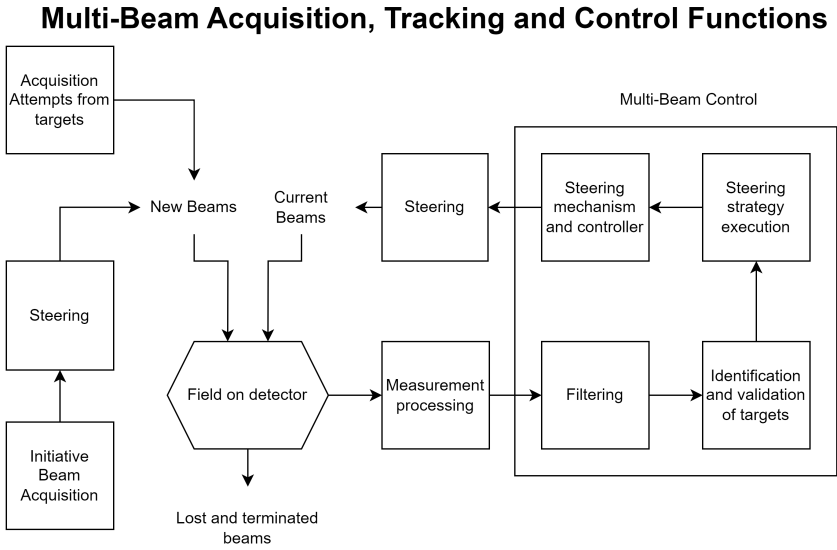


Figure 3.6.: High level function flow for a multi-beam steering system.

source allocation.

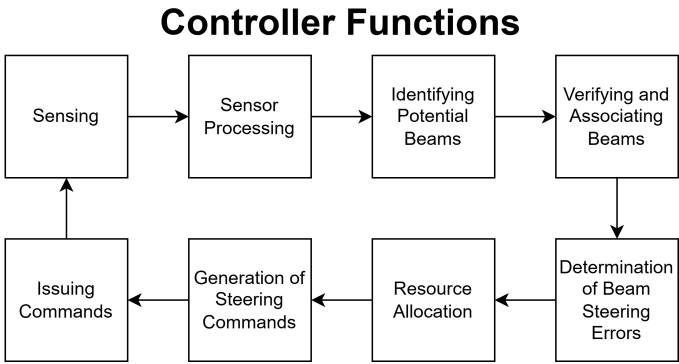


Figure 3.7.: Depicted are multi-beam controller functions arranged in a loop.

Another aspect is steering multiple beams. Multi-beam steering systems also have finite beam accommodation capacity and hence steering is a finite resource. Aside from resource allocation and steering commands, it is worth looking into the functions of a multi-beam steering stage. The multi-beam steering system employs multi-beam steering

mechanisms to steer multiple beams. The vast majority of steering mechanisms angularly change the direction of the beams. To correct for translation errors caused by motion of the targets, the optical system must convert the angular corrections into translational corrections. To correct angular errors, the optical system must ensure that the angular input is correctly projected onto the output plane. For example, angular changes in the pupil plane lead to translational changes in the image plane. The transmission as well as receiving functions are shown in Figure 3.8 while the steering stage functions are shown in Figure 3.9.

Observing in Figure 3.8 that the steering system must handle the transmitted as well as received beams. This process is almost exactly the opposite, with the difference being primarily the point-ahead angle and potentially different beam shapes or divergences. It is hence worth considering using the same system for both transmission as well as receiving. This concept will be employed in Chapter 5 and has been employed in our previous work.[31, 53]

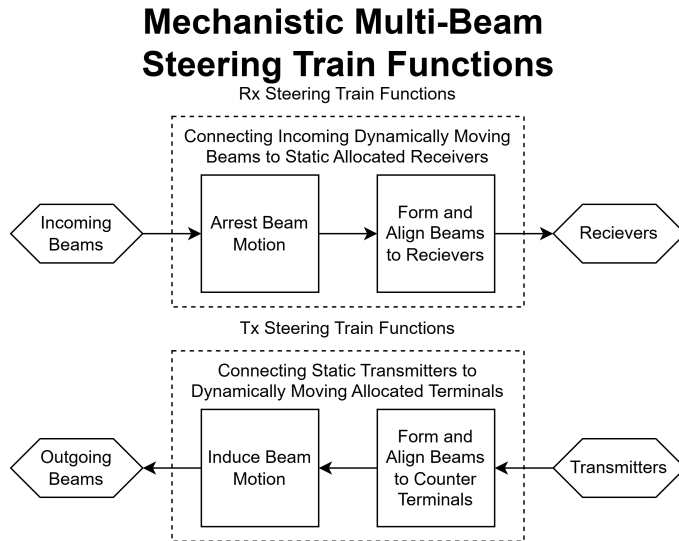


Figure 3.8.: Base functions of receive (Rx) and transmit (Tx) steering functions. The symmetry between Rx and Tx together with the two way symmetry of the underlying physics shows that Rx and Tx beams can share the same path in opposite directions. This saves components and size.

Depending on the receiver and transmitter, there might be a need to control translation as well as incident angular errors at the receiver plane for efficient coupling. This is the case for fiber based transceivers as well as same path steering layouts. As a result, a multi-beam steering system might employ multiple stages to control three rotational as well as three

translational degrees of freedom at the transceiver plane. These stages are shown in Figure 3.9 and are employed in Chapter 5. They have been discussed in previous work.[31, 53]

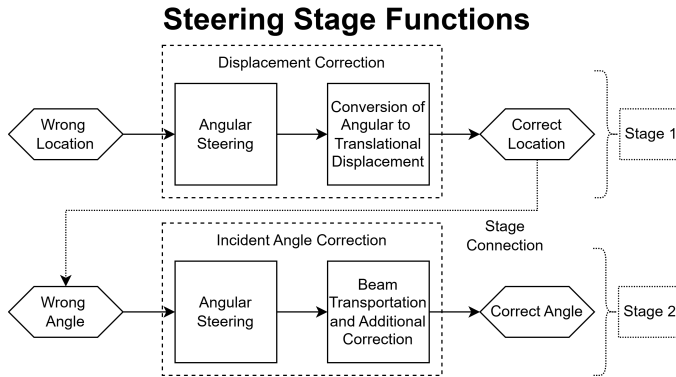


Figure 3.9.: Base functions of two steering stages with the purpose of positional correction (top) and angular correction (bottom). Combining two steering stages (depicted in the boxes with dotted lines) allows the system to correct both translation and angular errors.

In the next section the design options for the steering system will be discussed, which will also further detail each configuration which can be chosen.

3.3. DESIGN OPTIONS FOR MULTI-BEAM STEERING SYSTEMS

Now that the functions of multi-beam steering have been discussed, the design of the steering system can be investigated. When designing a multi-beam steering system, two questions arise: 1) what are the plausible design options? and 2) how can be selected between them?

To answer these questions, the approach is split into four parts: 1) An overview of the high level design choices made by other MBT designs, both for spacecraft as well as terrestrial applications. 2) A possible design decision tree is presented which can be followed as a recipe for a specific use case. 3) Example use cases have been selected to illustrate the application of the tree. 4) The results of this section are discussed.

While this chapter will shall stay on a high level, a more detailed design is likely dependent on the specific requirements at hand.

3.3.1. PREVIOUS MULTI-BEAM STEERING SYSTEM DESIGNS

Having detailed the MBT functions, it is now possible to look at design options to fulfill these functions. In this subsection, design choices will be gathered based on previously discussed literature on MBTs. The goal is to determine what designs are commonly used in which context. However, in order to overcome the lack of literature on MBTs, designs from adjacent fields which contain systems with overlap of space MBTs have also been selected. In total 20 systems were selected from space MBTs, 3D MEMS optical cross connects (OXC), Lifi, and fixed multiple input and multiple output (MIMO) free space laser communication systems. An overview of these systems including references can be found in [Appendix B section B Table B.2](#). This list is by no means exhaustive. However, it provides a selection of systems out there to illustrate their associated design options. Visual representations of the steering systems are provided in [Figure 3.10](#).

The evaluated systems showed that the design choices were influenced by the way multi-beam communication was applied. For example, if the application involved static targets, closed loop control systems were less likely to be chosen, unless it required adaptive optics to compensate for turbulence. The observed applications can be broken down into four categories, each with two distinct and juxtaposed application subcategories: 1) Transmission: broadcasting and point-to-point. 2) Target behavior: Static vs moving targets. 3) Target density with respect to steering system spatial resolution: higher or lower. 4) Communication direction: duplex or non-duplex.

The steering design choices were more diverse, both between and within categories from adjacent fields. For example: MBTs, LiFi and fixed MIMO systems all have examples of transceiver selection as a design choice for steering beams. It was found that when a different combination of these design options were chosen, it would drive the design and steering mechanism selection into a different direction from other systems. The steering system design choices were split into three main categories: 1) The chosen steering mechanism(s). 2) Type of steering control loop employed. 3) Number of steering stages used.

These systems were placed in a table to show combinations of application and design choice. This table can be found in [Appendix B section B](#) labeled [Table B.1](#) with [Table B.2](#) serving as index for the acronyms. This can be useful for readers looking for examples and literature. It also shows which application and design choices are most popular. Nevertheless, this table is cumbersome, making it difficult to evaluate which design choices could be used for space MBT steering systems or borrowed from adjacent fields. One clear choice that has not been made in the selected systems is broadcasting.

To show overlap with adjacent fields, show patterns and make the discussion clearer, a more digestible color coded version of the literature

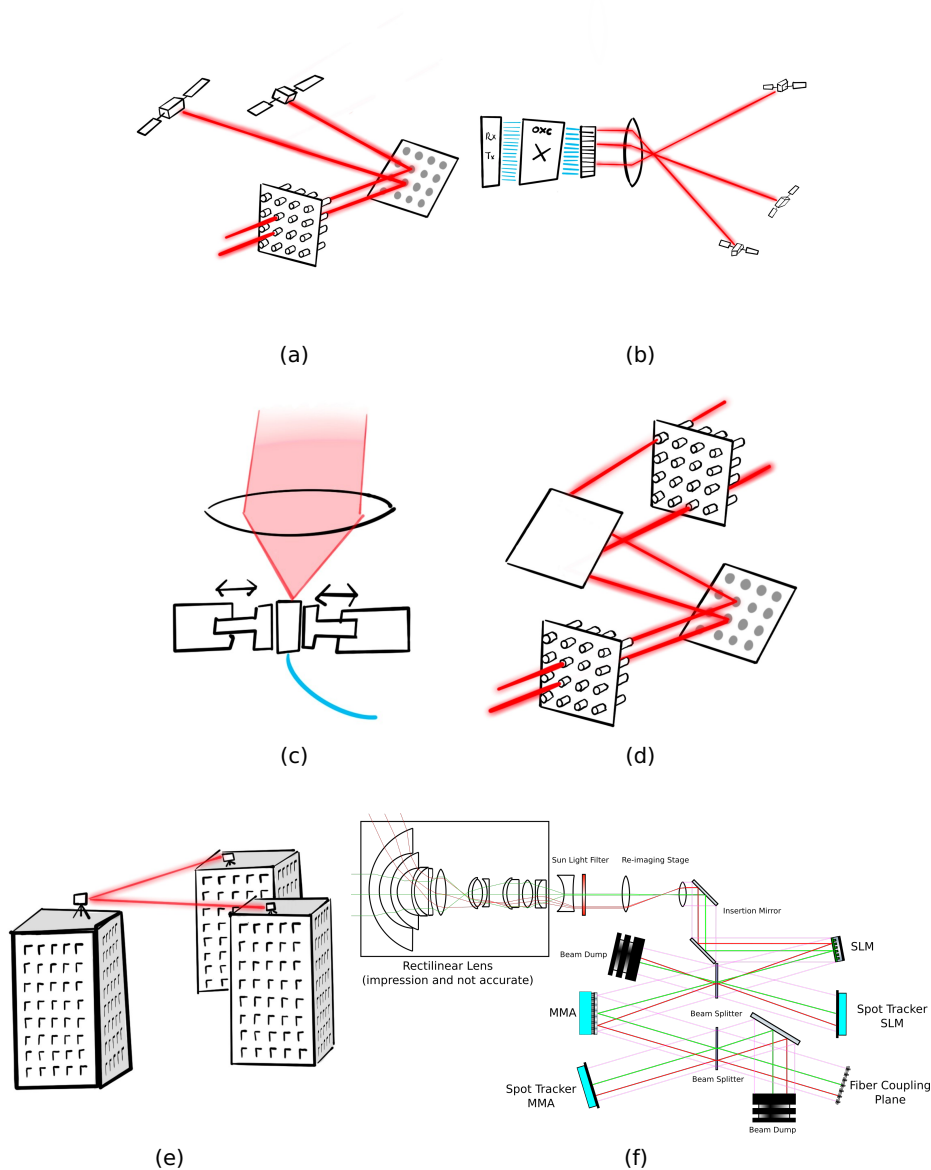


Figure 3.10.: Illustrations of multi-beam steering systems. (a) FSM and large mirror arrays. (b) Transceiver selection system. (c) Transceiver positioning. (d) 3D MEMS switch. (e) Fixed MIMO system. (f) Multi-staged multi-beam steering system. Figure taken from "Free-Space Multi-beam Optical Communication Terminal Design for Spacecraft" by J. Spaander on page 81 Figure 5.32[31], reprinted with permission.

tables for systems in each adjacent field are compared. These can be found in Table 3.1 with the color index presented in Table 3.2. Each cell in the table indicates that one of the considered designs has chosen that design option in combination with a particular application.

Table 3.1(a) shows that the design choices considered in the literature for space MBTs span most of the table. This is an indication as to the diversity of proposed MBT steering systems in literature and a main motivator for this chapter to organize these choices. Nevertheless, some observations can still be made. The most common design choice was to use a form of mirrors in a closed control loop. However, a number opt for transceiver selection. First, in order to gain insight into the design choices, we will compare these terminals with applications such as LiFi, fixed point-to-multi-point systems and optical switches (OXC) to gain insight based on overlap.

Comparing OXCs to space MBTs an interesting overlap can be observed. This is shown in Table 3.1(b). For one, the OXCs considered for this chapter use 3D MEMS micro mirror arrays (MMA) to connect one optic fiber to another one. These tend to use two steering stages to control four degrees of freedom: the angle and position of arrival. This aids fiber coupling, increasing efficiency through improved mode matching. Improved fiber coupling improves insertion losses (in this case analogous to fiber coupling efficiency).[54, 55, 56, 57, 58] Such functionality was already discussed in Section 3.2.4.

Furthermore, since both the optic fibers are static, each optic fiber on either end of the steering system has a dedicated micro-mirror. These MMAs are selected for their switch speed and their ability to connect any two fibers through a combination of two mirrors (see Figure 3.10(d) for illustration). This makes it possible to cross connect on the order of 1000x1000 fibers in a compact form factor.[54, 55, 56, 57, 58, 59, 60, 61] This demonstrates the scalability, performance and mechanism-sharing principles of such a steering system.

Since each fiber has a dedicated mirror, the beams are both of a smaller diameter than the mirrors and the angular target density must be smaller than the spatial resolution of the steering mechanism (referred to as the steering resolution, not to be confused with angular resolution). Lastly, since the location of each fiber is known, the control loop used is open and no tracking sensors are required. This in turn saves signal power due to no beam splitter being needed to feed light into a tracking sensor and thereby improving overall system efficiency.

While some space applications might use an open control loop for transceiver selection, when using mirrors this is likely not the case. Closed control loops are chosen primarily to correct for non-static targets and the need to compensate the target wander as well as the spacecraft jitter. This makes the transferability of the control aspects limited between 3D MEMS OXCs and MBTs. On the other hand the improvement in fiber

(a) Space terminals										
Application\Design Choice	Transmitter selection	Large Mirrors (beam diameter < mirror)	FSMs and MMAs (beam diameter < mirror)	MMAs and SLMs (beam diameter > effector)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point										
Static targets										
Moving targets										
Target density greater than steering system resolution										
Target density smaller than steering system resolution										
Duplex										
Non-duplex										

(b) Space terminals compared to 3D MEMS optical cross switches										
Application\Design Choice	Transmitter selection	Large Mirrors (beam diameter < mirror)	FSMs and MMAs (beam diameter < mirror)	MMAs and SLMs (beam diameter > effector)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point										
Static targets										
Moving targets										
Target density greater than steering system resolution										
Target density smaller than steering system resolution										
Duplex										
Non-duplex										

(c) Space terminals compared to indoor LiFi terminals										
Application\Design Choice	Transmitter selection	Large Mirrors (beam diameter < mirror)	FSMs and MMAs (beam diameter < mirror)	MMAs and SLMs (beam diameter > effector)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point										
Static targets										
Moving targets										
Target density greater than steering system resolution										
Target density smaller than steering system resolution										
Duplex										
Non-duplex										

(d) Space terminals compared to fixed point multi-point terminals										
Application\Design Choice	Transmitter selection	Large Mirrors (beam diameter < mirror)	FSMs and MMAs (beam diameter < mirror)	MMAs and SLMs (beam diameter > effector)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point										
Static targets										
Moving targets										
Target density greater than steering system resolution										
Target density smaller than steering system resolution										
Duplex										
Non-duplex										

Table 3.1.: Literature Comparison Tables, see Table 3.2 for the index. "B" and "M" denote beam and mirror sizes respectively.

Legend:	
Optical Switching and Interconnects	
Indoor LiFi	
Fixed point to multi-point	
Space <100 tragets	
Space >100 tragets	

Table 3.2.: Index for Table 3.1.

coupling efficiency when using multi-stage control can be considered to improve the system efficiency and signal to ratio. The MBT designed by the TU Delft proposes an SLM-MMA multi-stage steering system, using the SLM to correct for target wander (thereby spatially decoupling the targets from the transceivers) and an MMA for higher speed disturbance compensation.[31] Control over the position and angle has the additional benefit of allowing the transmitted and received beams to follow the same path. A closed control loop necessitates the addition of tracking sensors which in turn reduces signal power efficiency. A system with a similar control scheme is proposed by Mitchell et al.[62] to compensate for jitter, however, this is used to control the same degrees of freedom for a single beam.

Table 3.1(c) shows limited overlap between the selected LiFi systems and space MBTs. However, this approach is similar to transceiver selection and taken as a method to make a compact system without moving components. Furthermore, the wider beams also allow for users to move throughout the FoR without the need for high spatial resolution in both steering and tracking. As a result, the target density can be larger than the steering resolution.

Lastly, Table 3.1(d) compares fixed point-to-multi-point systems. These systems are used, for example, to communicate between buildings or server racks. There is significant overlap. For one, many of these systems also require closed loop control to compensate for jitter. However, the propagation distances are on the order of meters to kilometers, in stark contrast to 100s km to 10,000s km for space applications. Additionally, these terrestrial applications have considerably less strict SWaP requirements. This allows fixed point-to-multi-point systems to use mirrors larger than the beam diameters. Nevertheless, these proposed systems are free space multi-beam laser communication terminals used for MIMO network applications.

Also important to note, no system considered used light to broadcast information over the whole aperture. While not directly motivated in literature, it can be speculated that this has not been done due to it

removing the main benefit of optical communication, namely low beam divergences. The lower beam divergence in turn reduces power losses.

Coming back to space MBTs, it is clear that closed control loops are preferred due to target motion and jitter. However, when considering design choices for steering mechanisms mirrors and transceiver selection are most popular. Although these design choices are not fully justified in the literature discussed, it does seem that these systems intend to simplify the system by removing control loops and moving components. Nevertheless, creating a duplex system where the received beam is passively coupled into the receiver is a difficult task which requires high densities of receivers to cover the FoR and numerous hand-overs during the link sustainment phase.

It is important to note that the discussed design choices until now in this subsection have not been directly motivated from the perspective of SWaP or performance in their associated literature. It is difficult to find exact dimensions, mass and power consumption data as well as an analysis and motivation as to why.

Having considered the design choices and application context for examples of previous MBT steering system designs, [Section 3.3.2](#) will combine these design choices. The combined design options are presented with a proposed method for choosing between them.

3.3.2. DESIGN OPTIONS AND RECIPE

Having evaluated the design choices made by previous designs in [Section 3.3.1](#), an overview of design options and their associated method of applying multi-beam communication can be created. This section will investigate and propose a method on making choices between the design options at this preliminary stage. The design options were analyzed and organized. On this basis, a design choice model (recipe) in the form of a design option tree is proposed in [Figure 3.11](#). This tree can be used by answering simple yes or no questions based on the use case selected.

The first step in [Figure 3.11](#) is not chosen often, as shown in [Table 3.1](#), since this would negate the slow beam divergence benefits of optical wavelengths.

Having selected point-to-point communication, the question of the motion of the targets need to be answered. In static target applications, placing the terminals statically reduces the system complexity substantially. However, for inter-satellite and space-to-ground communication as discussed in [Section 6.1](#), this is not a valid assumption.

The target density in these applications could be higher than the steering spatial resolution. I.e., are there enough steering effectors to steer each beam individually or are the beams resolvable? As a result, distinguishing and serving the targets individually through the steering system might not be possible. This would imply that transceiver selection

Link Design Decision Duplex Tree Laser Communication System

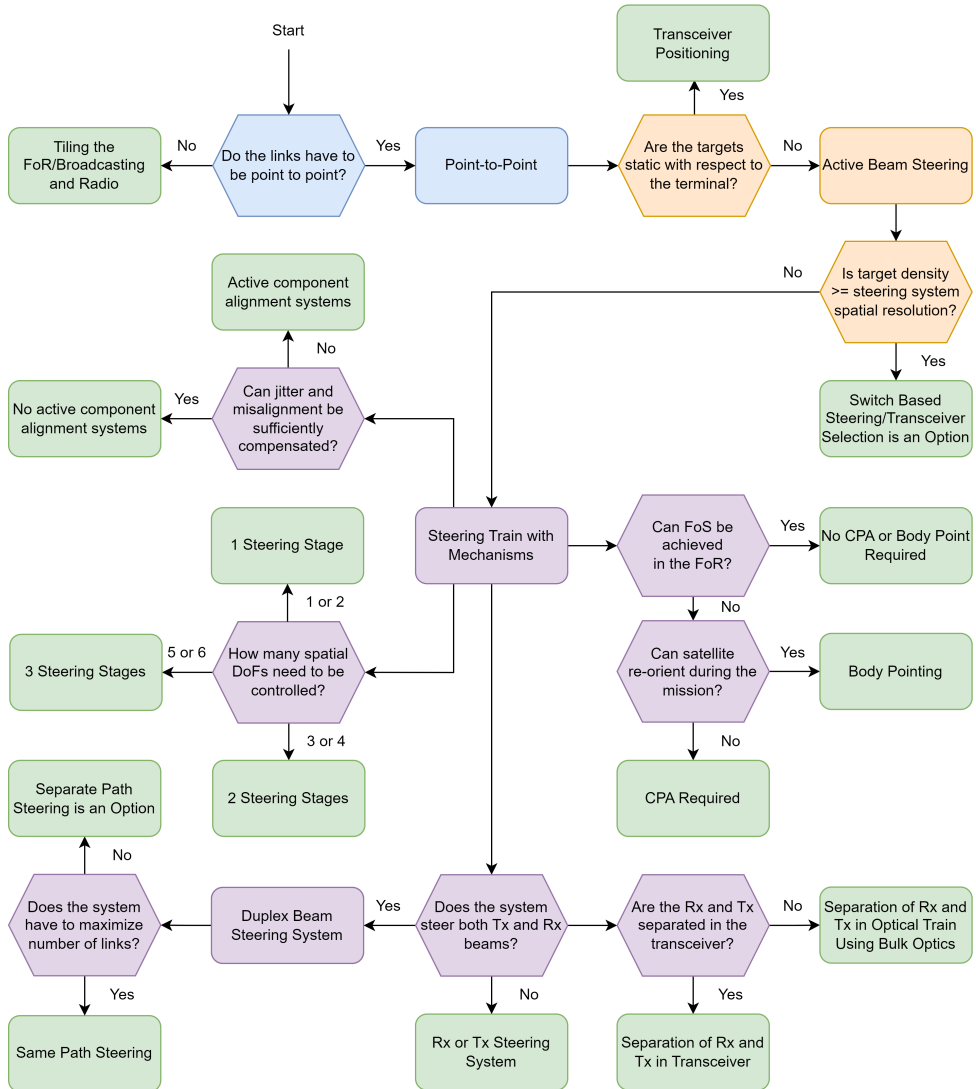


Figure 3.11.: Design options tree.

could be a possible design choice due to the discretization of the field of service not being problematic. In fact, choosing this option could be advantageous as it would not require any moving components in the optical system and reduce the steering system complexity. However, when communicating with resolvable targets which need to be served individually, this could become an issue. In such situations strong improvements in efficiency and cross talk can be achieved by steering beams individually.

At this stage steering mechanisms should be chosen. Due to the variety of options found in literature as well as functions discussed earlier, this part of the tree is more detailed. Moving clockwise starting with comparing the FoS to the FoR, the question of the need for a coarse pointing assembly (CPA) can be answered by whether or not the field of service can be achieved in the field of regard. An alternate formulation could be: can the terminal re-orient itself to point into a different direction? Should this not be the case and the satellite cannot reorient during the mission, then a CPA is required.

The transceiver type will influence the geometry of the steering system. Bulk optics or fiber based transceivers would have differing coupling requirements. Furthermore, the need for a duplex system will influence the choice on the need to simultaneously steer beams in multiple directions. This makes the steering system more complex. Lastly, the number of beams required to be tracked can be halved if the Rx and Tx beams share the same path. As a result, only one set of beams needs to be tracked, simplifying the system. On top of this, the system also becomes more signal power efficient not having to track as many beams.

As discussed in [Section 3.3.1](#) and [Section 3.2.4](#), multiple steering stages allow control over more degrees of freedom (DoFs). A single steering stage, for example, can influence the spot position, however not the angle of arrival i.e. two DoFs. Increasing the number of steering stages to two allows control over the angle of arrival along two axes, increasing the controllable DoFs to four. To also change the rotation and/or delay of the beam, as might be required in polarization-sensitive applications, another stage is needed to rotate the beam about its axis.

Lastly, should the jitter not be sufficiently compensated for, then active alignment of the transceivers could be an option. However, the added complexity of such a measure needs to be subject of a trade-off.

Considering the design options, a choice needs to be made as to which type of steering mechanism/technology would suit the application best. The next section will discuss the possible trade-offs of such a choice and present some of the considerations.

3.3.3. STEERING MECHANISM SELECTION

Having applied the design options tree, the resulting design might require a steering mechanism which can steer multiple beams. The pri-

mary function of a steering mechanism is to actively control and change the direction of the beams, thereby spatially mapping the FoR to the transceiver plane. However, ideally the mechanism should also be able to perform this function continuously for the duration the target is active and in the FoR. This is both a function of its ability to continuously steer the beam during beam wander as well as the density of targets it is capable of handling. These are just a few basic considerations.

Provided there are numerous options to choose from with various criteria, a selection of the options was narrowed down and investigated based on the systems in [Section 3.3.1](#). In order to help compare or select steering mechanisms, [Table 3.3](#) was created to provide a holistic view of the possible options and their strengths. A graphical trade-off table for steering mechanisms was chosen because it provides a structured way to evaluate and compare the various design options based on multiple performance criteria. [Table 3.3](#) is not complete, as the criteria of cost is left out. This is done due to the high variability in cost between components and a thorough cost analysis being beyond the scope of this chapter. Moreover, users may consider to introduce weights.

The criteria chosen, their explanation and their motivation are as follows:

1. **Continuous Rx beam steering during wander** is a criteria where the received beam might be lost when traveling through the FoR. This drop can occur when the beam moves between mirrors, or onto a mirror with another beam already steered. It could also occur when moving between selected receivers.
2. **Diffraction** can occur or worsen if the steering mechanism acts as a diffraction grating. Due to diffraction, the light is directed to directions other than the receiver. This can cause losses, cross talk and tracking challenges which need additional design to mitigate. SLMs suffer from diffraction depending on the device.
3. **Space heritage** is an important parameter for many spacecraft designers with regards to risk and performance.
4. **Flexibility and multi-purposeness** can be offered by a steering mechanism. These aspects in optics originate from the same functionality, namely, the ability to change the phase and amplitude of light spatially. SLMs for example, can edit the wavefront at high resolutions, allowing for aberration corrections and beam shaping. As a result, a commercial-off-the-shelf device can reduce the number and cost of optical components as well as correct dynamically to new changes in optical performance.
5. **Allowable proximity between beams** represents the closest distance allowable between beams. It is one of the determinants of the

Multi-Beam Steering Mechanism Trade-Off Table						
Steering Mechanism	Micro-Mirror SLM	Liquid Crystal SLM	MMA > Beam Diameter	FSM array with mirror > beam diameter	Large mirror array with mirror > beam diameter	Transceiver selection
Continuous Rx beam steering during wander	No loss of signal when beam wanders.	No loss of signal when beam wanders.	Beam wander must remain on the mirror.	Beam wander must remain on the mirror.	Beam wander must remain on the mirror.	Beam wander must remain on the mirror.
Diffraction	Diffraction is inherent but dependent on specific device.	Diffraction is inherent but dependent on specific device.	When on the mirror there is no diffraction.	When on the mirror there is no diffraction.	When on the mirror there is no diffraction.	When on the mirror there is no diffraction.
Space heritage	Limited.	Limited.	Limited.	Prominent in space SBTs but not as array.	Large mirrors are prominent in space telescopes and some SBTs.	Limited.
Flexibility and multi-purpose	Re-programmable to serve any optical functions.	Re-programmable to serve any optical functions.	Limited to tip-tilt mirror.	Limited to tip-tilt mirror.	Limited to tip-tilt mirror.	Limited to discrete transmission and receiving angles.
Control loop	High resolution devices can be computationally more expensive to control.	High resolution devices can be computationally more expensive to control.	Standard mirror control loop.	Standard mirror control loop.	Standard mirror control loop.	Tracking similar to standard control loops. Steering performed through optical switching.
Allowable proximity between beams	Beams can partially overlap.	Beams can partially overlap.	One mirror diameter.	One mirror diameter.	One mirror diameter.	One transmitter or receiver diameter.
Mass	Low.	Low.	Low.	Medium.	High.	Low.
Polarization limitations	None.	Polarization must align with crystal polarization.	None.	None.	None.	Device dependent.
Wavelength limitations	Mirror actuation range and accuracy dependent on wavelength. Element is dispersive.	Mirror actuation range and accuracy dependent on wavelength. Element is dispersive.	None.	None.	None.	None.

Table 3.3.: Multi-Beam steering mechanism trade-off.

allowable target spatial density and proximity to each other. Allowing beams to get closer together would allow for more beams to be accommodated at higher densities. For some devices, such as mirrors larger than the beam diameter, the allowable proximity would be one mirror. For SLMs, the subdiscretization of the beam diameter by pixels allows for the beams to even overlap, making the allowable proximity a function of allowable cross talk and resolvability.

6. **Mass** is an important cost and performance determinant for spacecraft. Larger and heavier systems, such as large mirror arrays, would increase substantially the mass of the spacecraft compared to small and condensed SLMs and MEMS micro-mirror arrays.

7. **Polarization limitations** can be imposed by the steering mechanism, which in turn could make the optical design more complex as well as reduce the multiplexing and modulation options. Liquid crystal SLMs are polarization sensitive in their working and as a result reduce polarization freedom. In contrast, FSM and MMA devices are generally not polarizing nor polarization sensitive.
8. **Wavelength limitations** in the form of specified bandwidth or specific wavelengths can be imposed by the selected steering mechanism. When mechanisms impose a wavelength bandwidth, they simultaneously impose multiplexing and modulation limitations. SLM actuators move/delay the wavefront, making the steering wavelength dependent. As a result, for dense wavelength multiplexing, SLMs can still be used. For broader spectra this becomes more difficult as the wavelengths will disperse.

Table 3.3 shows that micro-mirror and liquid crystal SLMs have strengths and weaknesses that complement those of laser micro mirror arrays, FSMs and large mirror arrays as well as transceiver selection. Therefore, in multi-stage steering, two different steering mechanisms could complement each other well. Combining these could also lead to the best of both worlds[31].

Furthermore, it is important to note that the diffraction effects of SLMs extend beyond losses. The diffraction pattern can also cause clutter and interfere with tracking. Methods to reduce the influence of diffraction include resorting to higher resolution SLMs, improved phase screens and algorithms.[63, 64, 65, 66, 67, 68, 69] Additionally, kilo-watt level continuous wave laser powers are available.[70]

In the next subsection, a use case is applied to the methods discussed in previous sections to illustrate the suitability of the presented methods.

3.3.4. APPLICATION ON EXAMPLE USE CASES

To demonstrate the working of Figure 3.11 and investigate patterns in the design of MBTs, the method is applied to use cases discussed in Chapter 2. Harkening back to Section 6.1 and Chapter 2, the primary applications of interest for MBTs are facilitating multiple links with non-static targets from space-to-ground or from space-to-space. As a result, the use cases selected for this subsection are a subset of the use cases discussed in Chapter 2.

Critical to the design options discussed in Section 3.3 are the densities and numbers of targets. Chapter 2 derives estimates for the density and number of targets on the basis of types, altitude, field of view and use case. Clear from the analysis there is that the angular resolution limits the number of resolvable targets from higher altitudes, however, at the same time higher altitudes allow for large numbers of consumers

to fall within the FoR. Furthermore, the number of users and their densities vary with selected target types. For example, when selecting target types such as aircraft or other satellites within a LEO constellation, the densities and target numbers drop. Furthermore, when selecting trains and communication towers, these densities and numbers go up.

As a result, two axes were identified for the selection of the use case: 1) Number of users. 2) Target density. The considered use cases are illustrated on [Figure 3.12](#).

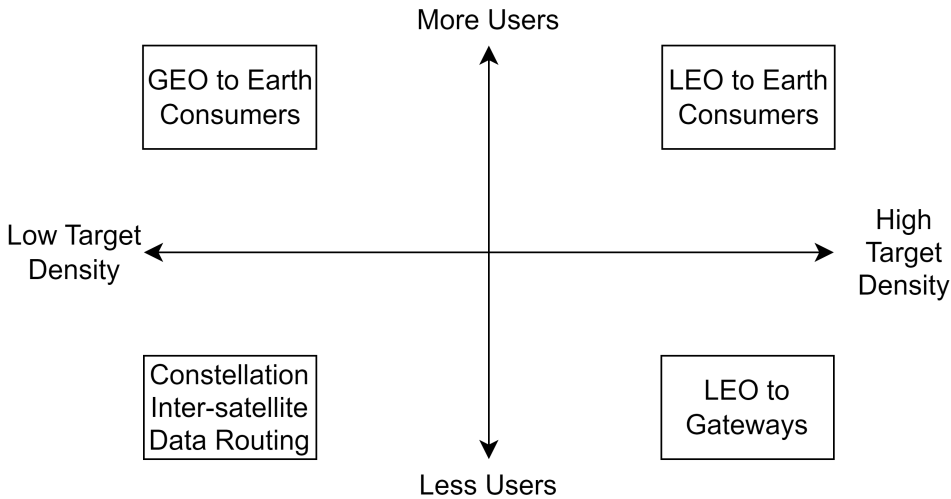


Figure 3.12.: Comparison of use cases on the basis of target wander and number of targets.

From the use cases in [Figure 3.12](#), LEO to Earth based Consumers (referring here to trains, communication towers, ships and aircraft discussed in [Chapter 2](#)) and Constellation Inter-satellite Data Routing were chosen. These were selected as these differ most in both target numbers and densities.

In addition, for this example, the LEO to Earth use case is said to have lower data rate requirements per link compared to the inter-satellite data routing.

The functions discussed in [Section 3.2.1](#) and [Section 3.2.2](#) center around compensating for the motion of numerous non-static targets. Fundamentally, multi-beam systems have sensors with limited spatial resolution when tracking and a limited density/number of actuators on steering mechanisms to steer beams with. However, from the use cases of interest, each target is provided a unique beam. This places the capacity requirements on the tracking and steering mechanism selection.

For these examples, for both the aforementioned use cases, the following criteria were specified:

1. Each link requires point-to-point communication.
2. The targets are not static.
3. The beams are resolvable both for tracking and steering.
4. The field of service falls within the field of regard.
5. The space environment includes jitter, requiring active jitter compensation by the steering system. Active alignment of transceivers through a transceiver alignment mechanism is avoided due to system complexity.

Now [Figure 3.11](#) can be applied for these examples. Based on the criteria list, both MBTs will use steering mechanisms over transceiver selection/switch based steering. Furthermore, both do not require a CPA and avoid transceiver alignment.

At this stage, the designs of each use case do not significantly diverge. By applying [Figure 3.11](#) to all the use cases in [Chapter 2](#), it was found that most cases result in such a combination. At this stage, what is left is the optical path with respect to the transceivers and a decision on the number of steering stages. These are more reliant on specific requirements of the terminal needs to be considered.

Combining the Rx and Tx into a single transceiver interface could save on steering system complexity. In these systems, fiber-based transceivers could be an attractive option as these have small form factors and high performance, attractive for both high target number and data relay applications respectively. Using such a scheme also allows the Rx beam to share the same path as the Tx, reducing the number of beams needed to track for duplex systems (note that this might not be possible for all steering system layouts, however, some might require multi-stage steering).

For the steering stages, the choice between one steering stage and two steering stages could be based on required degrees of freedom. A driver for this design choice could be coupling efficiency, as is the case in optical switches/cross connects. More steering stages could also be used to control polarization. In addition to increased complexity, another drawback is increased losses due to tracking demands.

Continuing the examples. In this case, the higher data rate use case could choose to use polarization for modulation and increased coupling efficiency. Hence, this application could require full control over all degrees of freedom and choose three steering stages. The lower data rates per link for the LEO to Earth Consumers might opt for just two steering stages.

Next the steering mechanism is selected using [Table 3.3](#). For an uninterrupted and geographically ambiguous service from LEO to ground a continuous steering capability during beam wander is a necessity. Furthermore, in this use case the target density could in some places be higher than others. Hence, an SLM would be required to spatially decouple the target from the transceivers. The SLM has the additional benefit of being able to correct for wide angle aberrations and distortions from the telescope, thereby potentially reducing optical components. In subsequent steering stages, the beams are already spatially decoupled. As a result, the translational wander is no longer a problem. A different steering mechanism can be selected to complement the first stage, such as a mirror array.

For data relay within constellations, lower target numbers and density as well as clear defined orbits implies less need for spatial decoupling. Using mirror arrays instead of an SLMs would be beneficial in this case. Additionally, this would allow for broad bandwidth and polarization based modulation and multiplexing options. However, such a choice reduces the steering flexibility and adaptability of this terminal.

3.3.5. TRANSCIVER ARRAY CONSIDERATIONS

In [Section 3.3.4](#) the design choices converge to a steering system based on SLMs or micro-mirror arrays. The transceiver arrays can consist of 2D fiber arrays, however, the number of links proposed in [Chapter 2](#) ranges from 10-1000 beams. If each beam has a transmit optical power between 1-10W with an efficiency of 10%, the resulting power dissipation within the satellite could be between 10-100W for 10 beams and from 1kW up to 10kW thermal dissipation. Hence, the efficiency of the transceivers together with the number of beams has strong impact on the thermal design. When combined with potential mass limitations, the number of beams might be limited to 100s for GEO platforms and 10s for LEO platforms.

3.4. CONCLUSION

In this chapter, an overview of the literature, application, functions and design options of multi-beam laser communication terminals (MBTs) steering system for satellites has been provided.

In this and the previous chapter ([Chapter 2](#)), it was found that MBTs are useful in increasing the connection reliability to a wider network and serve numerous customers. Furthermore, such terminals add routing options and functionality through a nodal network to laser communication. When accommodating multiple links in one system, where components can be shared, the cost and SWaP per beam decreases. This also allows scalability.

The functions of a multi-beam steering system were investigated by evaluating literature on previous designs of MBTs and by looking at adjacent fields of single beam laser communication terminals (SBTs), multi-beam radio systems and multiple target tracking. It was found that there are common functions all multi-beam steering systems have in common, such as parallel acquisition and sustainment of beams based on monitoring of a wide FoR. They apply tracking schemes based on probabilistic analysis and verification of the beams being tracked. The functions can be viewed from the perspective of a beam or the terminal as a whole. It was found that MBT acquire, maintain and terminate multiple links at once in parallel, in contrast to SBTs.

Furthermore, the design of the steering system was analyzed on the basis of a variety of design options. These design options were sourced from previous space MBTs together with systems of adjacent fields of 3D MEMS optical cross-connect switches, indoor LiFi and fixed point-to-multi-point systems. It was found that a significant portion of the design of MBTs overlap with 3D MEMS optical cross connect switches and fixed point-to-multi-point systems. When looking broadly at these systems, design choices were found and presented in a design decision tree which can act as a recipe for initial high level design choices depending on the use case.

Options for steering mechanisms were contrasted in a visual trade-off table. Found was that steering mechanisms of various types complement each other's strengths and weaknesses.

The design options and trade-offs were applied to two example use cases gained from [Chapter 2](#), one with high numbers of targets and another with lower numbers of targets. It was found that both can utilize multi-staged steering systems to provide control over all the relevant degrees of freedom. They differed, however, in the selection of the steering mechanism on the basis of data modulation freedom and spatial decoupling.

Furthermore, due to their ability to continuously steer wandering beams, MEMS micro-mirror array and liquid crystal SLMs are devices which show promise when used as a steering mechanism in at least one steering stage to spatially decouple the target from the field of regard. Additionally, they offered a high degree of flexibility, owing to their ability to adjust the wavefront at high resolutions.

As a result, research into- and demonstration of SLM based tracking and steering stages will be the subject of the remainder of this thesis. In the next chapter, the hardware setup used will be discussed.

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4

HARDWARE SETUP

I don't have a plan, but I do have a strategy.

C.J. Cregg (*The West Wing*)

This chapter presents the design and implementation of a novel experimental hardware setup for multi-beam laser communication, containing a new multi-beam source as well as a demonstration of a multi-beam steering layout. The setup is specifically developed to enable subsequent chapters to demonstrate multi-beam steering concepts and to experimentally verify and validate the underlying theoretical models and concepts. The chapter details the optical layout, including the architecture for generating multiple independently moving beams and projecting them through the optical system. Additionally, it explores the interfaces of key devices, such as the image detector and spatial light modulator (SLM). Furthermore, the methodology implemented for efficient management of interfaces and their relation to system memory will be explained. This setup not only addresses a gap in existing experimental infrastructure but also serves as a platform for advancing research in multi-beam laser communication systems.

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4.1. INTRODUCTION

The investigation into the design options and trade-offs in [Chapter 3](#) yielded a multi-beam steering system layout of interest based on spatial light modulators (SLMs). The SLM in this system functions to allocate individualized steering area and input to each beam dynamically as the beam wanders. As a result, the beams are then steered correctly between the targets and transceivers. In the coming chapters, steering and tracking concepts using this system will be further investigated. At the core of the employed methodologies are hardware experiments.

The goal of this setup is to create a representative environment to demonstrate multi-beam concepts. The setup should therefore be capable of producing and reproducing multiple independently moving beams. Additionally, it should be able to generate images of these beams through an image detector. Furthermore, this setup should be re-configurable to experiment with different aspects of steering and tracking separately. Lastly, the form factor and number of components should be minimal within the constraints of the lab environment.

Some hardware demonstrations have been performed in the context of multi-beam terminals for spacecraft. However, these have been performed for different steering system layouts.

Lab, Indoor and outdoor hardware demonstrations have been performed by Changchun University of Science and Technology, China. Huilin et al. presented initial experimental results for a mirror array.[3] Further analyses were performed on the parabolic confocal reflection array by Zhang et al.[4] Subsequently outdoor ground-to-blimp tests were performed in 2021 by Wang et al. using a prototype of this system[5] and again indoors in 2023 by Wang et al.[6] The steering system design mainly focuses on large mirrors followed by subsequently separate optical system with fine/fast steering mirrors (FSMs) for each beam.[3, 4, 5, 6]

A critical difference between these hardware setups is the underlying selected beam steering system designs. The SLM based steering system proposed in [Chapter 3](#) shares both tracking and steering components between beams.

Efforts by the German aerospace center (DLR), presented by Poliak et al. in 2022 and 2024, in collaboration with ESA designed and built a wide FoV telescope and steering system for an MBT in geostationary orbit. These have been demonstrated in a laboratory setting.[7, 8] However, due to the mission profile, this demonstration included a single MEMS mirror to control a beam.

However, this setup does not allow for individualized steering of each beam similar to the proposed SLM based steering system.

To the author's knowledge, SLM-based multi-beam steering stages for space-based multi-beam terminals have not previously been demonstrated.

This chapter presents the design and implementation of a novel experimental hardware setup for multi-beam laser communication, containing a new multi-beam source as well as a demonstration of a multi-beam steering layout. The hardware setup will serve as the foundation for the research, verification and validation activities in the remainder of this dissertation. This was done to verify that the theoretical behavior and performance correspond to practical experiments. In addition, performing hardware experiments was expected to yield additional practical challenges that could be taken into account in the subsequent research. Furthermore, it was also used to validate that the outcomes correspond to the desired outcome for the system as a whole.

The aim of this chapter is to provide a specific description of the setup and to document the choices and working thoroughly. Starting with the requirements, the specific capabilities will be detailed. Then, the individual components will be discussed in more detail, beginning with the multi-beam source, image detector and SLM. After this, the overview of the system and optical integration will be discussed. Lastly, different configurations for testing different concepts are highlighted. At the end of the chapter, a component list is provided before the conclusion.

4.2. REQUIREMENTS

Having discussed the high level system design and functions in [Chapter 3](#), this section will detail the requirements for the setup. Requirements will be denoted with "HSR" (hardware setup requirement). There will be four sets of requirements discussed:

1. The high level setup requirements. These will be denoted with "HL". These will prescribe the required capabilities and layout of the setup as a whole.
2. The multi-beam source requirements. These will be denoted by "MBS". These will define the capabilities of the multi-beam source.
3. The image detector requirements. These will be denoted by "ID". These will describe the technical specifications of the camera.
4. The SLM requirements. These will be denoted by "SLM" and will describe the technical specifications of the SLM.

These will also be discussed in this order, starting with the high level setup requirements. Focus was placed on proof of principle and on individual elements of the steering and tracking of multiple beams. Therefore, overall control loop latency requirements were deemed outside of the scope.

4.2.1. HIGH LEVEL SETUP REQUIREMENTS

The goal of the setup is to verify and validate SLM based multi-beam steering system concepts and theory. As a result, the following high level requirements have been deduced:

HSR-HL-1: The hardware setup shall use an SLM steering and image detector based multi-beam steering system layout.

HSR-HL-2: The hardware setup shall generate multiple individually moving beams.

HSR-HL-3: Individual elements shall be compatible with a metric optical breadboard system with grid of M6 tapped holes at 2.5 cm pitch.

4

HSR-HL-4: The selected wavelength will be in the visual range (630-400 nm).

HSR-HL-1 stems directly from the discussion in [Chapter 3](#). In order to evaluate this system, reproducing its layout is required. Furthermore, HSR-HL-2 specifies that multiple individually moving beams must be produced in order to create a better representation of moving beams. HSR-HL-3 is a practical requirement that allows both flexibility and compatibility with available hardware in the laboratory. The visual wavelength (specified by HSR-HL-4) was selected in order to make alignment easier, have a wider range of compatible hardware and reduce cost.

4.2.2. MULTI-BEAM SOURCE REQUIREMENTS

The multi-beam source creates individually moving beams in a form factor that is compatible with the rest of the setup. From this, the following requirements were specified:

HSR-MBS-1: The beam motion shall be reproducible to within one pixel on the image detector.

HSR-MBS-2: The beams shall be projected onto an area of 15x15 mm at the SLM plane.

HSR-MBS-3: The multi-beam source shall provide at least 10 beams and at most 1000 beams.

HSR-MBS-4: The multi-beam source shall provide beams such that they will not overexpose the image detector.

HSR-MBS-5: The dwell time of a beam shall not fall below 1 second.

In order to compare between concepts and noise profiles, reproducibility of experimental conditions and results is crucial. HSR-MBS-1 specifies that the beam motion must be reproducible and to what

extent. HSR-MBS-2 specifies the interface between the source and the SLM in order to achieve steering. Next, HSR-MBS-3 is derived from [Chapter 2](#), where an estimate with regard to the number of required beams was provided. HSR-MBS-4 is to ensure compatibility with the image detector. Lastly, HSR-MBS-5 ensures the dwell time is compatible with the dwell times discussed in [chapter 2](#).

4.2.3. IMAGE DETECTOR REQUIREMENTS

The image detector is the sensor used to track beams. It must therefore be able to spatially resolve them. Additionally, the camera should allow raw image acquisition without active noise suppression. The following requirements were specified for the image detector:

HSR-ID-1: The image detector shall have an API and SDK.

HSR-ID-2: The image detector will provide control over the image acquisition settings (see description below for further specification).

HSR-ID-3: The image detector shall have its sensor directly exposable, with only cover layers allowed.

In order to control and integrate the image detector, application programming interfaces (APIs) and software development kits (SDKs) should be provided and is specified by HSR-ID-1.

Furthermore, in order to change the signal to noise ratio, exposure and ensure reproducibility, the image detector must provide control over the image acquisition process. The settings that must be controlled include frame rate, exposure time, digital amplification and sensitivity. This is specified by HSR-ID-2.

The image detector should also not have any built-in optical components. These will interfere with the optical setup. Nevertheless, the sensor would be allowed to have a cover in order to protect the delicate pixels. Hence the requirement HSR-ID-3.

4.2.4. SPATIAL LIGHT MODULATOR REQUIREMENTS

The SLM lies at the core of the steering system concept. Its function is to separate and direct beams between the target and the transceivers. The following requirements were specified for the SLM:

HSR-SLM-1: The SLM shall be compatible with visual and near infrared wavelengths between 1550 nm and 400 nm.

HSR-SLM-2: The SLM shall have at least 1 million individually addressable pixels.

HSR-SLM-3: The SLM shall be directly addressable.

HSR-SLM-4: The SLM shall have a phase noise of less than 0.01π radians.

Within the context of future research and projects within the FREE program as well as within the group, a wide bandwidth SLM was selected. Hence the specification of HSR-SLM-1. HSR-SLM-2 ensures that the number of pixels is sufficient to perform individualized steering of each beam. HSR-SLM-3 ensures the phase screens can be directly displayed on the SLM from the controller. Lastly, HSR-SLM-4 ensures that the SLM does not induce significant jitter. Here, 0.5% of the wavelength was selected.

4

4.3. IMAGE DETECTOR

Having posed the requirements, the image detector can now be discussed. First the selection of the image detector and its properties are discussed. After this, the integration of the image detector is discussed.

4.3.1. SELECTION AND PROPERTIES

A selection was made of the available image detectors in the laboratory that operated in the visual range, as per requirement HSR-HL-4. Then from these the industrial vision cameras were selected due to the level of control over the image acquisition, in order to meet HSR-ID-2. In addition, these cameras were compatible with C-type lens mounts, implying the lenses could be removed, meeting HSR-ID-3. From the remaining cameras a selection was made with regard to the SDK and API. The result were two image detectors: the mono MER2-160-227U3M and the color MER2-160-227U3C.[9, 10] These two have identical performance parameters aside from the color capabilities. Due to the color sensitivity being unnecessary to the experiments, a mono camera was selected. This was done to simplify the setup and remove variables, such as color mixing and more complex spectral sensitivities among others. Both image detectors operate in visual wavelength ranges.

The image detector has a variable frame rate with a maximum frame rate of 227 frames per second (fps). Increasing the exposure time decreases the frame rate. Each frame consists of 1440x1080 pixels with a mono color depth of 8 bits. By changing the exposure time, illuminated intensity and internal amplification, the signal to noise ratio can be controlled. The data interfaces through USB 3.0.

4.3.2. INTEGRATION APPROACH

The image detector is the tracking sensor used to track multiple beams. It is therefore part of a control loop. During this control loop, the image detector takes an image which is subsequently used by the

tracking algorithm to determine the location of the beams. Based on this, correction commands are sent to the SLM. To optimize the control loop duration/latency, the integration of the image detector focused on increasing the time efficiency of the camera handling.

During operation, an image capture command is sent to the device after which an image is taken and loaded into an image buffer. The buffer content is then copied into RAM. The duration of this process depends, among others, on the exposure time, polling time and memory availability. In the multi-beam tracking experiments, discussed in [Chapter 6](#), this took around 10 ms.

As mentioned in the introduction, the initially tested multi-beam tracking algorithms were based on image processing. As a result, the initial execution time of these image-processing-based tracking algorithms was longer than the minimum frame interval of the image detector. For these scenarios an image acquisition was commanded and performed during each loop. However, after accelerating the tracking algorithm through temporal tracking methods, the tracking algorithm execution become an order of magnitude faster than the image acquisition time (around 1 ms).^[11] For the purpose of the experiments performed in [Chapter 6](#), this was of no consequence as the research focused on the tracking algorithm execution time and not the loop.

Nevertheless, this shows that image acquisition times can be a significant portion of the integrated multi-beam control loop duration. Considering the current setup, the frame rate of the camera became the limiting factor in the tracking latency. Two places of improvement with respect to the acquisition duration were determined: 1) The memory handling. 2) Parallelization of the image acquisition process. These were implemented together. This approach is shown in [Figure 4.1](#).

First, image acquisition was executed in parallel with the tracking algorithm. This implies that the time taken to acquire a new image at the end of each loop was reduced by the duration of the tracking processing.

Second, multiple memory locations were allocated for images. Once an image had been acquired, it could be copied from the image buffer into a free memory location. Then when the image acquisition function was called, a pointer would be shared with the main process. This process is shown in [Figure 4.1](#).

In addition, images were processed in place, avoiding unnecessary copy and locking operations. Furthermore, multiple memory slots were made available in order to ensure multiple images can be memory-locked by performance data tracking processes.

This method yielded a 15% loop duration improvement during the tracking experiments when the tracking algorithm execution time was 1 ms. For tracking algorithm execution times of 10 ms, this yielded a 50%

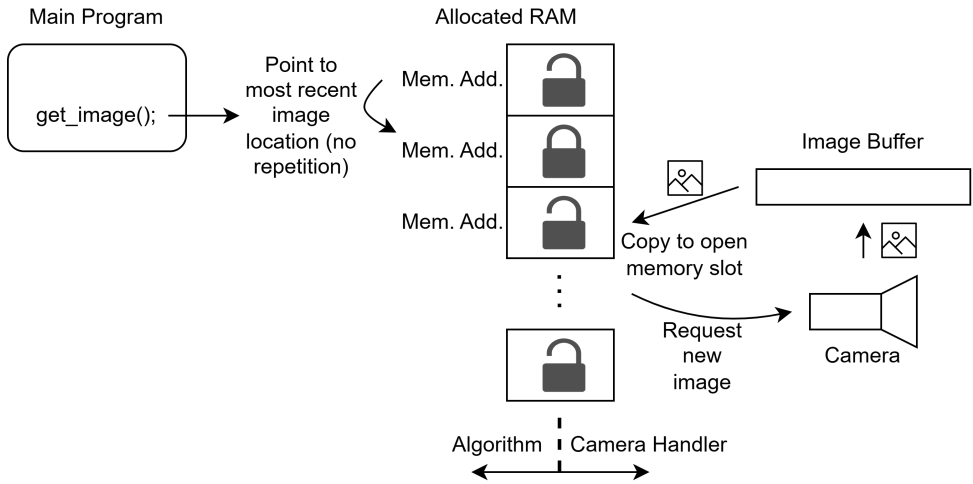


Figure 4.1.: Shown is a schematic representation of camera handling. While the main program runs tracking algorithms on the left, the right camera handling program prepares and stages new images.

loop duration improvement.

This method works well for tracking algorithms which are significantly slower or faster than the image execution process. However, when this is not the case, there is a danger of the control loop becoming multi-rate. While these control loops are possible to use, they are more complex. Hence, in addition to acquiring in parallel, time stamps should also be provided in this case to aid, for example, Kalman filters.

In addition to memory management and acquisition optimization, the provided API was used to adjust settings such as the exposure time and sensitivity. All the code was written in C and C++. The compilation was performed through CLS and GCC with performance settings enabled.

4.4. SPATIAL LIGHT MODULATOR (SLM)

The SLM is used to steer beams by modulating the wavefront through phase screens. The SLM consists of an array of individually addressable pixels, similar to a display. Each pixel can change the phase of reflected light through varying the wavefront delay. In this way, custom phase screens can be displayed. As a result, each beam can be allocated a steering area so that it can be steered individually. This process will be further detailed in [Chapter 5](#).

4.4.1. SELECTION AND PROPERTIES

Various suppliers were contacted with the requirements specified in [Section 4.2](#). The SLM selected was the SANTEC SLM-200 due to its versatility, broadband wavelength ranges (400-1600 nm) and ability to directly control the SLM.[\[12\]](#) This meets HSR-SLM-1 and HSR-SLM-3. Furthermore, this SLM has a resolution of 1920x1200, meeting HSR-SLM-2. The phase noise specified was 0.001π , meeting HSR-SLM-4. The SLM is controlled via HDMI and USB.

Additionally, the maximum frame rate of the SLM is 120 fps with 10 bit discretization of the phase change range (referred to as the color or pixel depth). This was interfaced with an 8-bit, 60 fps RGB graphics HDMI interface on the computer.

4.4.2. INTERFACE AND DATA HANDLING

To operate the SLM at full frame rate, 10 bit mono images at 120 fps need to be supplied via the HDMI. The interface and API handling were developed in-house in both C and Python. The principle behind these implementations is discussed below.

The SLM was driven as an external monitor by the controller. This implied that phase screens were directly displayed onto the SLM. Nevertheless, transferring 10 bit mono images at 120 fps over an 8 bit RGB 60 Hz channel remained a barrier. The solution implemented split two 10 bit mono images of 20 bits in total over three 8 bit channels totaling 24 bits. This method is illustrated in [Figure 4.2](#), the code snippet can be found in [Appendix C](#). Sending two images per frame at 60 fps allows for a total transfer of 120 fps with four bits per pixel per frame left over for other uses.

In order to minimize the computational load, these operations were programmed in binary bit shifts in both the Python and C implementations. These can be seen in [Appendix C](#).

While this solution allows for steering command inputs at 120 Hz, in reality two steering commands are sent at 60 Hz. Hence, the system effectively can only output steering commands at 60 Hz.

4.5. MULTI-BEAM SOURCE

The multi-beam source generates multiple beams and moves them independently and reproducibly. This section will detail the design and construction of the multi-beam source.

4.5.1. DESIGN SELECTION

To meet the requirements specified in [Section 4.2](#) numerous options were considered for generating multiple beams. These options were:

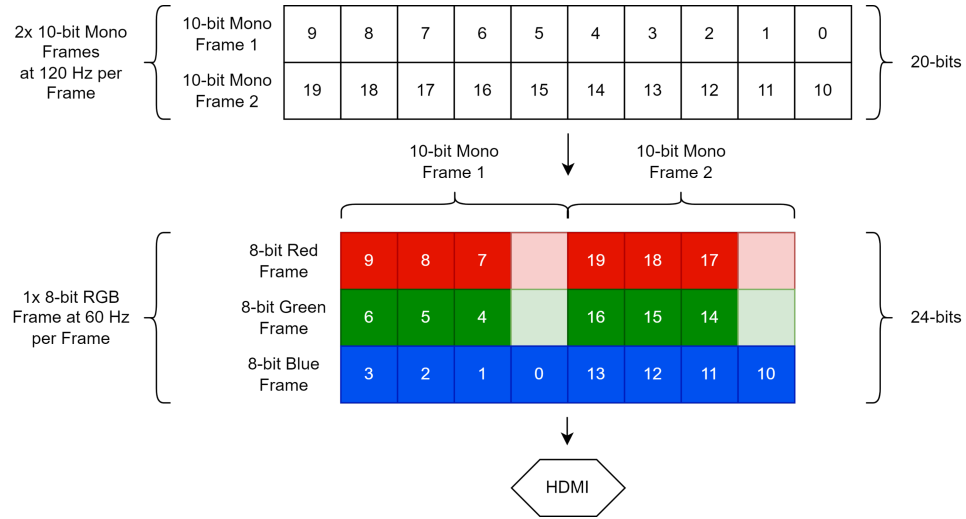


Figure 4.2.: Visual explanation of transferring 10 bit mono images at 120 Hz over an 8 bit RGB 60 Hz channel.

- Option 1: Multiple laser sources actuated through stepper stages.
- Option 2: Multiple laser sources actuated through fast/fine steering mirrors (FSMs).
- Option 3: One single laser source combined with multiple beam splitters.
- Option 4: Two rotating diffraction gratings actuated by stepper motors.

While all these options would meet the requirements, their implementation have varying levels of difficulty. A simple trade-off was performed empirically based on a difficulty rating out of 5 (with 5 being very difficult and 0 being very straightforward) to meet the requirements. This trade-off is shown in [Table 4.1](#).

Option 1 and 2 offer control over each beam. However, acquiring and integrating multiple stepper stages and/or FSMs in such a way that they do not interfere in each other's motion ranges is difficult. This would make meeting HSR-MBS-3 difficult. Furthermore, accommodating beams with the necessary spatial separation of the mechanisms also implies an extensive optical system. Additionally, acquiring and integrating 10 or more stepper stages is resource intensive.

Option 3 has similar problems. However, splitting beams into many equal parts which actuating them requires more extensive optics. This will hamper reproducibility due to optical alignment.

Option 4, shown in [Figure 4.3](#), offers a simple and compact solution which is easiest to integrate on all fronts.

Criteria	Option 1	Option 2	Option 3	Option 4
Reproducibility (HSR-MBS-1)	1	1	3	1
Format (HSR-MBS-2)	5	5	5	1
Number of beams (HSR-MBS-3)	5	5	5	1
Control over beam intensity (HSR-MBS-4)	1	1	5	2
Control over dwell time (HSR-MBS-5)	1	1	1	1
Total:	13	13	19	6

Table 4.1.: Trade-off table for multi-beam source design. Each option was given a difficulty rating.

4.5.2. GENERATION

To generate multiple beams, a laser source was used and the output passed through two diffraction gratings. The first grating is static while the second can be rotated. This is shown schematically in [Figure 4.3](#). The two gratings in series allow the diffraction orders created by the first grating to undergo a second diffraction by the second grating. This increases the number of beams. In total, 2500 usable beams could be generated and selected through clipping, meeting HSR-MBS-3. By actuating the second grating, the output diffraction can be moved, with each beam following a different path and crossing intermittently, meeting HSR-HL-2. The second grating interfaced with the gear box of the actuator through a pulley and belt. This gave fine control over the position of the beams, yielding a reproducibility to within 0.25 pixels, meeting HSR-MBS-1. Furthermore, the rate of rotation can be controlled as well, meeting HSR-MBS-5.

To avoid oversaturation of the camera, as specified by HSR-MBS-4, the source power output was attenuated. This was not possible through the laser driving electronics. As a result, this was done using three neutral density (ND) filters placed in series. These reduce the power of the lasers transmitted through them without significantly changing the beam shapes. The optical densities (ODs) of the ND filters in series were 2, 3 and 4, respectively. This yielded a maximum transmission attenuation of $(10^{-2})(10^{-3})(10^{-4}) = 10^{-9}$. Changing the image detector settings together with the selected ND filters allowed control of the signal to noise ratio. This fulfills HSR-MBS-4 for all the used image detector settings.

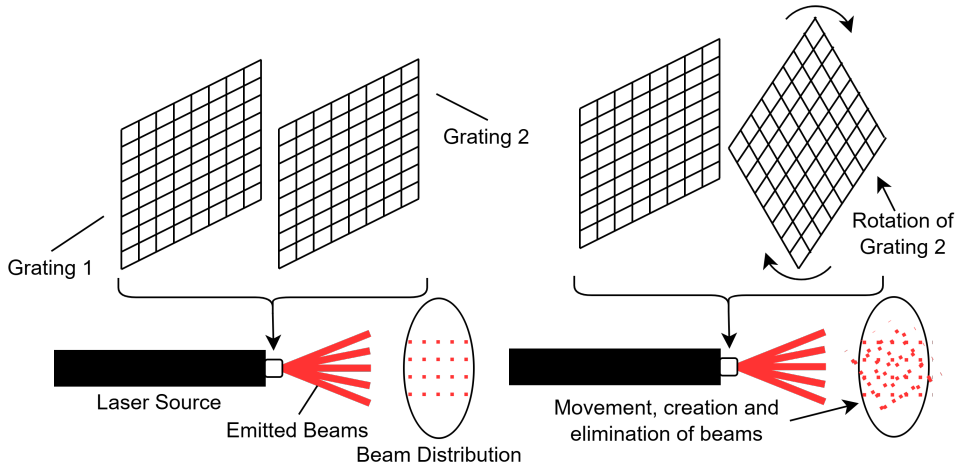


Figure 4.3.: Illustration of the gratings used to generate multiple beams. Multiple beams are created by stacking diffraction gratings, which diffract the incident laser into multiple diffraction orders. Right shows static gratings. The beams were then given motion by rotating the second grating, illustrated left.

The laser source was powered with a USB charger. Although the manufacturer specified an output power of 5 mW, the actual output power was found to be higher. As a result, additional OD filters were needed. The laser source is polarized and the polarization axis was aligned with that of the SLM by rotating the source.

To format the beams correctly, a collimation lens was used after the ND filters. This will be further specified in the overview section (Section 4.6) together with the other optical elements.

In short, this method, together with the collimation lens discussed in Section 4.6.1, generated multiple reproducible beams with reproducible motion. In addition, the beams move in different directions, and their paths often cross and overlap. This was particularly important for testing multi-beam tracking. Furthermore, there were variations in beam power allowing tests of various signal to noise ratios.

For static beams a simple perfboard was used.

4.5.3. ACTUATION

The multi-beam source was mounted on the breadboard through a 3D printed mount that interfaced with the breadboards, thereby meeting HSR-HL-3. This mount is shown in Figure 4.4. This mount constrained

the motion of the source on the breadboard. Furthermore, to control lateral, vertical and tilt alignment of the source, steel rails and sliders were used and could be adjusted using screw threads.

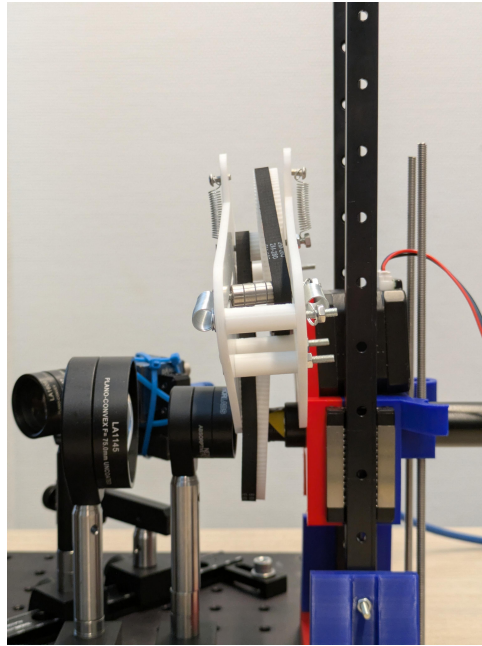


Figure 4.4.: Side view of gear box. Tilt of the gear box was due to overheating of the stepper motor melting the PLA support base.

The actuation of the multi-beam source is performed through a stepper motor via a gear box. The stepper motor was driven by a stepper motor driver powered by a 15 V source and commanded by an Arduino Uno micro-controller, shown in [Figure 4.5](#). A gear box was built to aid in stepping down the stepper motor speed and achieve HSR-MBS-5. In this case, the gear box created a step down gear ratio of 100:1.

To minimize slipping, step jumps, backlash and vibrations, tensioned timing belts were used. These belts were tensioned by spring loaded bearings. A side view can be seen in [Figure 4.4](#) and a top view in [Figure 4.8](#).

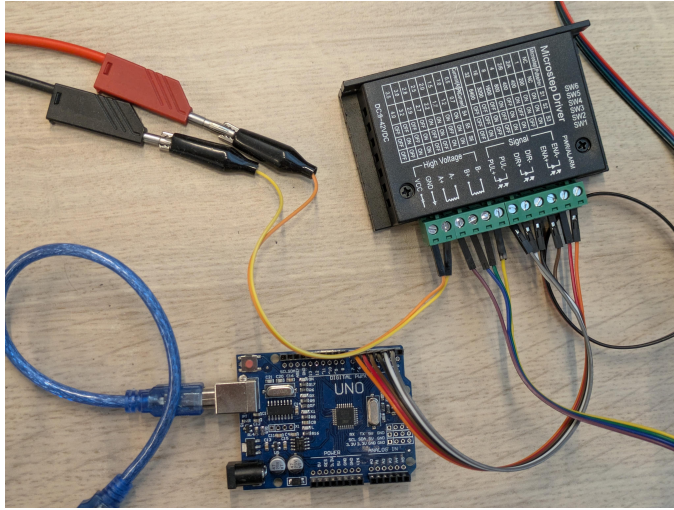


Figure 4.5.: The Arduino Uno (bottom) used to command the stepper motor driver (top) which drives the stepper motor.

4.6. OPTICAL INTEGRATION AND OVERVIEW OF THE SETUP

In the previous sections, the requirements as well as the integration of the image detector, SLM and multi-beam source have been discussed. Now the overall optical layout and overview will be presented. An illustration of the setup is provided in [Figure 4.6](#).

First the optical system will be detailed, followed by a description of different configurations used later on in the thesis.

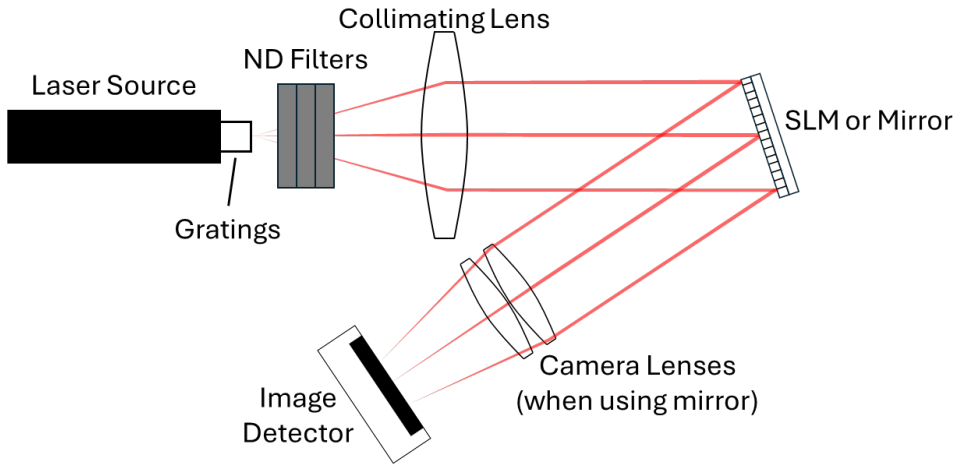
4.6.1. OPTICAL SYSTEM

The optics function to interface between the different components.

In the schematic shown in [Figure 4.6](#) and discussed in [Section 4.5](#), the laser beams immediately after transmission are attenuated to avoid overexposure of the image detector. This was done with three neutral density (ND) filters placed in series.

There are two important aspects to consider. First, the propagation axes of the beams diverge away from each other. Second, the diameter of each beam is small with respect to their emission angle/propagation axis. These two properties imply that these beams have ray-like properties over propagation distances on the order of 10-30 cm. As a result, a collimating lens was used to effectively arrest the relative propagation axis divergence in addition to reducing beam divergence. While the beams in [Figure 4.6](#) are shown to be collimated, real beams

Overview of Experimental Setup



4

Figure 4.6.: Schematic Overview of the setup. On the left, a laser source produces a laser which is diffracted into multiple beams using diffraction gratings. The beams are reduced in power by neutral density (ND) filters to prevent overexposure on the image detector. The beams diverge and the divergence is corrected by the collimating lens. The result is projected onto the SLM or mirror. The beams subsequently reflect and are focused onto the image detector. Three beams are shown to propagate through the optical system in red.

diverge slightly due to diffraction. The lens used was a 2" diameter bi-convex lens with a focal length of 100 mm. This also allows the system to meet HSR-MBS-2.

Due to image distortion, the projected beams are not spaced rectilinearly as they are emitted from the source. This provides the beams with more complex motion characteristics which are useful in determining tracking performance.

Once the beams are collimated, they are projected onto the SLM or mirror. In the case of a passive mirror, additional lenses are required to focus the beams onto the image detector. These are referred to as "camera lenses" in [Figure 4.6](#). In this case, the camera is in the image plane of the mirror.

In the case of the SLM when using phase ramp and Fresnel lens (PRFL) steering (discussed in [Chapter 5](#)), steering and focusing/imaging of the beams individually is performed through wavefront modulation by the

SLM itself during reflection. This implies that this configuration does not need any additional passive imaging/focusing lenses necessarily. However, these lenses can be used to aid the SLM. It is important to note that the image detector is no longer in a single defined image plane. This effect will also be discussed further in [Chapter 5](#).

The resulting images from the image detector have a number of important properties. Firstly, individual beams moving individually simulate individually moving counter terminals. Their motions are in various directions and at various speeds, providing diversity and a more representative tracking environment with diverse counter terminal platforms. In addition, their motion paths have a slight curve, cross and are reproducible. This allows testing of whether a tracking predictor can adjust over time and continue tracking after a loss of signal, as well as comparison of different algorithms. Lastly, the number of beams projected onto the image detector can also be varied by reducing the size of the lens and clipping. This allows demonstration of acquisition and loss in tandem with link sustainment with various numbers of beams. All these aspects combined generate a good environment for testing tracking and steering.

In summary, the layout together with the integration of the image detector and the SLM is a representative lab setup of an SLM based multi-beam steering stage discussed in [Chapter 3](#). Therefore it meets HSR-HL-1.

4.6.2. SETUP CONFIGURATIONS

There are four configurations owing to mirror vs SLM and static vs dynamic beams options. A combination of mirror with static beams was used for calibration and alignment. The combination of SLM and static beams were used to demonstrate PRFL steering and is shown in [Figure 4.7](#). Combining the mirror with dynamic beams was used to demonstrate multi-beam tracking and is shown in [Figure 4.8](#). Lastly, the SLM with dynamic beams combination is used for end-to-end control loop demonstration of multi-beam steering. This is not reported here due to the experimental time frame not fitting in the PhD project. The configurations are presented in [Table 4.2](#).

	Static	Dynamic
SLM	Testing of SLM phase screens	Demonstration of multi-beam steering
Mirror	Calibration camera and alignment	Demonstration of multi-beam tracking

Table 4.2.: Configuration combinations.

Based on the purpose of the experimental demonstration a configura-

tion was selected. The benefit of demonstrating SLM steering through static beams was the beam positioning accuracy of the perf-board and isolating SLM steering performance from beam motion and positioning.

For multi-beam tracking the SLM was not required. Hence, to remove additional setup, calibration and verification complexity by integrating PRFL and control algorithms, the SLM was omitted. Instead the SLM was substituted by a passive mirror. This allows for the beams to be imaged directly onto the image detector through the use of camera lenses.

Adjusting the configurations allows for variable isolation and demonstration of specific aspects of multi-beam steering and tracking.

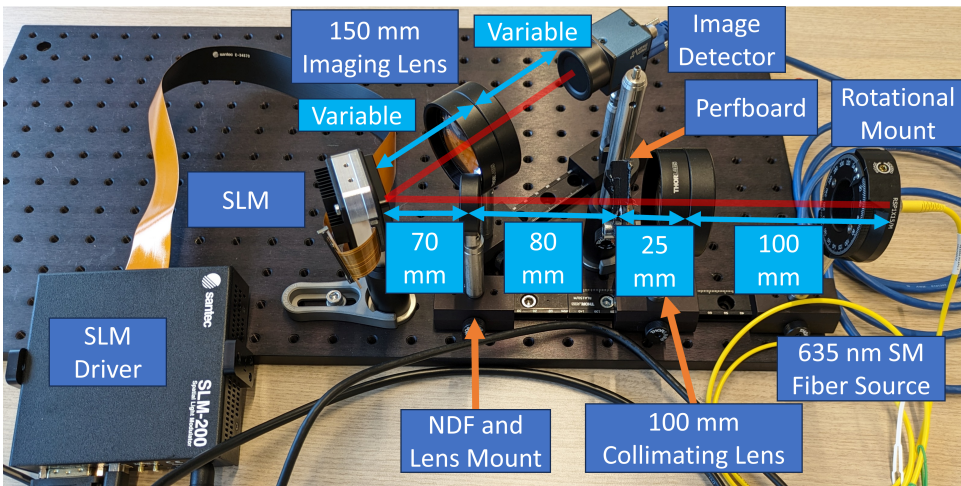


Figure 4.7.: Static beams and inclusion of SLM. This setup was used to test static steering of multiple beams. This setup is used for demonstration in [Chapter 5](#). The static beams are generated by illuminating a perf board.

4.7. SUMMARY AND CONCLUSION

The results in [Chapter 3](#) determined that SLM based steering system designs were promising for multi-beam steering systems. As a result it will be studied further in the remaining chapters of this dissertation. It was decided to use hardware to research and test multi-beam steering system concepts. This chapter has presented and discussed a novel experimental setup for demonstrating and experimenting with multi-beam steering system concepts. In particular, this setup was used to demonstrate steering using SLMs and multi-beam tracking.

In [Section 4.2](#), requirements were set for the hardware selection

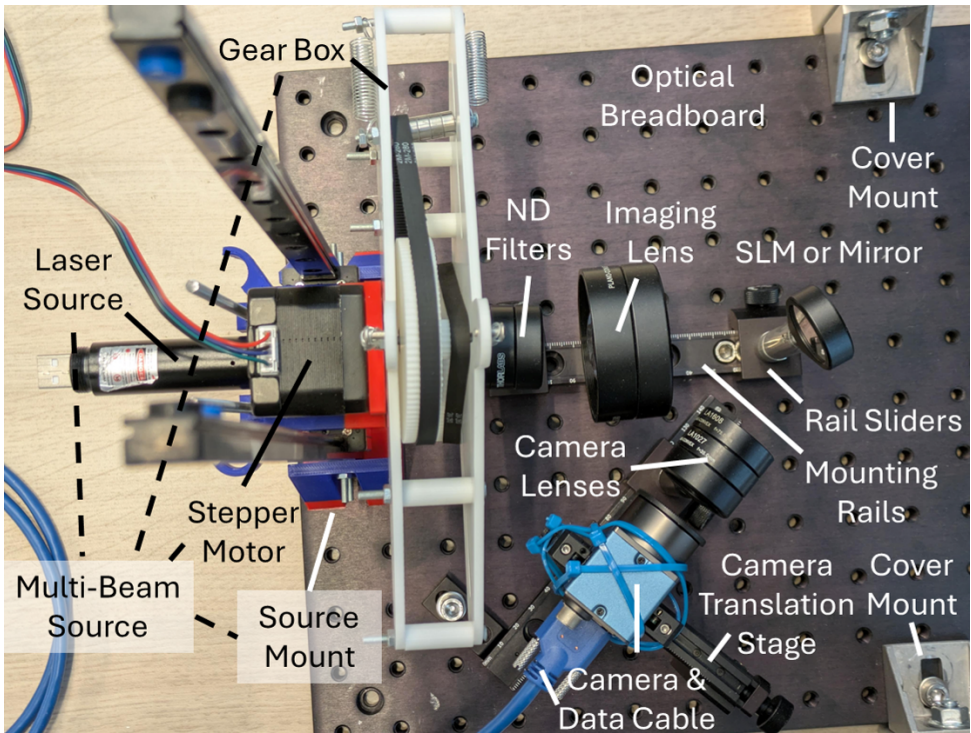


Figure 4.8.: Dynamically moving beams with multi-beam source. In this particular photo, the SLM was replaced with a mirror. However, the SLM would be in the same position. This setup was used to demonstrate multi-beam tracking in [Chapter 6](#).

and setup. The high-level requirements focused on the interfaces and layout of the system as well as compatibility within the context of the lab. These requirements were met and the optical setup was able to generate multiple beams and steer them.

The generation of multiple beams which dynamically move in a reproducible fashion was required for the setup. However, various design options relying on multiple laser sources and actuators promised to be challenging to accommodate and integrate. Instead, the solution found was using two diffraction gratings to generate a diffraction pattern which was then collimated and projected. This created an ample number of beams. The second diffraction grating was rotated using a stepper motor and gear box to create beam motion. This solution was compact and straightforward to integrate. Investigation also yielded that this system was sufficiently repeatable to within a pixel.

The image detector was selected based on its versatility and control.

Integration into tracking was performed relatively straightforwardly through the supplied API. Under most tested conditions the execution of the tracking algorithm was an order of magnitude smaller than the frame grabbing rate. In order to optimize this for later control integration, the memory management and parallelization of the image grabbing was performed. Additionally, all image processing and tracking as well as performance data logging was performed in place.

The selection of the SLM was done in light of versatility, capability and future research. It was decided to select a broad-band SLM without an anti-reflection coating operating at 120 fps in 10 bit phase screens. This allowed investigation of methods for mitigating diffraction and modulation effects, as well as demonstration of multi-beam steering. To control the SLM at 120 Hz in 10 bit mono, a method was devised to carry the data over 8 bit RGB images at 60 Hz via HDMI also. To optimize this process, binary bit shifting in parallel was performed.

Additionally, variations in the setup, namely the choice between SLM and mirror as well as static and dynamically moving beams, allows for variable isolation. Static beams and an SLM allowed for steering experiments while dynamic beams together with a static mirror allowed for tracking experiments. Although some experiments have been performed with multiple steered beams, due to lack of time, these experiments and demonstrations were not completed. Hence, they have not been implemented in the thesis.

This chapter has shown that an experimental setup for multi-beam hardware demonstration can be made to meet the requirements. Hardware demonstrations played a vital role in testing and understanding the theory as well as understanding practical implementation. It will play a central role in [Chapter 5](#) and [Chapter 6](#) on steering and tracking, respectively.

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5

MULTI-BEAM STEERING

The best way to solve a problem is not to create one in the first place.

Ashoka Tano (Star Wars)

Steering multiple laser beams using spatial light modulators (SLMs) creates unwanted diffraction and reflections that are not modulated by the SLM can make beam tracking difficult. A novel and simple beam steering methodology is proposed, which aims at reducing the influence of this clutter while maintaining tracking performance. The beam(s) are deliberately defocused before steering with a superposition of a phase ramp and Fresnel lens (PRFL) phase screen on the SLM. As a result, the non-modulated reflections and diffracted light are decreased in relative intensity to the steered beam. This, in turn, allows to apply simple and standard peak intensity and center of gravity (C.G.) algorithms for tracking. Hardware demonstration shows tracking performance using PRFL remained on par with more complex filtering approaches, while adding no additional hardware. This method has the potential to improve the communication performance of multi-beam laser communications terminals for a variety of applications.

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5.1. INTRODUCTION

Laser satellite communications requires beam steering accuracy in the order of μrad , with kHz control bandwidth.[2] As a result, beam tracking requirements are similarly stringent. This is no different in multi-beam laser satellite communications but applied to multiple beams. To control multiple beams, micro-mirror arrays (MMAs) and spatial light modulators (SLMs) are being considered as potential solutions. The results from Chapter 3 indicate that these steering mechanisms offer flexibility in multi-beam steering stages. This is due to these devices' ability to generate phase screens dynamically. This in turn allows dynamic allocation of individual steering surfaces and unique steering angles to each beam.[3]

A drawback of these devices is that they act as diffraction gratings, causing diffraction patterns, while non-modulated reflections form non-modulated beams (NMBs).[4, 5, 6] These effects interfere with the intended image and could potentially compromise beam tracking.[5] Figure 5.1 shows an over-exposed image which illustrates this effect.

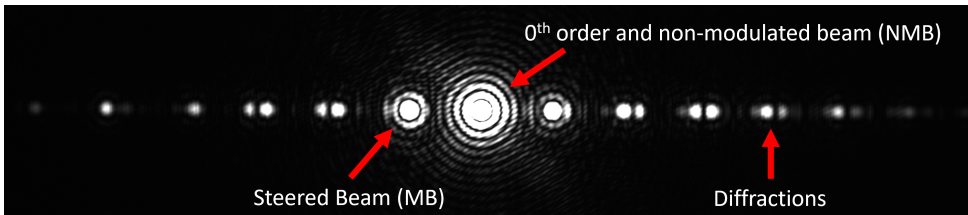


Figure 5.1.: Over-exposed image of an in-focus beam steered from the center slightly to the left, showing the effect of undesired reflections at the SLM. Note that the spots have different intensities, which is not obvious from the overexposure.

These effects can occur in a multi-beam steering control loop which uses an image detector to track beams together with an SLM or MMA to steer beams. The location determination of each beam needs to be determined accurately and fast enough to sustain high enough bandwidths for disturbance suppression. The presence of NMB and diffraction patterns could be particularly challenging, as these can be mistaken for communication beams in addition to the before mentioned drawbacks. To be able to perform multi-beam steering in such scenarios, algorithms are needed to filter out the incorrect beams. This increases complexity and required computational resources. Furthermore, the NMB and diffraction could couple into the wrong detector causing cross talk. These challenges could potentially become difficult to overcome, especially when NMB and diffraction are higher in amplitude than the

communication beams themselves. These drawbacks make SLMs as well as MMAs less attractive options for multi-beam steering.

The severity of diffraction and NMB are dependent on the SLMs or MMAs chosen. Namely factors such as anti-reflection coatings, liquid crystal vs mirror-based and pixel size affect the performance.[4] Choosing such improvements comes at a higher cost.

Furthermore, from the design choices discussed in [Chapter 3](#), a multi-staged steering system was chosen. However, integration of such a system using SLM has not been investigated.

This chapter will determine the SLM performance as well as integration into multi-beam steering systems. First, SLM steering performance using a phase ramp (PR) will be investigated in the form of efficiency envelopes and steering ranges. Furthermore, the integration challenges of using SLMs for beam steering through using purely PR is discussed.

After this and based on these challenges in the previous section, a solution was devised in the form of phase ramp Fresnel lens (PRFL) steering phase screens. Here the theory behind PRFL will be detailed and demonstrated as well as contrasted with PR steering. Additionally, the performance envelopes of PRFL are determined and contrasted with PR steering. Lastly, the integration of a steering system using PRFL is detailed.

5.2. SLM STEERING PERFORMANCE USING PHASE RAMP (PR) STEERING

SLMs consist of an array of discrete and individually programmable pixels, where each pixel modulates the phase of light reflected off the surface. The phase difference between each pixel can be used to generate phase screens, similar to how a computer or television screen can use pixels to generate an image. In fact, as discussed in [Chapter 4](#) and later in [Section 5.3.2](#), controlling SLMs is not dissimilar to controlling monitors.

In order to steer beams, a straightforward option would be to mimic the phase screen of a steering mirror; i.e. a phase ramp (PR). In PR steering, the phase is incremented linearly over the steering area. This generates a discretised approximation of a ramp, as depicted in [Figure 5.2](#). When a beam is reflected off the SLM with a PR phase screen, it is reflected in the steered direction.

However, there are technical challenges to SLM operations stemming from four main areas. First, the discrete nature of the SLM implies it acts as a diffraction grating which in turn generates diffraction orders as shown in [Figure 5.1](#). Second, non-modulated light (stemming from polarization mismatching and reflections) creates a beam copy that are unresponsive to steering inputs, also shown in [Figure 5.1](#). Next, in

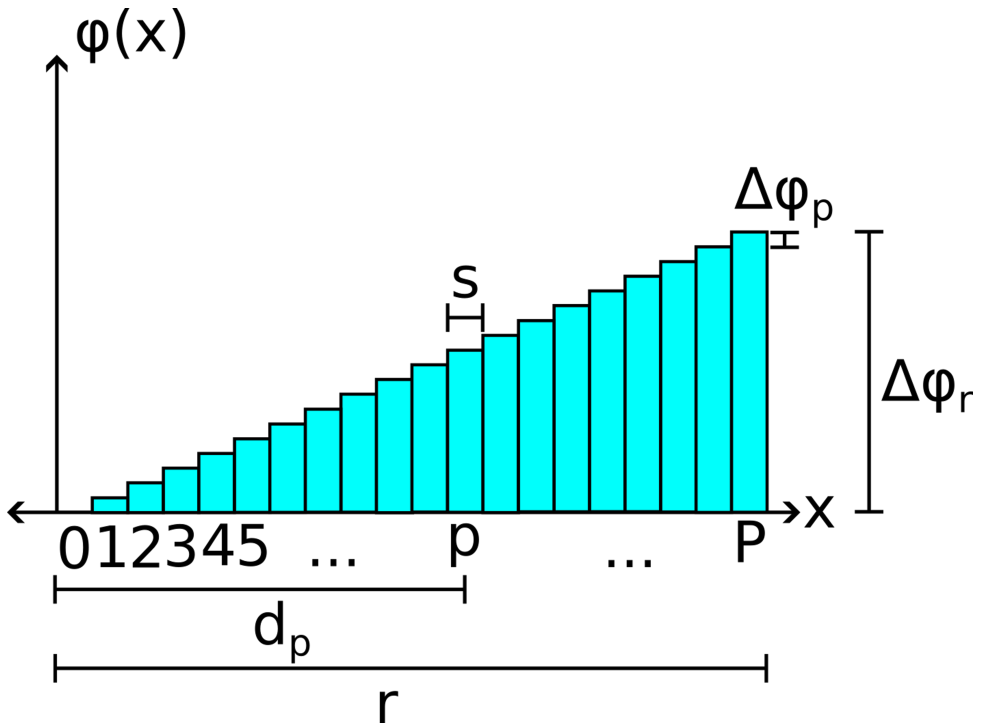


Figure 5.2.: Schematic depiction of a phase ramp including definitions.

the same way monitor pixels have limited spatial density, SLMs have limited spatial densities as well. This implies aliasing can occur when generating phase screens with spatial frequencies near to the pixel spatial frequency. Lastly, another aspect that needs to be taken into account is the phase input range. Similar to color depth in pixels, SLM pixels have a limited range for phase delays. As a result, phase wrapping is required.

This section will discuss the steering performance of SLMs using PR. To do so, first the aliasing and phase wrapping will be discussed. These effects imply that an SLM can steer in five different steering regimes. The theory and details of these regimes will be discussed.

After this the angular steering resolution, range and efficiency performance envelopes of SLMs are determined.

Lastly, the challenges associated with integrating SLMs using PR in a steering system are detailed followed by a brief summary and discussion.

5.2.1. STEERING REGIMES AS A RESULT OF ALIASING

It is important to highlight that there are five regimes throughout the SLM steering range denoted in this work. The first is the pure phase ramp, second the phase wrapped phase ramps, third aliasing, fourth reversal and lastly the arrest. These are shown in Figure 5.3.

When small steering angles are applied, a pure PR can be generated by the SLM. The pure phase ramp occurs when the phase change generates a wave delay of less than one wavelength over the width of the steering area. This is illustrated in Figure 5.3(a).

When the angle/slope of the phase ramp is increased, the second regime is entered once the phase change has exceeded the phase change range of the SLM. This is illustrated in Figure 5.3(b). The phase wrapping creates a sawtooth pattern, which still functions to steer beams using a PR.

Increasing the angle further results in the third regime: aliasing. Aliasing occurs once the required rate of change of phase exceeds half the pixel phase range. This is illustrated in Figure 5.3(c). This event is equivalent to under-sampling a sawtooth wave and no longer meeting the Nyquist criterion. This regime is identical when steering in the opposite direction. As a result, the beam is split.

Increasing the phase gradient further yields a reversal in the pixelated phase ramps displayed on the SLM. This is the fourth regime and is illustrated in Figure 5.3(d). As will be explained later, the motion of the resulting diffraction patterns is still in the desired direction. However, the relative intensity of the steered diffraction mode falls under that of secondary diffraction orders. This is due to the PR being effectively reversed.

The primary diffraction order decreases in intensity to the point where it becomes zero and the phase ramp displayed on the SLM is of zero gradient. This is the fifth regime and is illustrated in Figure 5.3(e). This occurs when a wrapping frequency occurs within a single pixel. As a result, the steering is completely arrested.

In the following subsection, the steering resolution and range of PR steering will be discussed with these regimes at its basis. Diffraction losses will be discussed in Section 5.2.3 to analyze the efficiency of SLM based steering.

5.2.2. SLM ANGULAR STEERING RESOLUTION AND RANGE

To determine the steering resolution and range, the SLM is considered to be a reflective phased array consisting of pixels. A beam can be steered by applying a phase ramp, as shown in Figure 5.2. The steering angle is denoted as α , α_{max} the maximum steering angle input (the full end-to-end range being $\pm\alpha_{max}$ i.e. $2\alpha_{max}$), α_{min} the smallest possible steering angle change, r the range of pixels used to steer the beam and

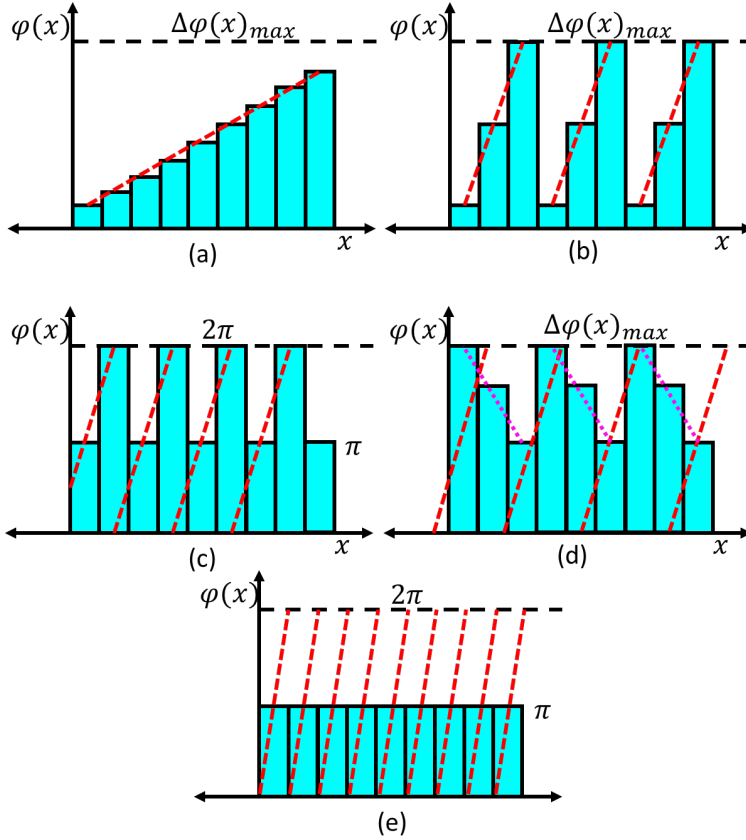


Figure 5.3.: Five steering regimes. (a) is the regime where the change in phase over the phase ramp is smaller than the maximum phase shift of the SLM. The desired ramp is indicated with the red dashed line. (b) is a phase-wrapped phase ramp, each wrapping occurs after the ramp. This gives a sawtooth like pattern to the phase screen. (c) shows the start of aliasing where more than a π phase shift between pixels occurs. The resulting pattern is a grooved π shift phase grating. At this stage steering has no preferential direction. (d) shows steering reversal which occurs after aliasing. The increased desired slope indicated by the red dashed line causes steering in the opposing direction indicated by the purple dotted line due to pixelation. Lastly, (e) shows complete steering arrest at phase gradients requiring larger than 2π phase shifts within one pixel leading to no steering at all.

s the pixel width. P is the steering area width in terms of number of pixels through $P = r/s$.

First, the largest possible steering angle will be determined. The maximum steering angle for an SLM can be defined in multiple ways. In this chapter, the aliasing angle is used. This occurs when the PR creates a phase wrap over a distance smaller than or equal to $2s$. In other words, this is when the Nyquist criterion is no longer met, as discussed in [Section 5.2.1](#). The phase jump between pixels is π radians in phase and therefore equivalent to a slope of $\lambda/(2s)$, and to a π shift line phase grating. This yields the maximum steering angle of,

$$\Delta\alpha_{max} = \arctan \frac{\lambda}{2s} \quad (5.1)$$

The smallest steering angle achievable is the smallest change in phase achievable over the width of the steering area. The smallest change in phase is defined by the steering resolution of the SLM over the maximum phase range of the SLM at the used wavelength, $\Delta\phi_{max}$,

$$\Delta\phi_{min} = \frac{\Delta\phi_{max}}{2^{N_{bits}}} \quad (5.2)$$

with N_{bits} being the number of discretizations in the phase range in bits, equivalent to pixel depth in monitors. Relating this to the wavelength and using the maximum width of the steering area r yields an expression of the smallest beam deflection,

$$\Delta\alpha_{min} = \arctan \frac{\lambda\Delta\phi_{max}}{2\pi r 2^{N_{bits}}} \quad (5.3)$$

where $\lambda/2\pi$ relates the phase change to the local wave delay. The work by Xu et al.[7] investigated the number of steering positions for phased arrays. There it states that the number of resolvable steering positions, N_{steer} , is tied to the number of controllable elements in the array, N_{pixels} through,

$$N_{dir} = \frac{\theta}{\delta\theta} \propto \frac{A}{a} = N_{control} \quad (5.4)$$

Using the nomenclature of this work as well as [Equation \(5.1\)](#) and [Equation \(5.3\)](#) gives,

$$N_{steer} = \frac{\arctan \frac{\lambda}{2s}}{\arctan \frac{\lambda\Delta\phi_{max}}{2\pi r 2^{N_{bits}}}} = \frac{\arctan \frac{\lambda N_{control}}{2r}}{\arctan \frac{\lambda\Delta\phi_{max}s}{2\pi N_{control} 2^{N_{bits}}}} \quad (5.5)$$

If steering angles are considered relatively small, [Equation \(5.5\)](#) can be simplified to,

$$N_{steer} = \frac{\pi r 2^{N_{bits}}}{s \Delta \phi_{max}} = \frac{\pi 2^{N_{bits}}}{\Delta \phi_{max}} N_{control} \quad (5.6)$$

Equation (5.3), 5.5 and 5.6 show that angular steering resolution, the pixel size/spatial steering resolution and allocated steering areas are directly related. By increasing the steering area size a higher angular steering resolution can directly be achieved. These relations are plotted in Figure 5.4. It shows that for the Santeo SLM 200[8] μrad steering resolution is achievable when using a steering area width of between 15-20 pixels with 10 bit phase discretization over 2π radians. This would also imply at most 5184 beams can be steered when perfectly spaced on the SLM.

For the same SLM, a steering range of $\pm 2.25^\circ$ can be found. This is comparable with the steering ranges for FSMs found in literature.[9, 10, 11, 12]

This shows that SLMs can match the performance of FSMs. However, in the cases discussed in Chapter 2, steering requirements become more stringent with increased field of regard.

Taking an example from Chapter 2, 4° and 12° field of view (FoV) telescopes were discussed. If an optical system was to be designed where the steering angle at the SLM was mapped directly to the FoV, the SLM would yield an angular steering resolution of $1.7 \mu\text{rad}$ and $5.3 \mu\text{rad}$ respectively (if a 15-20 pixel steering radius was used in combination with $8.1 \mu\text{m}$ pixel width). These results are comparable to those found in Table 2.9 and Table 2.10.

Having found the steering range and resolution performance envelopes of SLMs, the efficiency of the SLM can be determined.

5.2.3. DIFFRACTION LOSSES AND CHALLENGES FOR TRACKING

SLMs cause diffraction, which in turn cause losses. These losses are in the form of unwanted diffraction orders, which are not directed at the target location nor the transceivers. Aside from signal losses, this also creates unwanted artifacts which then have to be filtered by the tracking system. In this subsection, the efficiency of SLMs will be determined as well as the associated challenges.

The array of pixels shown in Figure 5.2 defines the pixel width s at a lateral distance d along the x -axis. The amplitude after reflection is denoted by A . The phase shift induced by a pixel is ϕ . The modulated field immediately after reflection, $E_m(x_m)$, can be estimated by a rectangular function Π . To determine the electric field E_z after reflection of the pixelated phase ramp in Figure 5.2, a series is used and propagated using the Fraunhofer diffraction equation as follows:

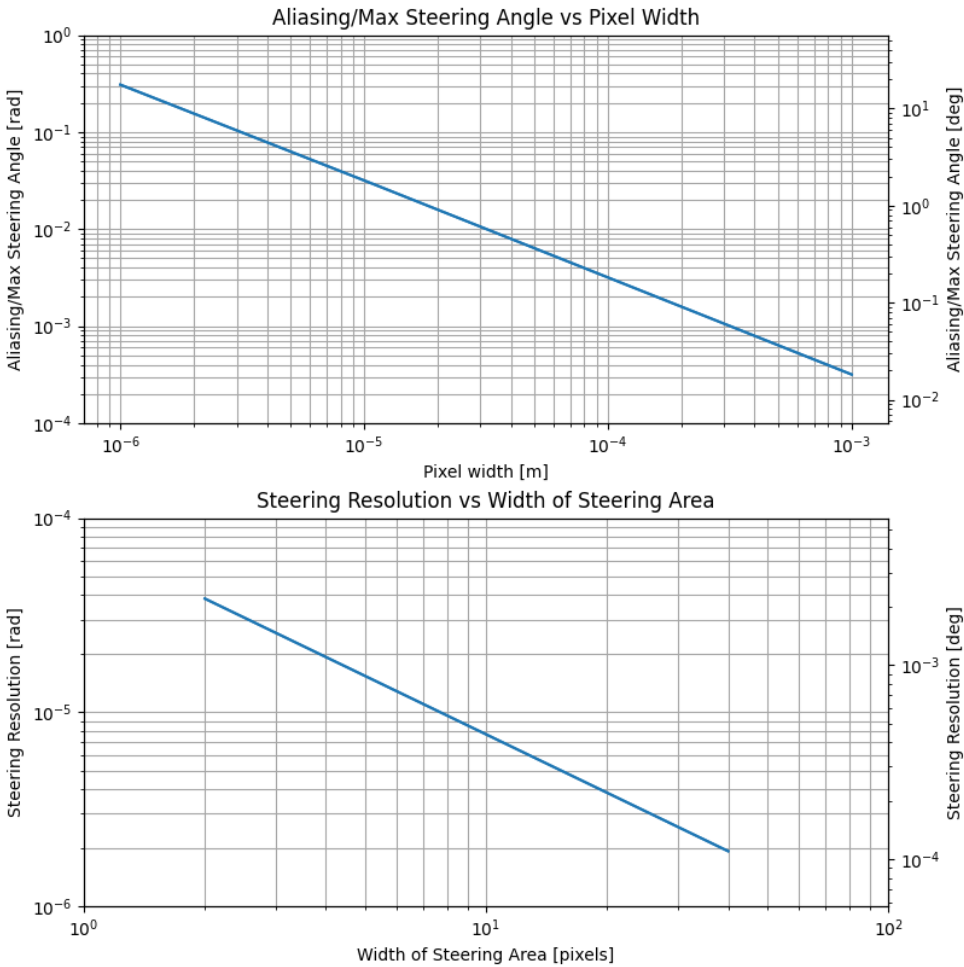


Figure 5.4.: Figures showing maximum and minimum steering angles. Top figure shows the log-log plot of the max steering angle (in this text equal to the aliasing angle) as a function of pixel width. As can be seen, decreasing the pixel width increases maximum steering angle. Bottom figure shows the steering resolution for a pixel size of $8.1 \mu\text{m}$ with 10 bit phase discretization over 2π radians, similar to the Santeo SLM 200.[8] Both plots are based on a wavelength of 635 nm.

$$\begin{aligned}
 E_z &= \int_{-\infty}^{\infty} \sum_{p=0}^P A \Pi\left(\frac{x_m - d_p}{s}\right) e^{j\phi_p} e^{-j\frac{2\pi}{\lambda z} x_m x_z} dx_m \\
 &= sA \operatorname{sinc}\left(\frac{\pi}{\lambda z} x_z s\right) \sum_{p=0}^P e^{j\left(\phi_p - \frac{2\pi}{\lambda z} x_z d\right)}
 \end{aligned} \tag{5.7}$$

with λ the wavelength, x_z the x-axis at the evaluated distance and z the distance propagated. Assuming the phase difference and distance between each pixel are constant, the phase change over the distance r , denoted as $\Delta\phi_r$, is related to the pixel phase shift through

$$\phi_p = \Delta\phi_r p = \frac{\Delta\phi_r}{P} p, \quad d_p = sp \tag{5.8}$$

When inserting this into Equation (5.7) this yields,

$$E_z = sA \operatorname{sinc}\left(\frac{\pi}{\lambda z} x_z s\right) \sum_{p=0}^P e^{j\left(\frac{\Delta\phi_r}{P} - \frac{2\pi}{\lambda z} x_z s\right)p} \tag{5.9}$$

To determine the result of the series, the geometric series identity can be used,

$$\begin{aligned}
 s_n &= ar^0 + ar^1 + ar^2 + \dots + ar^{n-1} \\
 &= \sum_{k=0}^{n-1} ar^k = \sum_{k=1}^n ar^{k-1} = a \left(\frac{1 - r^n}{1 - r} \right)
 \end{aligned} \tag{5.10}$$

when $r = e^{j\left(\frac{\Delta\phi_r}{P} - \frac{2\pi}{\lambda z} x_z s\right)} \neq 1$, $p = k - 1$, $n = P$ and $a = 1$, Equation (5.9) simplifies to,

$$E_z = \underbrace{sA \operatorname{sinc}\left(\frac{\pi}{\lambda z} x_z s\right)}_{\text{Amplitude Envelope}} \underbrace{\left(\frac{1 - e^{j\left(\frac{\Delta\phi_r}{P} - \frac{2\pi}{\lambda z} x_z s\right)P}}{1 - e^{j\left(\frac{\Delta\phi_r}{P} - \frac{2\pi}{\lambda z} x_z s\right)}} \right)}_{\text{Diffraction}} \tag{5.11}$$

the normalized intensity of which is plotted in Figure 5.5. Next, taking the amplitude envelope from Equation (5.11) and normalizing this to the input power yields the overall efficiency:

$$\eta_{\text{steering}} = \left(\frac{A \operatorname{sinc}\left(\frac{\pi}{\lambda z} x_z s\right)}{A} \right)^2 = \operatorname{sinc}^2\left(\frac{\pi}{\lambda z} x_z s\right) \tag{5.12}$$

From this equation, the efficiency in different steering regimes can be determined. First, the highest efficiency occurs at zero steering

angle input, with an efficiency of 100%. The lowest efficiency occurs at arrestment (i.e. the arrested regime illustrated in Figure 5.6). This happens when the beam reaches a null in the amplitude envelope, shown in Figure 5.5. The efficiency at this steering angle is therefore 0%. When first aliasing occurs at $\frac{\pi}{\lambda z}x_zs = \frac{\pi}{2}$, the steered beam equals in amplitude to the next most powerful diffraction order (see Figure 5.3 and Section 5.2). The efficiency at aliasing is 40.5%. These results are corroborated by experiments done in the lab and in the work by Ketchum et al.[13] According to Figure 5.4, this angle occurs at $\pm 2.25^\circ$ for an SLM with pixel size of $8.1\text{ }\mu\text{m}$ such as the Santec SLM 200. This is confirmed when using Equation (5.11) in Figure 5.6(b).

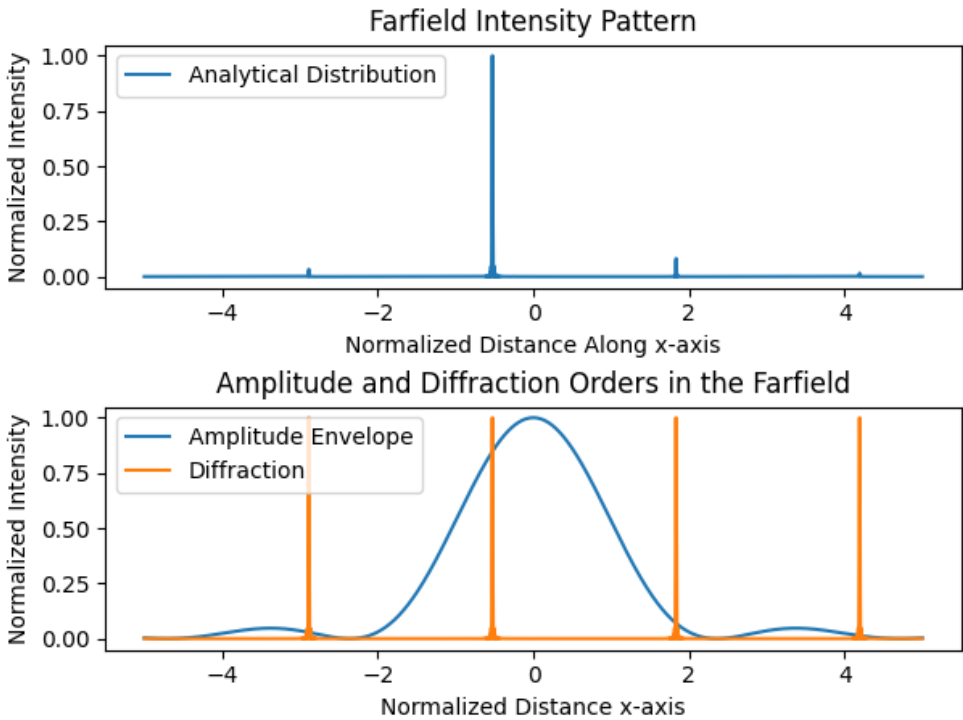


Figure 5.5.: Fraunhofer propagation of phase ramp steering in the far-field using SANTEC 200 SLM.[8] A 1° steering angle is used for illustration. When the diffraction is multiplied with the amplitude envelope in the bottom figure, the resulting line is equal to that of the top figure.

In addition to the above described diffraction due to the phase screen, diffraction patterns originating from the space between each pixel as well as the non-modulated reflections cause additional patterns.

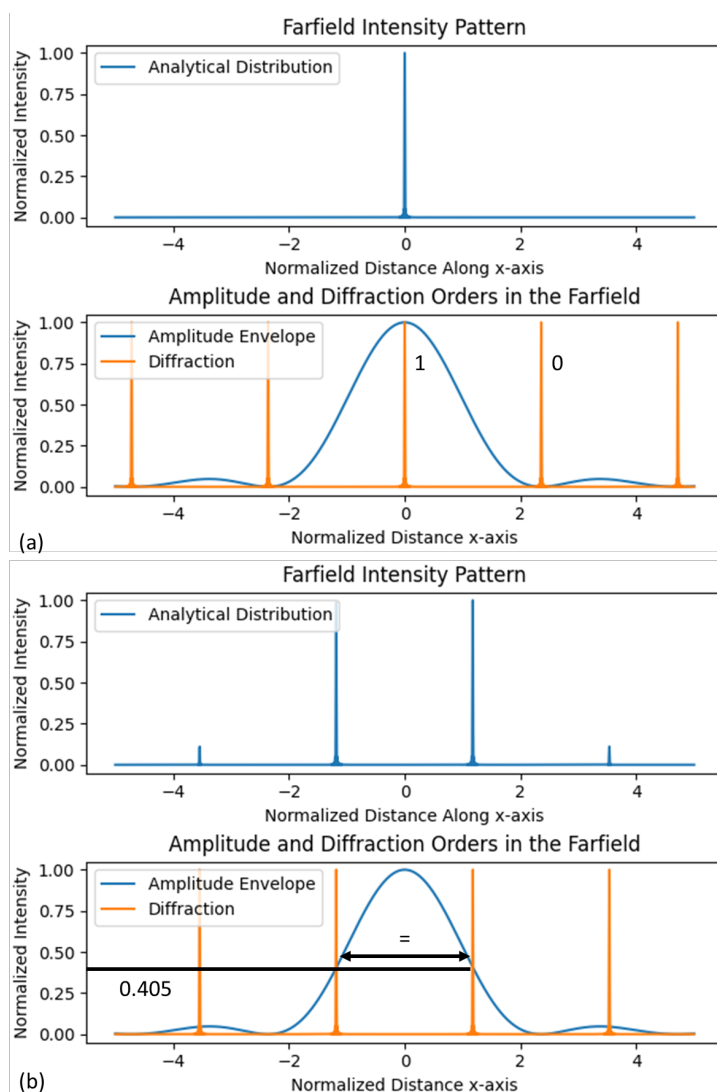


Figure 5.6.: Various important steering angles. (a) shows steering to the first null as well as no steering input, illustrated by the normalized amplitude of 1 and 0. (b) shows the aliasing angle, yielding 40.5% of the amplitude. It also shows that at this point the steered diffraction order is equal to the second largest diffraction order. Increasing the steering angle yields equivalent results as steering reversal, shown in [Figure 5.3](#)

These were also modeled extensively numerically, however, will not be presented in this text for brevity. Nevertheless, these explain the differences between [Figure 5.1](#) and [Figure 5.6](#).

Steering using SLMs therefore has significant and inherent drawbacks. SLMs become increasingly less efficient with increased steering angle. This is in stark contrast with steering mirrors which do not change efficiency. [Equation \(5.12\)](#) shows that efficiency can be improved by decreasing the pixel size and/or increasing the wavelength.

In addition to signal loss, the diffraction caused by the SLM can mislead tracking algorithms into detecting and tracking diffractions and NMBs. This in turn will yield unwanted behavior and take up resources. As a result, filtering during tracking is required. Moreno et al. investigated alternative phase ramps which improve SLM steering efficiency.[14] Nevertheless, diffraction complicate the multi-beam tracking process and increases computational load during tracking. This problem will be addressed in [Section 5.3](#).

5.2.4. REQUIRED SPATIAL STEERING RESOLUTION

As mentioned in [Chapter 2](#), larger FoVs and high density use cases require higher angular tracking and steering resolutions. This in turn requires more pixels to sufficiently sample the FoV. Decreasing the number of steering pixels needed per beam would therefore be beneficial. However, as the analysis of [Section 5.2.2](#) shows in [Equation \(5.5\)](#) and [5.6](#), increasing the number of steering pixels improves steering accuracy. This yields an important question: what is the minimum number of pixels required to steer beams?

Considering the results of the analysis performed in [Section 5.2.3](#), [Equation \(5.11\)](#), shows that beam steering requires at least two pixels. This is due to the fact that a beam falling exactly on one pixel would simply experience piston.

A numerical Fresnel propagation simulation which compared different beam diameter sizes was undertaken. The results are shown in [Figure 5.7](#). These confirm these findings.

Nevertheless, there are wavefront and diffraction quality improvements gained by increasing the number of pixels, which is also shown in [Figure 5.7](#). [Equation \(5.11\)](#) shows this: when P is decreased the diffraction width increases. Furthermore, the steering accuracy is also improved as discussed in [Section 5.2.2](#) and shown in [Figure 5.4](#). However, if more steering area is allocated per beam, fewer beams can be accommodated.

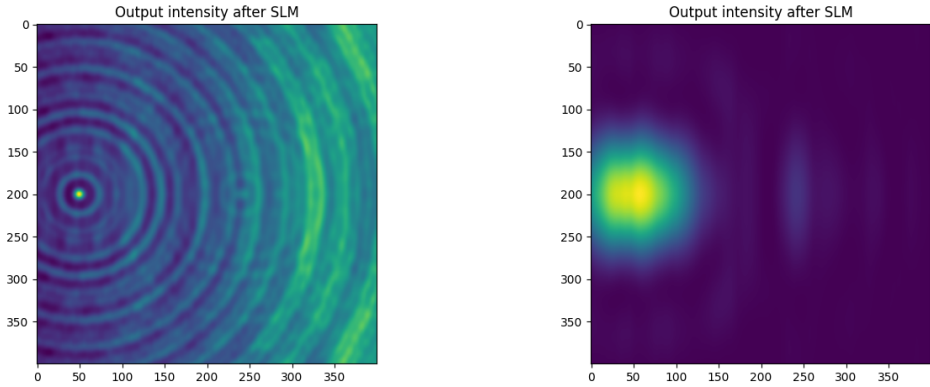


Figure 5.7.: Fresnel numerical propagation of steering with different Airy beam diameters. Left, a beam diameter of 2 pixels and right of 20 pixels. The pixel size was taken to be $8.1 \mu\text{m}$. The propagation distance was 1 meter. As seen, the beam centers are in the same location, showing that the steering efficacy is the same. However, the 2 pixel case has more diffraction losses than the 20 pixel case.

5

5.2.5. INTEGRATION OF PHASE RAMP STEERING IN MULTI-BEAM STEERING SYSTEMS

The integration of an SLM for multi-beam steering is not as straightforward as simply replacing the FSM in a single beam terminal (SBT). The purpose of the FSM within an SBT is to correct for angle of arrival fluctuations in the telescope entrance/pupil plane of the telescope due to jitter and turbulence.

To explain this specifically, consider the 4F system in Figure 5.8 with indicated (conjugated) planes and two beams traveling through the system. The pupil plane is imaged by the first lens and subsequently the second lens images the image plane to the pupil plane. In this case, each plane is placed exactly one focal length from the lens, with four focal lengths (hence 4F system). Important to note here is that angle of arrival deviation from the optical axis in the pupil plane causes translation in the image plane. Any changes in either the pupil or image planes will change the subsequent pupil and image planes.

In SBTs, the fine/fast steering mirror (FSM) is placed in the pupil plane as shown in Figure 5.9. Here, angular deviation from the optical axis causes the spot in the fiber coupling plane to wander which in turn causes signal loss. This angular deviation can be corrected for through angle inputs from the FSM. This is not suitable for multi-beam terminals (MBTs) for two reasons. Firstly, the FSM has one control surface and

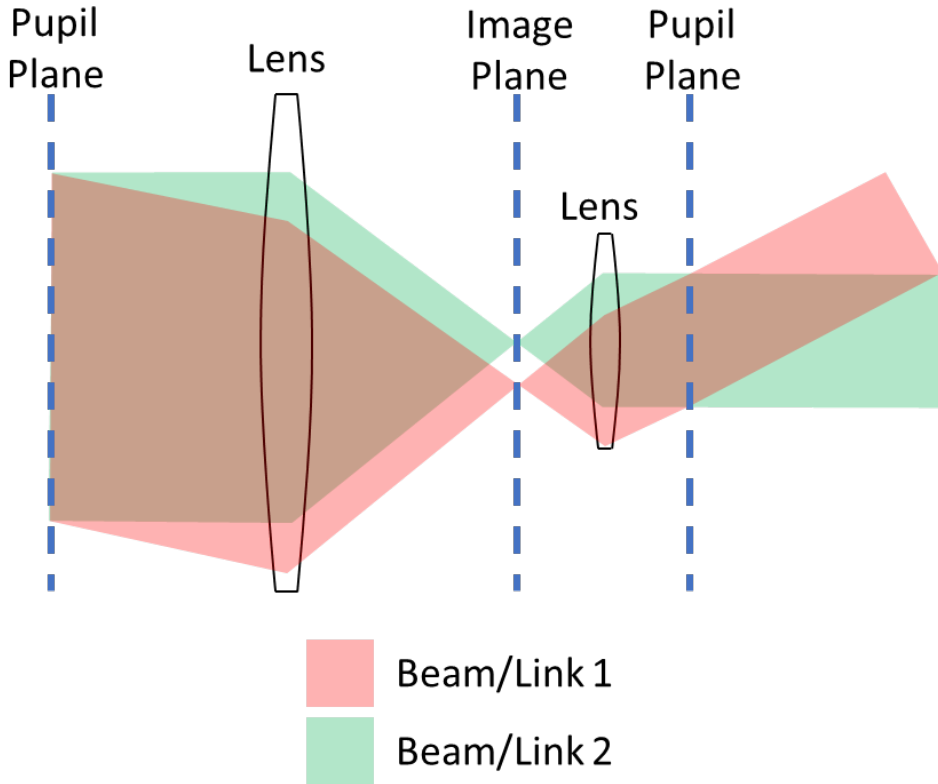


Figure 5.8.: 4F system with beams being captured at 2 angles, with different (conjugate) planes indicated.

cannot actuate each beam individually. Secondly, the beams overlap in the pupil plane (mixed beams).

The mixing of beams in the pupil plane implies that replacing the FSM directly with a multi-beam steering capable SLM would not yield a satisfactory result. This is depicted in [Figure 5.10](#). In MBTs with wide FoV telescopes or multiple telescopes, the pupil plane is shared between all beams implying that steering inputs in this plane have no utility. Instead, the steering plane should be in a plane which can resolve each beam spatially. This can only happen in a plane between the image and pupil planes or on the image plane itself.

However, placing the SLM directly in the image plane, as shown in [Figure 5.11](#), and using PR steering fails to steer beams at all. This is because the subsequent image plane where the fibers are coupled

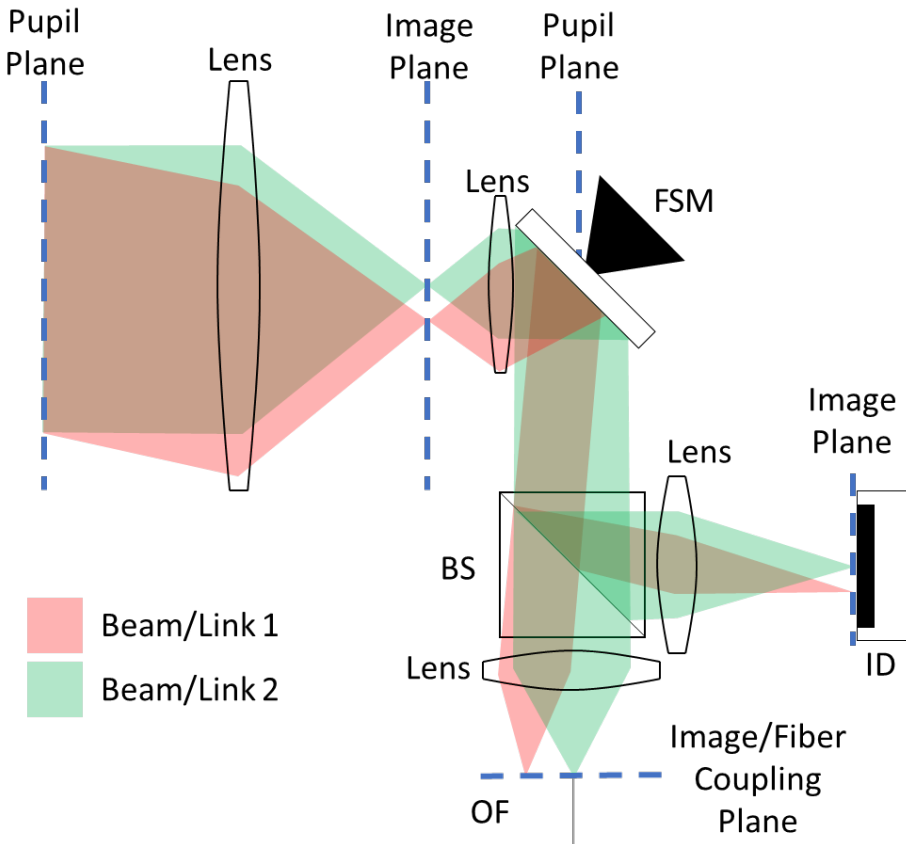


Figure 5.9.: Standard layout for single beam systems. FSM stands for fast/fine steering mirror, BS for beam splitter, ID for image detector and OF for optic fiber(s). When considering beam 2 as a deviation of beam 1, correction is conceptually straightforward as the FSM needs to be directly actuated to correct for the angular deviation. However, the FSM cannot separate each beam and steer it individually. This is because it can actuate only a single mirror and is located in the pupil plane where the beams overlap.

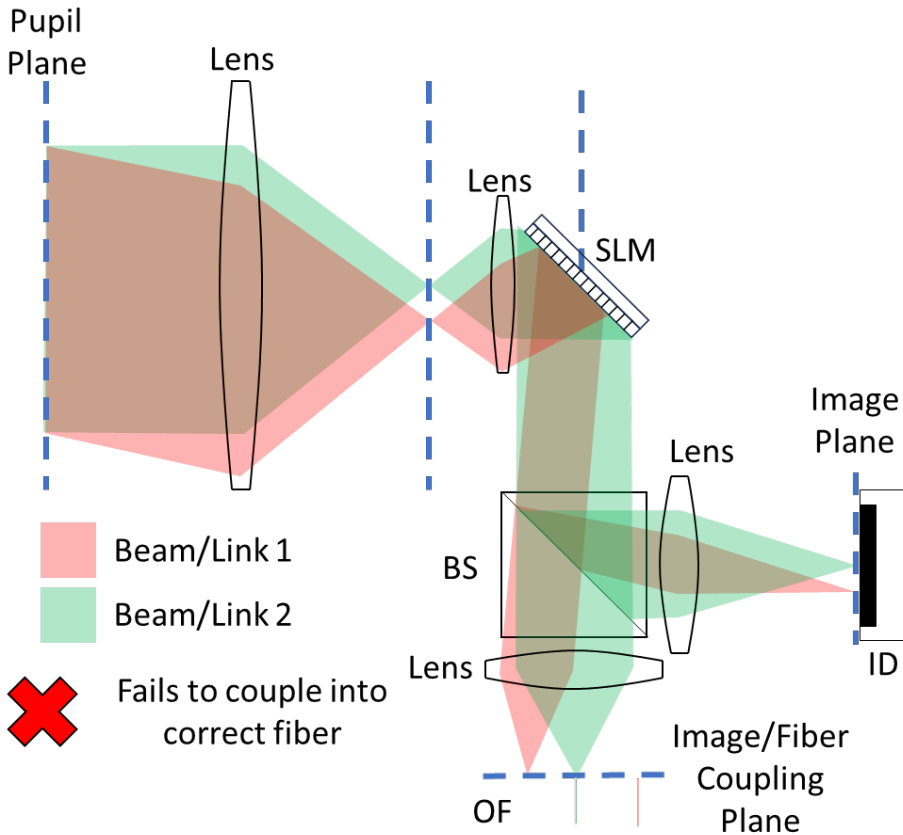


Figure 5.10.: In this case, the FSM depicted in [Figure 5.9](#) has been replaced with an SLM capable of steering multiple beams. However, it is placed in the pupil plane, meaning that the beams overlap and cannot be individually actuated. This illustrates that the multi-beam steering mechanism cannot be placed directly in the pupil plane. SLM stands for spatial light modulator.

yields no translation with any PR steering inputs. This directly shows that multi-beam steering requires a different plane and phase screen for steering altogether.

A final challenge, which is not overcome by the placement of one SLM in the steering system, is the alignment of the optic fibers with the beam axis. While off-axis fiber or detector coupling is possible at the cost of efficiency reduction, it is best avoided. In SBTs, such as the one illustrated in Figure 5.9, there being only one beam implies that placing the FSM on the optical axis allows for aligned coupling into the fiber. However, for multiple spatially resolved beams, this is not possible due to the optical axis of each beam not being aligned with any other.

5.2.6. SUMMARY OF SLM PERFORMANCE USING PHASE RAMP STEERING

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Steering using PR phase screens generated using SLMs can achieve the desired steering performance when configured correctly. However, PR steering using SLMs also has a number of key drawbacks. From a tracking perspective, the pixelation causes multiple diffraction orders, each a copy of the original beam. Tracking in this regime can become complicated. SLMs' steering efficiency reduces with increased steering angle, placing more emphasis on correct optics design as well as high resolution SLMs.

Furthermore, PR-based steering is difficult to implement in a multi-beam steering system. This is due to the placement of the SLM within the steering system with respect to image and pupil planes. While there are solutions possible, these generally require additional components.

The challenges of individual multi-beam steering, SLM positioning, angle of arrival as well as the tracking difficulties were addressed by a single solution: phase ramp and Fresnel lens (PRFL) steering, which will be discussed in the next section. In that section, an individual optical system for each beam is dynamically created using the SLMs.

5.3. PHASE RAMP AND FRESNEL LENS (PRFL) STEERING

In literature, improvements in SLM beam steering have focused on optimizing phase ramp (PR) phase screens and filtering out the 0th order diffraction as well as non-modulated light through algorithms.[5, 6, 13, 14, 15, 16] SLMs have also been used as lenses as part of optical steering systems and increasing its steering range limitations through optical design.[17]

As discussed in Section 5.2, the problem with PR steering are threefold: tracking difficulty due to diffraction, location in the optical train for effective steering and losses during steering. In this section, a method for mitigating the tracking difficulty and SLM location within

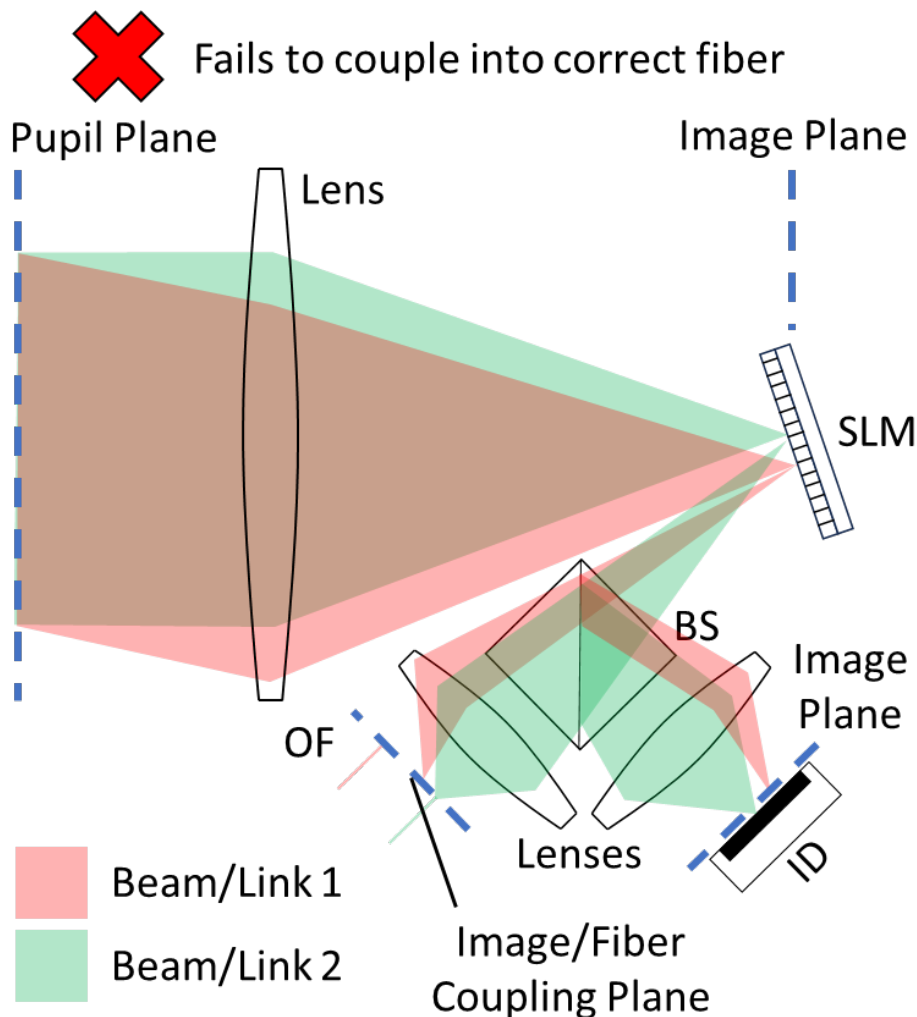


Figure 5.11.: Placing the SLM in an image plane allows for each beam to be spatially resolved. However, any phase ramp steering input would not yield translation within other image planes, such as the fiber coupling plane. This reveals a limitation of phase ramp steering.

the optical train will be discussed. Then, using the properties of PRFL, a suitable the SLM based steering system layout will be discussed.

5.3.1. PRFL AND TRACKING PERFORMANCE

Figure 5.1 shows an image from a steered beam using PR. It clearly shows multiple diffraction orders and a large non-modulated beam (NMB). The severity of these phenomena depend on the SLM design. Reducing the pixel size reduces the diffraction effects while applying an anti-reflection coating could reduce the NMB.

Nevertheless, these effects complicate tracking since each diffraction order looks similar to the target beam. Furthermore, actuation of the steered beam yields displacement of each diffraction. Tracking in such a system can become complicated very quickly.

Instead of improving steering by adjusting the phase ramp or applying software solutions, this work takes a different approach by separating NMB from the modulated beam (MB) using the SLM itself. This comes at little to no additional computational cost while also saving optical components in the optical system (which will be discussed in Section 5.3.3).

Using this novel approach, the influence of NMB and diffraction is reduced by changing the diffraction pattern and relatively increasing the MB intensity through steering using PRFL phase screens shown in Figure 5.12. To assess the suitability of this new method, three criteria were considered:

1. **Tracking can be done simply through peak intensity and center of gravity (C.G.) tracking.** If met, it reduces tracking complexity and/or increases reliability due to not having to resort to filtering.
2. **Tracking error of PRFL is the same or less than PR steering.** If met, it would imply implementation of PRFL would not reduce tracking performance and hence make it a potential candidate in a trade-off with PR.
3. **Reduction of diffraction patterns and NMB amplitude on the image detector.** If met, there could be a substantial reduction in cross-talk in multi-beam receivers and clutter for multi-beam tracking. This in turn could potentially increase the number of beams which the system could accommodate.

In this method, separation and amplitude reduction of non-modulated light (which is the source of NMB) from modulated light is a key concept. Since the non-modulated light is not altered by the SLM, it can be separated by deliberately diverging/defocusing the incident beam (just) before or after the SLM. Subsequently, converging/refocusing is done

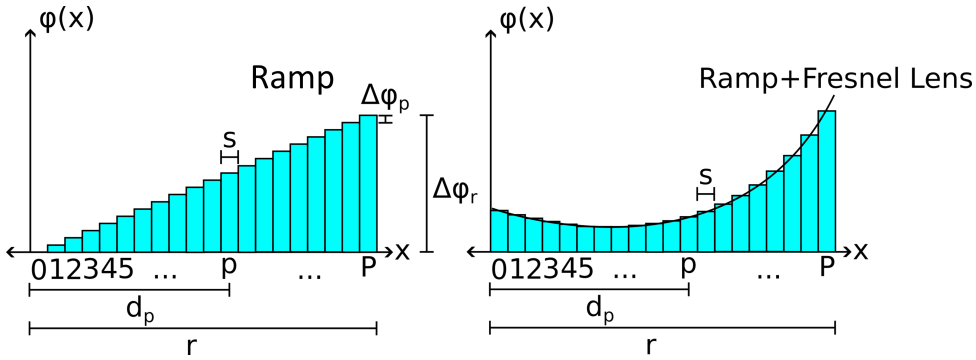


Figure 5.12.: Illustration of a phase ramp (PR) (left) and phase ramp and Fresnel lens (PRFL) (right).

on only the modulated light through PRFL, illustrated in Figure 5.13. Although this method increases the control complexity of the SLM, it reduces the complexity of tracking the beam.

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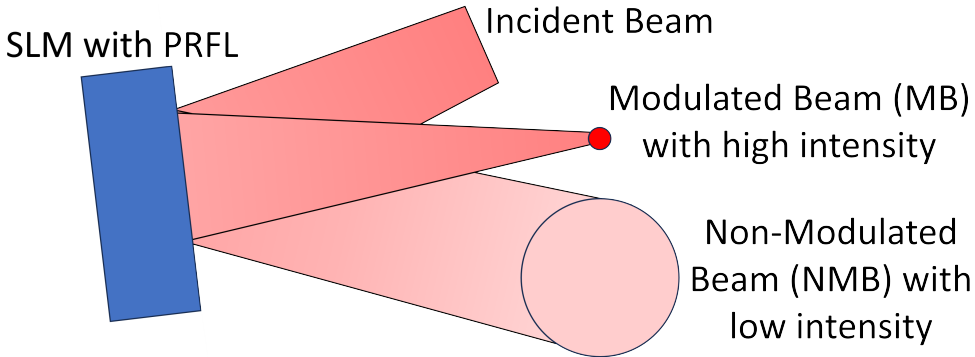


Figure 5.13.: Schematic concept of separation of NMB and MB through PRFL.

As for the diffraction pattern, the implementation of PRFL changes the shape, intensity and pattern of the steered beam and diffraction. This can be estimated analytically. The array of pixels shown in Figure 5.12 defines the pixel width as s at a lateral distance d along the x -axis. Again, the amplitude after reflection is denoted as A . The phase shift induced by this pixel is $\phi = \phi_p + \phi_L$. The modulated field immediately after reflection, $E_m(x_m)$, is approximated by a rectangular function Π :

$$E_m = \sum_{p=1}^P A \Pi\left(\frac{x_m - d_p}{s}\right) e^{j\phi_p} e^{j\phi_L} \quad (5.13)$$

Equation (5.14) is used to describe the pixelated phase ramp in Figure 5.12, assuming the phase difference and distance between each pixel is constant.

$$\phi_p = \Delta\phi_r p = \frac{\Delta\phi_r}{P} p, \quad d_p = sp \quad (5.14)$$

The phase profile of the Fresnel lens, conceptually shown in Figure 5.12, can be approximated in 1D using,

$$\phi_L = -\frac{k}{2f} x^2 = -\frac{k}{2f} s^2 p^2 \quad (5.15)$$

Where f is the focal length and k the wave number. It is convenient to use Fresnel Diffraction for propagation in the near field as the exponential term, i.e. the quadratic phase term across the pupil $\exp(jkx_m^2/2z)$, cancels out the Fresnel lens phasor at the focal length f . Note, this cannot be done when considering the pixelation, hence only the ramp phasor is propagated pixelated. Inserting Equation (5.13) into the Fresnel Diffraction equation and setting the propagation distance $z = f$ yields:

$$\begin{aligned} E_f &= \frac{e^{jkf}}{j\lambda f} e^{j\frac{k}{2f} x_f^2} \\ &\int \sum_{p=1}^P A \Pi\left(\frac{x_m - d_p}{s}\right) e^{j\phi_p} e^{-j\frac{k}{2f} x_m^2} e^{j\frac{k}{2f} x_m^2} e^{-j\frac{k}{f} x_f x_m} dx_m \\ &= \frac{As}{j\lambda f} e^{jkf} e^{j\frac{k}{2f} x_f^2} \text{sinc}\left(\frac{ks}{2f} x_f\right) \sum_{p=1}^P e^{j(\phi_p - \frac{2\pi}{\lambda f} x_f d)} \end{aligned} \quad (5.16)$$

Using the geometric identity:

$$s_n = \sum_{k=0}^{n-1} ar^k = \sum_{k=1}^n ar^{k-1} = a \left(\frac{1 - r^n}{1 - r} \right) \quad (5.17)$$

When $\phi_p = \Delta\phi_r/Pp$, $r = \exp j(\Delta\phi_r/P - 2\pi x_f s/(\lambda z)) \neq 1$, $p = k - 1$, $n = P$ and $a = 1$, Equation (5.16) simplifies to:

$$E_f = \frac{1}{j\lambda f} e^{jkf} e^{j\frac{k}{2f}x_f^2} \underbrace{\text{Asinc}\left(\frac{ks}{2f}x_f\right)}_{\text{Amplitude Envelope}} \underbrace{\left(\frac{1 - e^{j\left(\frac{\Delta\phi_r}{P} - \frac{k}{f}sx_f\right)P}}{1 - e^{j\left(\frac{\Delta\phi_r}{P} - \frac{k}{f}sx_f\right)}}\right)}_{\text{Diffraction}} \quad (5.18)$$

This equation does not include diffraction from gaps between the pixels, pixelation of the Fresnel lens as well as discrepancies in phase command and output. This result is plotted in [Figure 5.14](#) and shows a pattern formed in the focal plane which follows an amplitude envelope. The steered spot is well defined and simple to track, making PRFL compatible with criterion 1. Furthermore, the diffraction pattern is spaced apart which allows for the steered beam to be imaged alone on the detector as illustrated in [Fig. 5.14](#). As a result, the influence of the diffraction pattern on tracking and cross talk can be reduced using PRFL, which together with NMB amplitude reduction, makes it compatible with criterion 3.

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5.3.2. EXPERIMENTAL DEMONSTRATION OF PRFL

To verify these conclusions and assess the tracking error performance of PRFL compared to PR in the presence of NMB and diffraction for criterion 2, an experiment was conducted. The setup, including components and dimensions, is illustrated in [Figure 5.15](#). The beam was aligned with the optical axis when zero degree PRFL was displayed on the SLM. The perfbboard is used to create a small beam from a larger collimated beam to simulate a homogeneously illuminated finite aperture.

The setup allowed for deliberate defocus and focusing by varying the imaging lens distance to the image detector. The image detector exposure time was set to 20 μs . Lastly, the constant position of the 0th order and NMB allowed for masking in the same position. An illustration of masking is shown in [Figure 5.16](#).

Three settings were chosen to assess the suitability of PRFL according to criterion 2 mentioned above:

1. **PR:** to show this method is sensitive to incorrectly tracking the NMB and diffraction instead of the steered beam without masking.
2. **PR with the NMB and 0th order masked:** for a tracking baseline to assess criterion 2.
3. **Defocus with PRFL and no mask:** to verify the working of PRFL and its ability to meet criteria 1 and 3.

Beam tracking is done in two steps. The beam is first coarsely tracked using peak intensity and subsequently refined using a local center of gravity (C.G.). The steps are shown in [Figure 5.17](#).

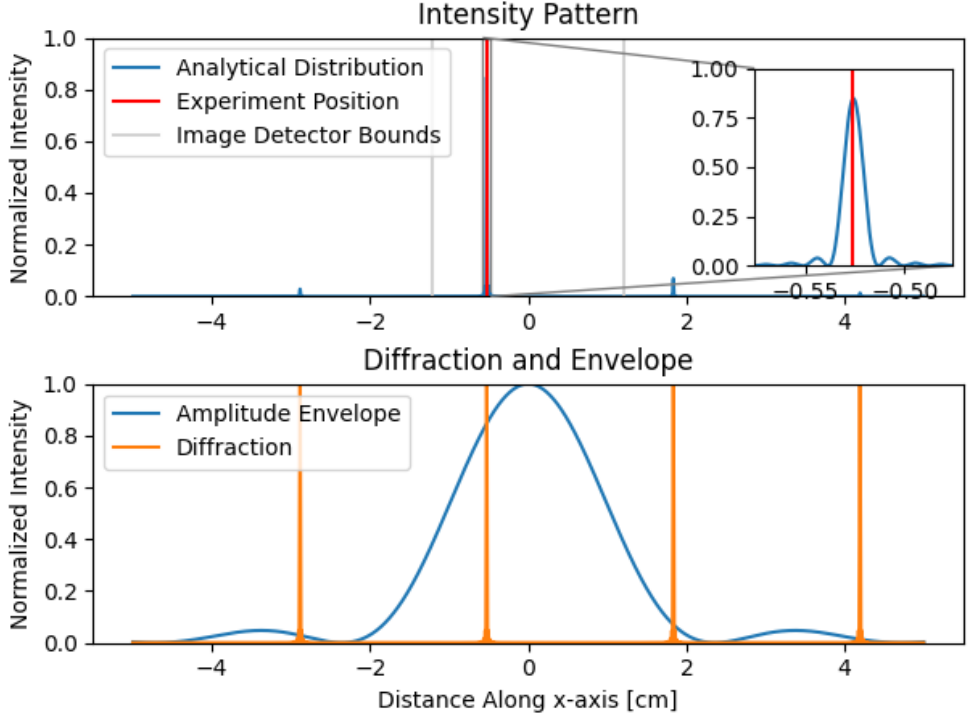


Figure 5.14.: Results of the analytical approximation of PRFL in the focal plane. (a) Plot of an output pattern compared to the position detected in the experiment ("Experiment Position") for verification. The experiment will be explained later. For clarity, a zoom of the steered beam as well as the image detector bounds are provided. (b) Decomposition of the diffraction pattern in a diffraction pattern and an amplitude envelope to help illustrate the behavior.

The C.G. error propagation was analyzed as a way to compare tracking performance of PRFL and PR. The norm of the signal error vector, Δr_{cgs} , is determined using

$$\Delta r_{cgs} = \Delta r + \frac{\Delta I + \Delta I_{nav}}{\sum_i^N I_{si}} \sum_j^N |r_j - r_{cgnav}| \quad (5.19)$$

where Δr , ΔI and ΔI_{nav} are the offset errors of the pixel position, pixel value and the noise average, respectively. The number of pixels in the local frame is denoted by N . The norm of the position vector of the signal C.G., r_{cgs} , is the absolute distance from the origin in the

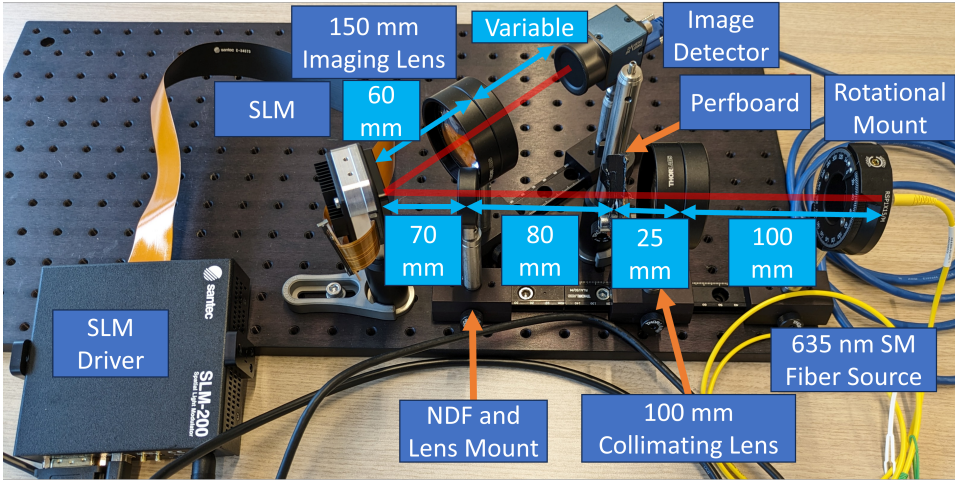


Figure 5.15.: Labeled image of experimental setup. The SLM and image detector are the uncoated SLM-200 and MER2-160-227U3M respectively.[8, 18]

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local frame. Position norm is defined as $r = \sqrt{x^2 + y^2}$ with x and y denoting the coordinates along their respective axes. The value of pixel i is denoted as I_i , average noise level, I_{nav} , C.G. position is denoted as r_{cgnav} and resides in the center of the local frame. The pixel position error, Δr , is driven by manufacturing tolerances. This was set to 0 as it was assumed that the pixel location error is negligible. ΔI was taken to be the 8-bit discretization of the pixel which is 1 out of 2^8 for the image detector (MER2-160-227U3M).[18] Finally, ΔI_{nav} was set to $\sigma_n/\sqrt{N}$, where the standard deviation of the noise, σ_n , is taken from the whole image after the NMB and MB pixels have been masked and ignored. Note that the image after masking includes diffracted light. The variables are assumed to be independent. The beam diameter was determined by finding the intersection between the beam and the noise floor once at the start.

The error propagation results in Figure 5.18 (b) show that the tracking performance of masked PR can be met without a mask using PRFL, meeting criterion 2. From example images in Figure 5.16, it can also be observed that NMB and diffraction for PRFL are less dominant than for PR, satisfying criterion 3. Figure 5.16 and Figure 5.18 (a) also show that tracking can be performed purely through peak intensity and C.G. tracking, satisfying criterion 1. Having met all the criteria, PRFL has the prospect of being a suitable candidate for use in multi-beam steering systems.

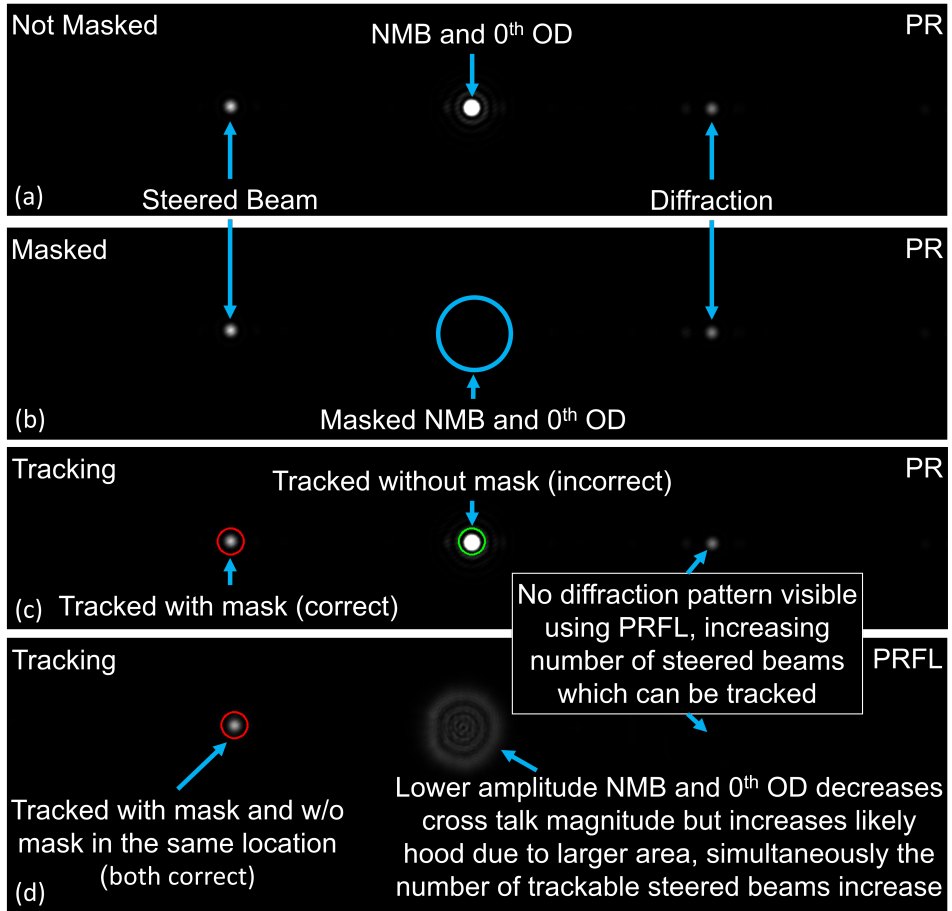


Figure 5.16.: Figures (a-d) show differences in tracking when using PR and PRFL. These are real images captured during the experiment. (a) Labeled image of a steered beam. "0th order diffraction" is abbreviated to "0th OD". (b) Demonstration of digital masking, the blue circle shows where the mask is placed. When the mask is applied, all the masked pixels are ignored. (c) Algorithms tracking when using PR without masking, shown in the green circle, tracks the NMB and 0th OD and not the steered beam due to higher peak intensity. When masking, the correct beam is tracked, shown in red. (d) Algorithms tracking beams when using PRFL does not require masking, the red and green circles coincide (with the green circle underneath the red circle). Additional benefits of PRFL are mentioned in the figure.

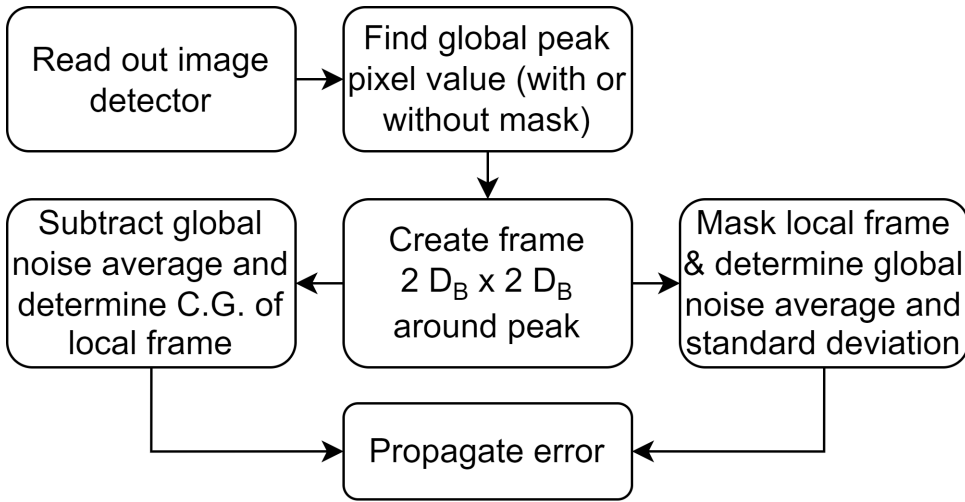


Figure 5.17.: Spot tracking flow chart. The tracking algorithm uses a peak intensity informed local C.G. algorithm as well as error estimation steps. D_B denotes beam diameter.

The results demonstrate that PRFL could be particularly effective when NMB and diffraction are dominant over the signal. Due to no additional hardware components being needed to implement PRFL, the cost of implementation can be minor. Furthermore, not needing masking or filtering algorithms could make tracking non-static beams using PRFL easier and more reliable. Lastly, fewer artifacts to track could also increase the number of beams the system can track.

For SLMs that reduce NMB by an anti-reflection coating, PRFL is less relevant. Still PRFL can further reduce the amount of cross-talk originating from NMB leaking into the other comms channel, at the cost of a higher probability of cross-talk due to an increased NMB area (discussed in [Figure 5.16](#)). Other aspects that form a limitation in applying PRFL are: 1) the limited spatial resolution of the SLM limits the steering angle and the minimum focal length of the FL; 2) Computational load and modeling complexity of synthesizing multiple FLs is increased; 3) for long focal lengths, the effects are reduced.

In the next subsection, PRFL will be used in the design of a multi-beam steering stage.

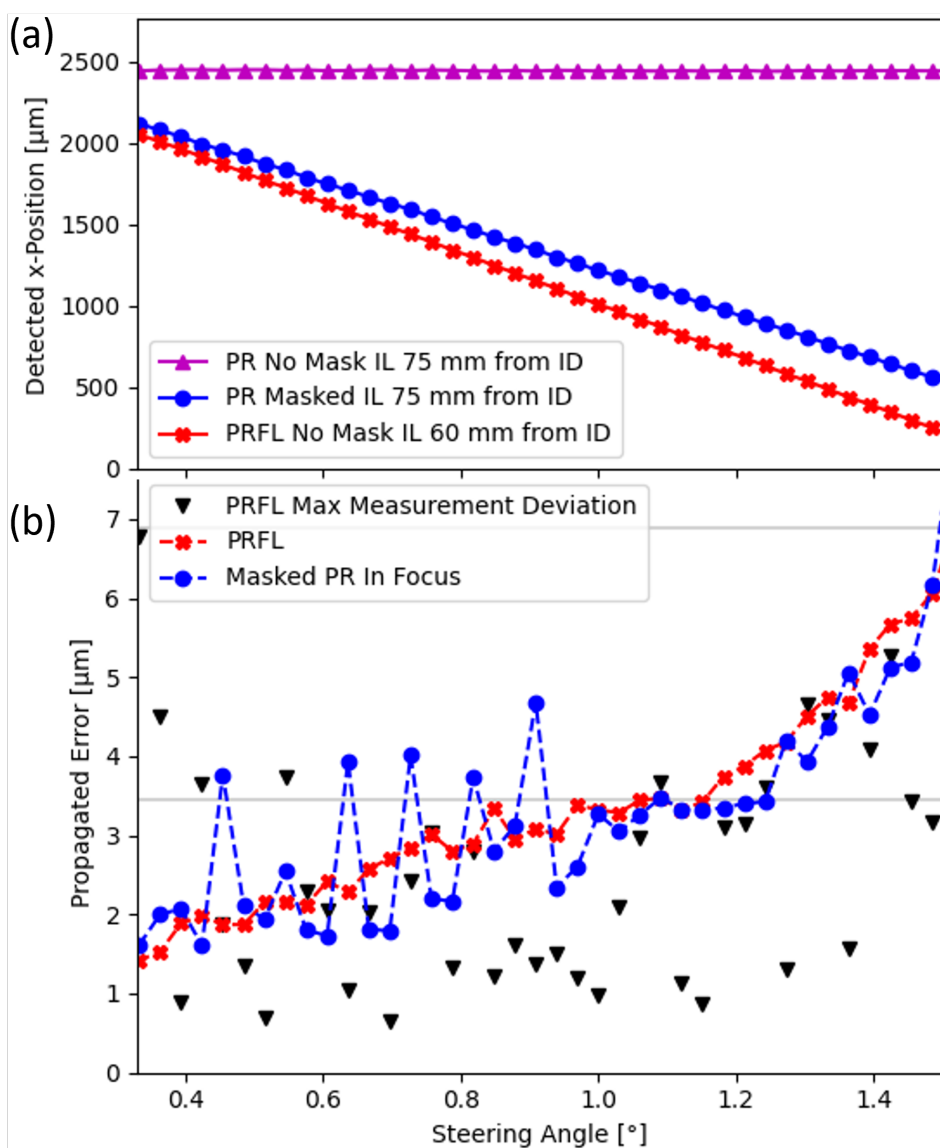


Figure 5.18.: (a) Relation between steering angle and detected x-position for PR and PRFL. The distance from the imaging lens (IL) to the image detector (ID) changes between PRFL and PR runs and changes the perceived angle. (b) Propagated error together with the maximum measurement deviation from the average detected C.G. at each beam position. The gray lines indicate one pixel [18].

5.3.3. INTEGRATION OF PRFL INTO MULTI-BEAM ACQUISITION AND STEERING SYSTEMS

Section 5.2.5 mentioned four challenges with integration of SLMs in multi-beam steering systems; individual multi-beam steering, SLM positioning within the steering system, angle of arrival as well as the tracking difficulties.

The result of Section 5.3.2 demonstrates the ability to individually focus and steer beams using SLMs with individualized PRFL phase screens. Considering the challenges facing integration of SLMs into the steering system in Section 5.2.5, PRFL can dynamically map and image different beams individually in any location where beams are spatially resolvable. Thereby solving the first two challenges of individual multi-beam steering and SLM positioning within the steering system. In addition, imaging lenses can also be removed from the optical system shown in Figure 5.9 as the function of these will be performed by the SLM.

The angle of arrival into the optic fibers can be improved using a second steering stage, as also discussed in Chapter 3. The second steering stage is needed because the steering mechanism (SLM) can only control angular degrees of freedom as well as the focal point. However, the SLM cannot translate the beams directly. To control angle of arrival, translation as well as focus, two steering stages are needed.

Lastly, using PRFL the diffraction patterns can be controlled to remain outside of the tracking sensor.

The resulting steering system is illustrated in Figure 5.19. This system resembles earlier work by the TU Delft, with important improvements.[3, 19]

The first SLM is used to separate the beams spatially and determine the spot size on the second stage SLM (SLM 2 on steering plane 2). The placement of this SLM is in accordance with that discussed in Section 5.3. In order for the system to operate, the FoV image from the telescope and the SLM size should be matched, potentially needing additional optics. The second steering plane controls coupling angles and spot sizes of each beam individually on the coupling plane. This creates a bespoke optical path for each beam. Within the fiber, Tx and Rx can be separated through an optical circulator.[3, 19]

Using the same path for down-link and up-link ensures that the number of tracked beams is reduced by half and more components can be shared between beams. To achieve a point ahead angle, a small offset between each beam path must be created. Using the system in Figure 5.19 and simplifying the second steering stage, the point ahead angle can be achieved through multiple methods as shown in Figure 5.20.

The point ahead angle is achieved through deliberately changing the coupling angle of the Rx beam. Two schemes are based on inducing

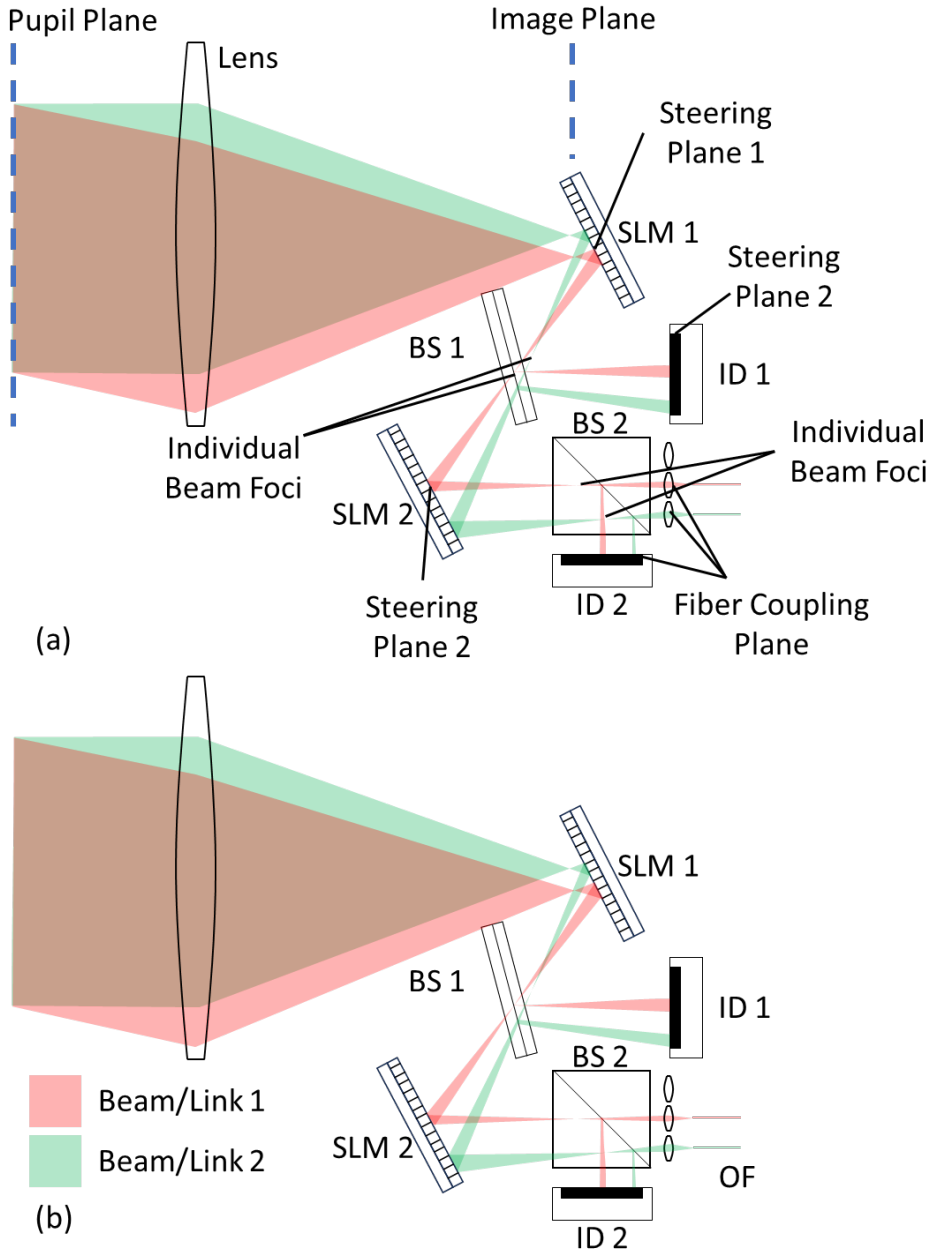


Figure 5.19.: Overview of a two stage multi-beam steering system using phase ramp and Fresnel lens (PRFL) steering phase screens. Figure (a) has labeled planes while (b) shows the same figure without labels for ease of viewing. This system dynamically creates individual optical systems for each beam, allowing for each to be steered individually. In addition to this, a number of lenses are removed due to their functions being replaced by the SLMs.

a lateral offset and one is based on angular offset, indicated by A, B and C in [Figure 5.20](#). This approach comes at the cost of reducing coupling efficiency. To analyze the efficiency degradation, the efficiency of normalized offsets can be compared in literature. The normalization is done by

$$\Delta x' = \frac{\Delta x}{\omega}, \quad \Delta \theta' = \frac{f \Delta \theta}{r}, \quad (5.20)$$

where $\Delta x'$ and $\Delta \theta'$ are the fiber mode radius (ω) normalization of the lateral offset Δx and angular normalized angular offset $\Delta \theta$ respectively. With f the focal length and r the steering area radius. The lateral offset Δx is induced through angular offset $\Delta \theta$ in the pupil plane of the focusing lens on the SLM or the coupling lens. This angle can be approximated by

$$\Delta x = f \Delta \theta. \quad (5.21)$$

Determination of the resulting angular offset can hence be determined by

$$\Delta \theta = \frac{\omega \Delta x'}{f} \quad (5.22)$$

for lateral offsets and

$$\Delta \theta = \frac{r \Delta \theta'}{f} \quad (5.23)$$

for angular offsets. Comparing [Equation \(5.22\)](#) and [Equation \(5.23\)](#) shows that the coupling efficiency is more tolerant to angular misalignment compared to lateral misalignment when the mode field radius is less than the steering area ($\omega < r$), keeping focal length equal. Furthermore, reducing the focal length can also yield larger angular offsets.

To compare A, B and C (shown in [Figure 5.20](#)), A and C are given a focal length of 10 cm, while B is given a focal length of 1 cm due to the use of a coupling lens. The steering area width is set to 10 pixels (20 pixel full width), with each pixel having a width of $8.1 \mu\text{m}$ yielding $81 \mu\text{m}$. The mode field radius is taken to be $10.4 \mu\text{m}$. Next, the normalized efficiency degradation limit for fiber coupling is set to 50%, implying the maximum allowable normalized lateral and angular offsets to be 0.8 and 0.7 respectively.[\[20, 21\]](#) The results are shown in [Table 5.1](#). Note that are for a spot size that is optimized for coupling.

Another method is to increase the spot size. This yields a lower peak coupling efficiency, however, can increase the coupling efficiency with translated and angular offsets. Increasing the spot size by 43% can

approximately yield $99\text{ }\mu\text{rad}$ for A, $988\text{ }\mu\text{rad}$ for B and $648\text{ }\mu\text{rad}$ for C. This comes at the cost of 15% peak coupling efficiency.

These angular offsets are not directly equal to the point ahead angles as the optical system would likely amplify them. Nevertheless, typical point ahead angles range between $20\text{ }\mu\text{rad}$ to $50\text{ }\mu\text{rad}$ for ground to LEO[22], showing that the selection of the design of the relevant parameters is important. Furthermore, in the presence of jitter, the effective offsets should be reduced in order to accommodate excursions.

Method	A	B	C
Focal Length	10 cm	1 cm	10 cm
Steering Area Radius	-	-	$81\text{ }\mu\text{m}$
Min Norm. Efficiency	0.5	0.5	0.5
Normalized Offset	0.8	0.8	0.7
Max Angular Offset	$83.2\text{ }\mu\text{rad}$	$832\text{ }\mu\text{rad}$	$567\text{ }\mu\text{rad}$

Table 5.1.: Example maximum allowable angular offsets for each method in [Figure 5.20](#) for a given minimum normalized efficiency.

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5.4. DISCUSSION AND CONCLUSION

In conclusion, this chapter presented the theory and experimental demonstration of phase ramp and Fresnel lens (PRFL) based steering. It shows that deliberate defocus followed by a PRFL phase screen on an SLM reduces the influence of non-modulated beams (NMBs) and diffraction on tracking. It does so without loss of tracking performance or additional hardware. While phase ramp steering required filtering to track, tracking using PRFL required no additional filtering steps.

Furthermore, PRFL also offers a solution to a critical challenge in multi-beam steering mechanism (SLM in this case) placement. This is due to the ability to dynamically generate individual optical systems for each beam using the SLM. It can also eliminate the need for intermediate imaging optics.

The theory was verified in experimental demonstration through the experimental setup discussed in [Chapter 4](#). Furthermore, the steering performance of the SLM was compared to the values found in [Chapter 2](#).

While this chapter has discussed some important and novel innovations with respect to multi-beam steering, there is still much to be done. For one, the wide field of view requirements are more challenging than those for narrow field of views. Applying formal control theory analysis to the control loop to investigate the dynamics of including SLMs into steering systems is also needed. As part of this, the computational load and optimization would need to be considered.

Lastly, PRFL is a demonstrated principle, however, a full multi-beam closed-loop steering system is still requires demonstration.

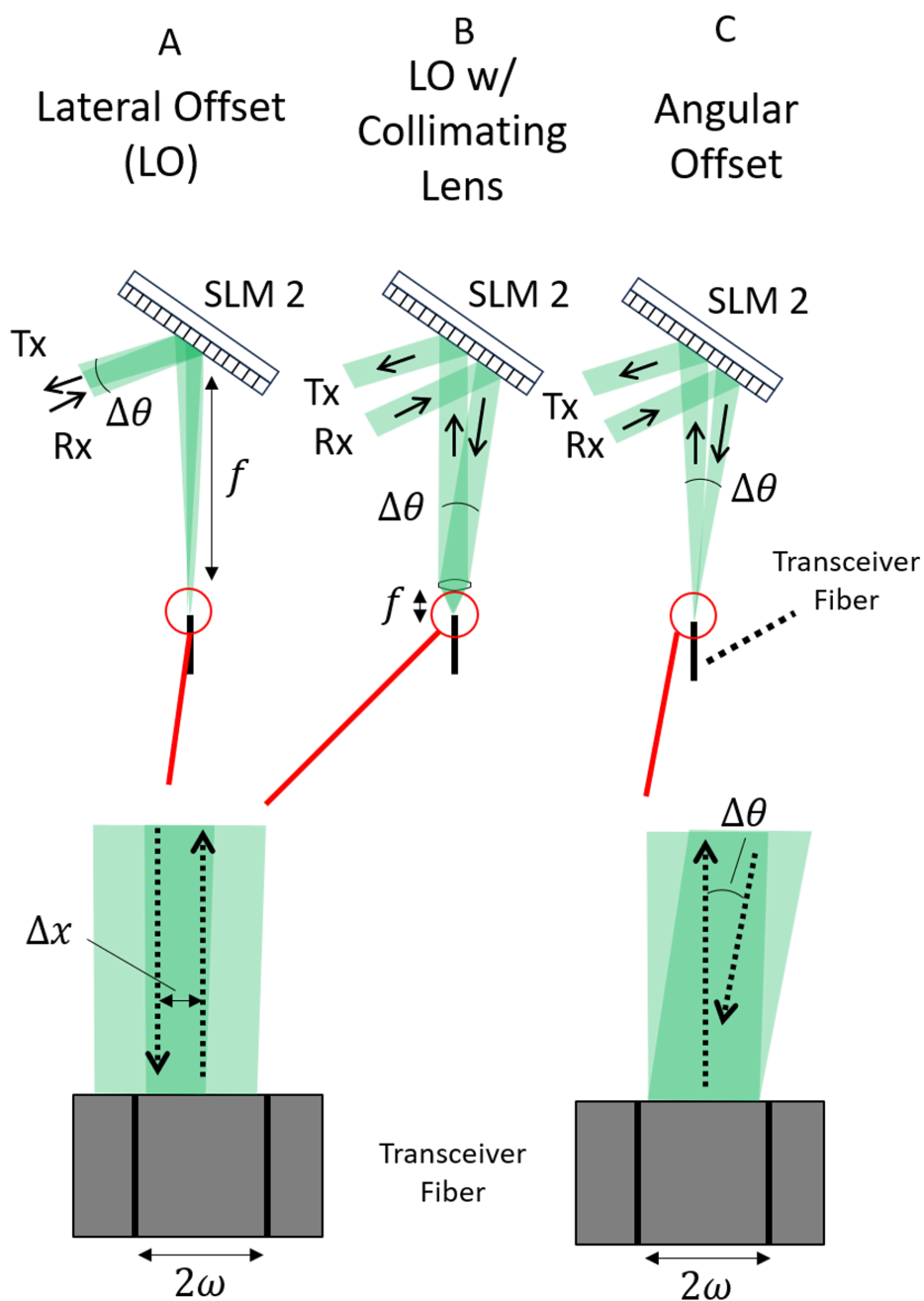


Figure 5.20.: Point ahead angle methods. The left (A) and middle (B) show lateral offset methods with the middle using a coupling lens, while the right (C) shows an angular offset.

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6

MULTI-BEAM TRACKING

All we have to decide is what to do with the time that is given us.

Gandalf (*The Lord of the Rings*)

Both single and multi-Beam laser communication terminals (SBTs and MBTs) require efficient algorithms for tracking multiple beams with sub-millirad accuracy and between 100Hz - 1kHz control bandwidths. In addition, MBT tracking systems track the full frame in order to acquire and track multiple beams in multiple places on the detector at once. To our knowledge, no suitable algorithms exist that offer multi-beam tracking for MBTs which simultaneously allow beams to move and (dis)appear randomly. In this chapter, we propose a novel multi-beam tracking algorithm using computationally inexpensive temporal-based techniques inspired by multiple target tracking. This method leverages frame association based on directional beam behavior and statistical analysis for accurate beam classification and labeling. Experimental results using commercially available hardware show that our algorithm can track 1000 beams (false and true positives) with over 99% precision at 1 ms per frame overhead, utilizing a 1.8 GHz processor. The tracked beam location is within 1 pixel of the true center. An analytical model of the algorithm was derived from mixed replacement urn problems and complete homogeneous symmetric polynomials. Combining these yielded in a, to our knowledge, new probability distribution we coined CombiTron. Our temporal-based tracking technique significantly enhances MBT performance with minimal computational overhead. This approach can be useful for applications outside of multi-beam tracking, including single beam tracking. The theory matches simulations and experiments, allowing for accurate estimation of tracking performance and requirements.

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6.1. INTRODUCTION

Chapter 3 and Chapter 5 discussed the steering system design and layouts. It has been shown that beams can be steered using SLMs but drawbacks, namely diffraction and non-modulated beams (NMB), which disallow tracking directly through peak intensity and center of gravity. However, through phase ramp and Fresnel lens (PRFL) steering and hardware layout, these drawbacks can be largely mitigated.[2] System layouts have been shown and demonstrated experimentally where individual beams can be steered and projected onto an image detector. This leaves a crucial part of the system: the tracking and classification of multiple beams at once. As mentioned in Chapter 2, use cases can be envisaged where these beams can move dynamically and independently as well as in and out of frame. In this chapter, a novel tracking algorithm will be discussed.

Multiple multi-beam terminal (MBT) designs have been proposed. They can be broadly classified into single beam terminal (SBT) arrays[3], large mirror arrays[4, 5, 6, 7, 8, 9] and wide field of view telescope[10, 11, 12, 13, 14] based designs. Each of these require spatial awareness to track each beam across a wide field of view using image detectors.

While the theory in this work can be applied to all the mentioned terminals, to help understand the mechanics, previous work by the TU Delft[10, 11, 15] as an example for illustration shown in Figure 6.1. The system consists of two almost identical steering stages that are placed in series, each interfaced with a beam splitter. The steering systems consist of a spatial light modulator (SLM) and an image detector (ID). The first system is to arrest lateral motion of the beams in the system, and the second to couple the light into the transceivers.

Some multi-beam tracking algorithms (MBTA) have been proposed. Skryja et al.[17] propose an intensity distribution based technique for a GEO satellite mounted MBT. However, this technique has static counter terminals. A creative solution is offered by Wang et al.[5], who assume the incoming beams are differently modulated. The system subsequently uses a quad cell to track them. While computationally low-cost, it constrains counter terminals to those which are modulated. Our previous work[15] demonstrated separating multiple beams from noise and tracking their center of gravity (CoG) using spatial light modulators (SLMs).

Single beam tracking algorithms (SBTA) in the basis rely on three techniques. First, peak intensity tracking where the algorithm searches for the brightest pixel, as used by Wang et al.[18] and our previous work[2]. Second, CoG weighted by pixel intensity in the case of an image detector or approximated through a quad cell. This technique has been used in SILEX[19] and OPALS[20]. Lastly, centroiding, which finds the geometric center of a beam, is used by TBird[21] and NODE[22, 23]. Algorithms using convolutional neural networks to aid in tracking, such

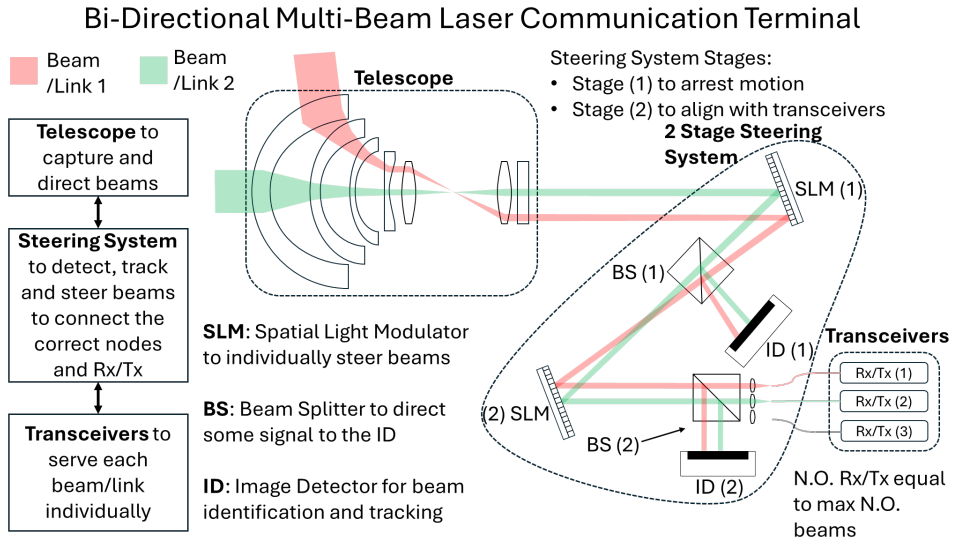


Figure 6.1.: Illustration of the optical path of a bidirectional, multistage, multi-beam laser communication system. Figure adapted from "Free-Space Multi-beam Optical Communication Terminal Design for Spacecraft" by J. Spaander on page 81 Figure 5.32[10, 16], reprinted and edited with permission.

as demonstrated in the work by Li et. al[24], have been proposed.

While these techniques are foundational for this work, the above SBTAs cannot track multiple beams directly. Multiple target tracking (MTT) algorithms can take various sensor inputs and are able to track multiple targets. Hairui et al.[25] provide an overview of these algorithms. One of the main methods used in MTT is multiple hypothesis tracking (MHT), proposed by Reid[26] in 1979. This method applies statistical analysis on past data and generates multiple hypotheses for the labeling and classification of all tracked objects at the same time. The most likely is subsequently chosen. Variations of this method have been proposed, such as those by Zheng et al.[27], and have been used in various applications such as LIDAR[28].

However, these algorithms are computationally costly compared to the aforementioned SBTAs. This was already mentioned by Reid[26] and the works by Zheng et al.[29] and Wenzl et al.[28] show tracking loop latencies on the order of seconds. Platforms which use MTT have been integrated into more size, weight and power (SWaP) tolerant systems compared to spacecraft. Examples include systems used in military or commercial aviation tracking.[30, 31, 32] Furthermore, the neural based

SBTA proposed by Li et al.[24] is also computationally more costly than the other SBTAs, requiring a GPU and CPU with 1.4 FLOPS to achieve 34 fps.

In this chapter a novel MBTA is proposed based on the insights from SBTAs and MTT. This chapter will analyze and derive theoretical behavior and performance as well as demonstrate this experimentally.

This chapter will first look at the methodology. The optical setup and synthetic images used to test and demonstrate the algorithm are described there. After this the target classification and algorithm will be detailed. Each subpart will be discussed with the theoretical equations derived, starting from image processing, target association, hypothesis tracking and behavior prediction. This includes a solution to a mixed replacement Urn problem which was solved along the way. The limitations and performance of the algorithm will be theoretically derived. Lastly, the results of the experiment will be compared to the theory and discussed.

6.2. METHOD

This section will discuss the methods used to analyze and demonstrate the algorithm. First the hardware experiment will be discussed in 6.2.1, the tracking image modeling in 6.2.2, the algorithm and the analysis will be discussed in 6.2.3 and finally the overall computational cost and limitations of the algorithm will be discussed in 6.2.4.

6.2.1. HARDWARE EXPERIMENT

An experimental setup was devised which can demonstrate multi-beam tracking by mimicking the beam wander. This comprises four parts: First the multi-beam source, second the optics, third the sensor and fourth the controller.

First starting with the multi-beam source, its function is to generate numerous beams moving in different directions at different speeds. A low cost laser source with two diffraction gratings in series was selected. These create multiple beams in a 30 degree expanding cone which move while turning one diffraction grating with respect to the other. These beams move in different directions at different speeds and cross periodically. Rotation was done using a stepper motor and gear box. The wavelength of the source was 635 nm at a laser power of 5 mW. The source output was attenuated using three ND filters of OD 2, 3 and 4 mounted sequentially just after the source to not over-expose the image detector (ID).

Second, the optics image the beams onto a detector. This was achieved through a 2" lens to arrested the divergence and focus the beams on the mirror. The mirror is used as a stand-in for a multi-beam

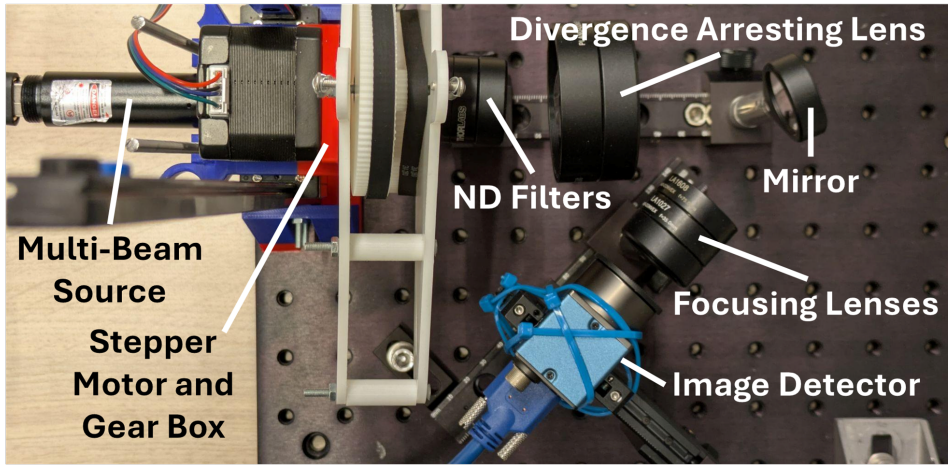


Figure 6.2.: Optical Setup. Note that the mirror is a stand-in for a steering mechanism such as an SLM or micro-mirror array.

6

steering mechanism such as an SLM or MMA, such as the SLM used in our previous work.[15] The same plane is imaged onto the ID through a combination of two lenses such that the imaged beams resembled those found in our previous work.[15]

Third, the MER2-160-227U3M[33] was chosen as the image detector. It uses a USB 3.0 interface, providing 1440×1080 8-bit mono resolution with 227 fps.

Last, the controller consisted of a 11th generation Intel i7-1185G7 logic core running at 1.8 GHz within a Dell Latitude 7420 laptop[34].

6.2.2. TRACKING IMAGE MODELING

Synthetic images were generated and fed into the algorithm to test a wide range of scenarios. These images were generated by superimposing Gaussian intensity profiles as beams and wandering them with random velocities. Gaussian noise was subsequently added. This process is shown in Figure 6.3. Despite spot size differences, the noise distribution and algorithm performance were compared with the experimental results and found to be indistinguishable from them. It is expected that increased distortion will eventually cause detrimental performance due to the spot size increase necessitating increase in tracking window size, this will be mentioned in Section 6.2.3.

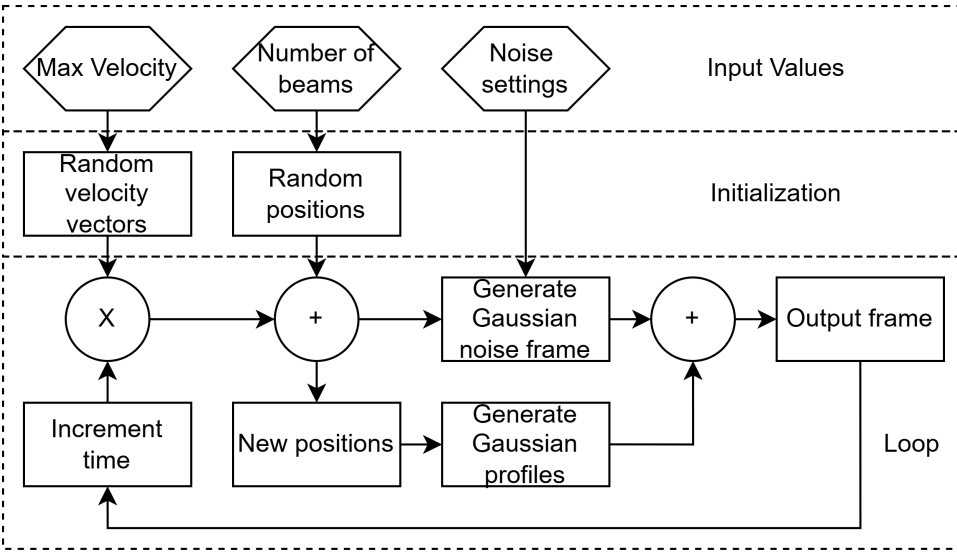


Figure 6.3.: Method of synthetic image generation. The output frames are a superposition of Gaussian noise and Gaussian beam profiles placed in random locations. The locations are linearly propagated through the frame to simulate beam wander caused by the relative motion of the counter terminals.

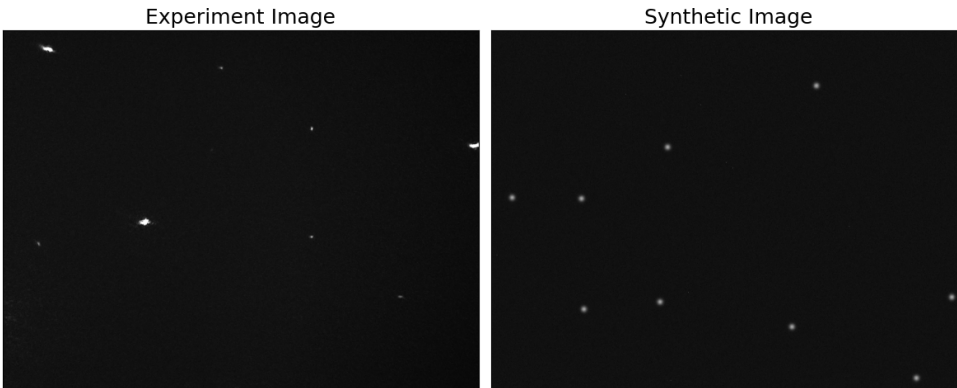


Figure 6.4.: (a) An image from the experimental setup and (b) a synthetic image.

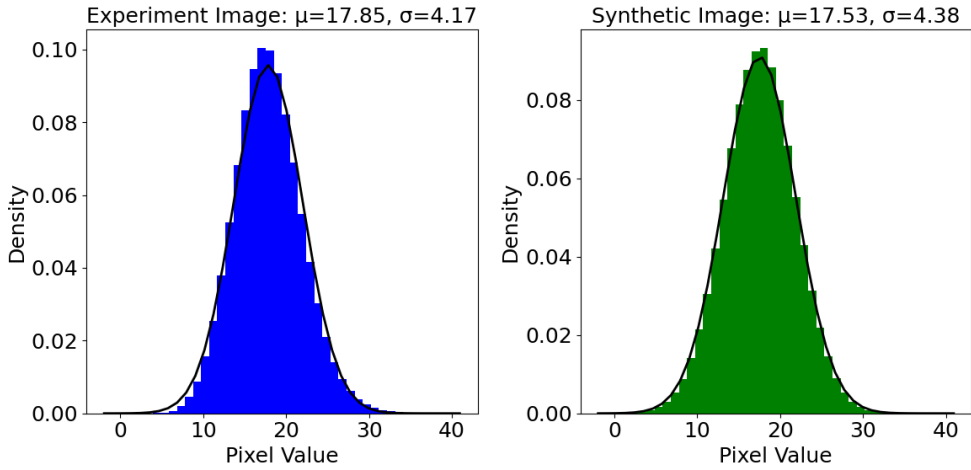


Figure 6.5.: Shown is the noise distribution of the images in [Figure 6.4](#).

6

6.2.3. MULTI-BEAM TRACKING ALGORITHM

MBTAs use attributes and patterns exhibited by the beams and noise to filter and accurately track them. As discussed in the introduction, in the basis SBTAs directly use ID data during image processing to track beams. Further noise suppression can be done using additional image processing steps. These operations scale computationally as a function of the number of pixels, on the order of $O(N_{pixels})$, $O(N_{pixels}^2)$, etc... depending on the algorithms used. For SBTAs this cost can be largely mitigated through region of interest, however this is not possible for MBTAs which track full frame.

On the other hand, multiple hypothesis tracking (MHT) processes targets originating from detections resulting from sensor processing. Maintaining and re-evaluating/back-propagating multiple hypothesis over time scales computationally factorially with the time and the number of targets tracked. The method presented in the following subsection was inspired by this approach. In short the back-propagation process was simplified to be less demanding. As a result, the method discussed scales with the number of tracked targets/beams. Since the number of detections are at most equal to the number of pixels or less, this would add $O(N_{objects})$, $O(N_{objects}^2)$, etc... (depending on the algorithm used) of overhead to track multiple beams.

Time Related Definitions: Loops can be used to express time using the following definitions:

Time: $t \in \mathbb{R}$

The loop number: $l \in \mathbb{Z}$

The loop duration: $\Delta t_l \in \mathbb{R}_{\geq 0}$

such that: $\Delta t_l = t_{l+1} - t_l$

Notation of Targets and Detections: Targets are unique in both space and time and have a history. A target can be active, i.e. when it is in frame, or non-active as a result of being out of frame or rejection by the algorithm. If all targets in space and time are considered as a set, then the vectorized representation of the set can be denoted as T . Detections are denoted as D , with D_n as the n th detection. The vectorized set of targets and detections are denoted as T and D respectively.

Since each detection is considered independently, the set of detections is organized from 0 to N detections. Targets however, have persistence between frames, and hence the designation of the target must remain persistent. As a result, there exists a mapping matrix which correctly maps previous measurements to the tracked targets. This is expressed as follows:

$$\bar{D} = \begin{bmatrix} D_0 \\ D_1 \\ \vdots \\ D_N \end{bmatrix} = M_T \begin{bmatrix} T_0 \\ T_1 \\ \vdots \\ T_M \end{bmatrix} = M_T \bar{T} \quad (6.1)$$

It is computationally economical to focus on the active targets set, $\bar{T}_A$, simplifying Eq. 6.1 to:

$$\bar{T}_D = M_{T_A} \bar{T}_A \quad \text{where} \quad \bar{T}_A \subset \bar{T}. \quad (6.2)$$

The mapping matrix (i.e. which previous known targets belong to which detections) is unknown and can only be estimated. This estimation takes place in the association step of the algorithm discussed in 6.2.3.

Position is defined as the location of the beam/target in the image according to:

$$\vec{r} \in \left\{ \mathbb{R}^2, \begin{bmatrix} x \in \mathbb{Z} \\ y \in \mathbb{Z} \end{bmatrix} \right\} \quad (6.3)$$

where x and y are the coordinates of the beam/target. The position of the n th detection is denoted as: $\vec{r}_{D_n}$. The position of the n th target is denoted as: $\vec{r}_{T_n}$

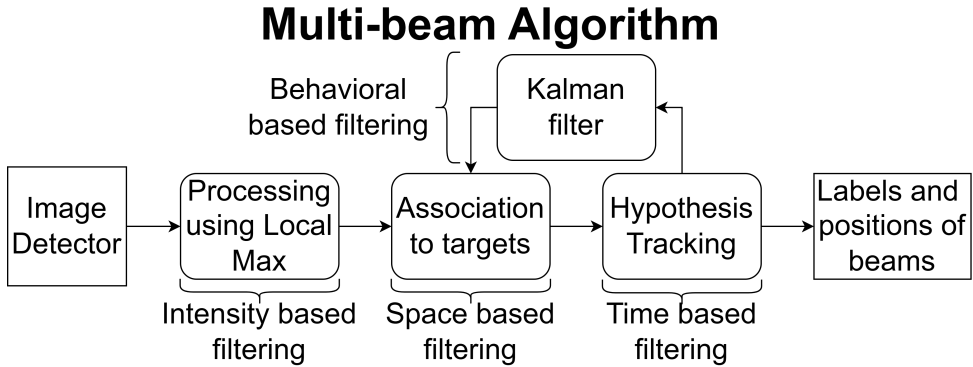


Figure 6.6.: Multi-Beam Algorithm with Attributes Labeled.

Binary Actual Classification System of Targets: An overview of the algorithm can be found in [Figure 6.6](#). The algorithm statistically analyzes this over time to filter noise and uses this to classify targets. The local max (LM) processing step and the hypothesis tracking (HT) steps perform binary tests and subsequent classifications. The steps yield test classifications and are compared to the actual classification. The actual classification system used in this work can be seen in [Figure 6.7](#). This classification will be used throughout this text for analysis of the system performance. The test classification system will be discussed later.

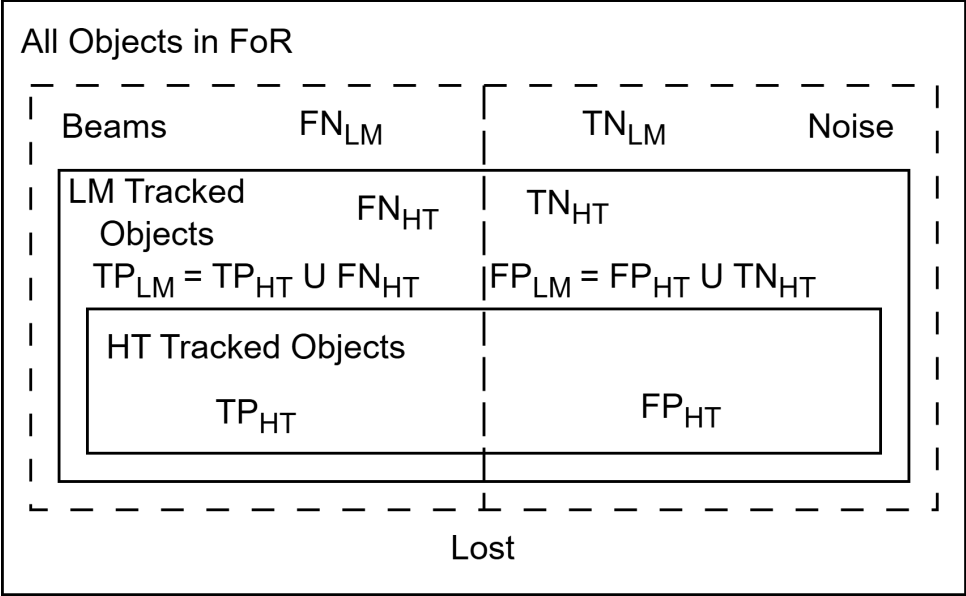
Each part of the algorithm will now be discussed and analyzed, starting with the image processing step in [6.2.3](#), then the association in [6.2.3](#), the hypothesis tracking in [6.2.3](#) and finally the Kalman filter in [6.2.3](#). The analysis of each step will look at the sensitivity to noise by looking at the number of false positives and overall precision as performance metrics. In [6.2.4](#) the computational load and overall limits of the algorithm will be discussed.

SENSOR PROCESSING/LOCAL MAX

In short, the sensor processing step takes raw pixel values and finds a thresholded local maxima (LM) which can be fed into the measurement association step. Each pixel is evaluated. The local area size is a square window of n pixels centered around the maximum pixel within those pixels. To save time, first the threshold is applied before comparing the pixel to the highest value of the other pixels exceeding the threshold in the window. This is schematically explained in [Figure 6.8](#).

The number of **True Positives**, TP, are the number of beams that exceed the threshold. If instead noise is detected in the same window

Actual Classification Scheme



TP: True Positives i.e. correctly identified beams/targets
FN: False Negatives i.e. incorrectly identified beams/targets
FP: False Positives i.e. incorrectly identified noise/false targets
TN: True Negatives i.e. correctly identified noise/false targets
LM: Sensor Processing (Local Max)
HT: Hypothesis Tracking

Figure 6.7.: Set diagram of actual classification of targets. The local max and hypothesis tracking steps filter data into binary classification to either accept as beams or reject as noise. The actual classification, used to determine algorithm performance later, is shown here. Starting with all objects, the set shrinks after each algorithm step. The figure is split between noise and beams for clarity.

as a beam, this would still be considered a correct detection and be a TP. Beams are assumed to be wandering in any direction in any place, which can cause multiple beams to occupy the same window.

Local Max Algorithm

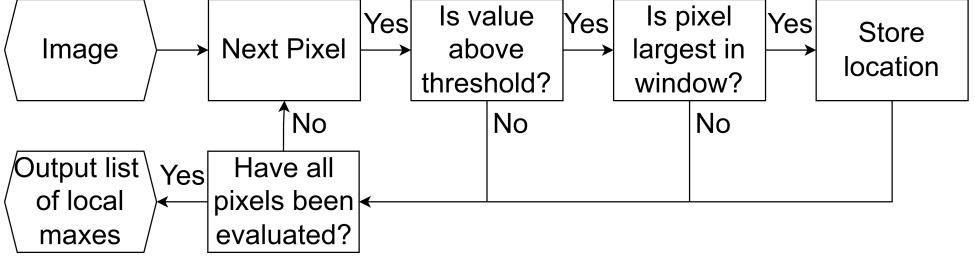


Figure 6.8.: Local max algorithm

It therefore is assumed that beams have a uniform probability density function (PDF) of being at any point within the frame. Furthermore, although beams can illuminate multiple pixels, the center of the beam is contained within one pixel, which is subsequently tracked. The spatial density and the expected number of beams within a randomly selected window is given by

$$\rho_B = \frac{N_B}{N_{pixels}} \quad \text{and} \quad \lambda_B = \frac{nN_B}{N_{pixels}}, \quad (6.4)$$

with ρ_B and λ_B the pixelated spatial density and expected number of beams in a window of size n respectively. The total number of beams is N_B and the total number of pixels in the frame is N_{pixels} . The resulting distribution of finding k beams in a window follows a Poisson distribution as follows:

$$P(X_W = k) = \frac{\lambda_B^k e^{-\lambda_B}}{k!} = \left(\frac{nN_B}{N_{pixels}} \right)^k \frac{1}{k!} e^{-\frac{nN_B}{N_{pixels}}} \quad (6.5)$$

Making use of the always positive and discrete nature of the problem and taking N_W as the number of possible windows, the expected number of true positives is hence:

$$\begin{aligned} TP &= N_W P(X_W \geq 1) = \frac{N_{pixels}}{n} (1 - P(X_W = 0)) \\ &= \frac{N_{pixels}}{n} \left(1 - e^{-\frac{nN_B}{N_{pixels}}} \right) \leq N_B \end{aligned} \quad (6.6)$$

Eq. 6.6 shows that increasing the number of beams, N_B , yields a proportionally lower number of true positives, TP, due to overlapping.

The number of **False Positives**, FP, can be used as an indicator for the algorithm filtering performance. Relating FP to the noise would allow us to relate algorithm performance to noise. For the sensor processing step, this is done by taking the probability of noise meeting the thresholded local max and multiplying it with the maximum number of allowable windows. Take a window W , consisting of pixels with (Gaussian) noise values I of which none belong to a beam in the subset of all beams at time t_l , $\mathcal{B}_{t_l}$ (where $\mathcal{B}$ is the set of all beams in time on the detector), then the probability of the max pixel value in the window, p_{LM} , is

$$\begin{aligned} p_{LM} &= P(\max(W) \geq T \cap W \notin \mathcal{B}_{t_l}) \\ W &= \{I_0, I_1, \dots, I_n | I \sim N(\mu, \sigma)\} \end{aligned} \quad (6.7)$$

Taking that the pixel noise and the beam distributions are independent, these can be split. Mapping the pixels to the ordered statistic and multiplying with the maximum number of windows, yields the number of false positives,

$$\begin{aligned} FP_{LM} &= N_{windows} p_{LM} \\ &= \frac{N_{pixels}}{n} P(\max(W) \geq T) P(W \notin \mathcal{B}_{t_l}) \\ &= (1 - e^{-pn}) \left(\frac{N_{pixels}}{n} - TP \right) = p_n \left(\frac{N_{pixels}}{n} - TP \right) \end{aligned} \quad (6.8)$$

where p is the probability of a pixel (without a beam) exceeding the threshold due to noise.

As can be seen from Eq. 6.8, increasing the number of beams yields fewer false positives when keeping other parameters the same. This is due to the aforementioned statement that when a window is accepted due to noise also contains a beam, then this will be considered a TP. Hence, the number of false positives should decrease with increased number of beams. Furthermore, increasing the window size has the effect of reducing the number of possible windows, which in turn has the effect of decreasing the number of false positives. However, at the same time this increases the rate at which windows are falsely accepted. This is because the window has more pixels with the same probability of exceeding the threshold due to noise. As a result, increasing the window size increases the probability of having at least one FP while simultaneously decreasing the total possible number of FP. As a result, increasing the window size is detrimental for the overall FP rate. This is captured in Eq. 6.8 by the factor $1 - e^{-pn}$ approaching 1 faster than N_{pixels}/n approaches 0. Limit cases and setting the threshold will be discussed in Section 6.2.4. Nevertheless, this is particularly relevant

where the lowest threshold possible is preferred (to, for example, minimize the required signal power on the tracking image detector).

It is important to note that optical distortion requires window size to increase in order to encapsulate the beam and limit multiple detections per beam. As a result, the level of optical distortion can have direct influence on the tracking performance when larger than the positional uncertainty.

ASSOCIATION OF MEASUREMENTS TO TARGETS

The goal of association is to approximate as closely as possible the mapping matrix M in Eq. 6.2. Association is performed by comparing detection locations from the sensor processing step described in 6.2.3 with the predicted locations which will be described in 6.2.3. In the following it is assumed that the measurement closest to the predicted location of a previously known target and/or candidate target is most likely to be the target. By likelihood, we mean the likelihood of observing the correct outcome for an assumed set of parameters. The observations are position locations and the parameters are the previously known targets and candidates.

The detection proximity matrix at time t is shown in Eq. 6.9:

$$\Delta \mathbf{r}_t = |\mathbf{J}(\mathbf{r}_{T_D} - \mathbf{r}_D)|$$

$$= \begin{bmatrix} |\hat{\mathbf{r}}_{T_{D0}:l|l-1} - \mathbf{r}_{D_0}| & \cdots & |\hat{\mathbf{r}}_{T_{Dn}:l|l-1} - \mathbf{r}_{D_0}| \\ \vdots & \ddots & \vdots \\ |\hat{\mathbf{r}}_{T_{D0}:l|l-1} - \mathbf{r}_{D_n}| & \cdots & |\hat{\mathbf{r}}_{T_{Dn}:l|l-1} - \mathbf{r}_{D_n}| \end{bmatrix} \quad (6.9)$$

where $\hat{\mathbf{r}}_{T_{D0}:l|l-1}$ is the "a priori" position estimate. A cut-off radius is applied to save compute time on highly unlikely associations. Then a row min is applied to determine the most likely association between measurement and previously known target:

$$\text{Association Matrix} = \text{RowMin}(\Delta \mathbf{r}_t \leq r_{max}) \quad (6.10)$$

A simple *RowMin* operation was chosen over comparing the distance to a probability distribution and evaluating the probability. Here there is a departure from MHT. In order to improve the speed of the algorithm, probabilities from previous associations are not stored and re-evaluated. This can be factorially more costly in terms of computational and memory resources. Hypotheses over time are adjusted in loop, and will be discussed in 6.2.3. Nevertheless, it can be considered in future.

All non-associated detections are passed as new candidate targets. An overview of the algorithm can be found in Figure 6.9.

Multiple beams can be associated to the same detection. Should this be the case, the oldest one is associated while the others are not

Association Algorithm

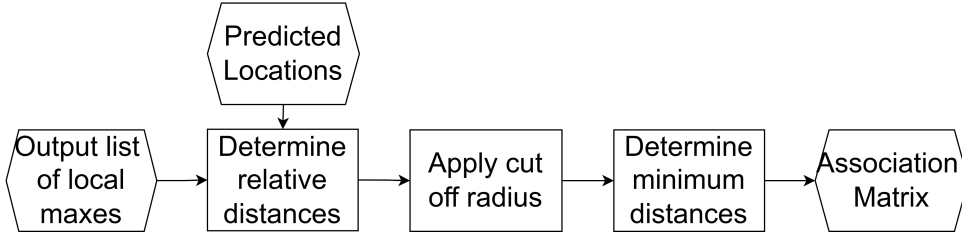


Figure 6.9.: Association algorithm block diagram.

associated. This was chosen as the persistence of a beam can be expected to be higher than noise in normal operation.

The probability of association of a particular FP due to noise is dependent on the number of associations before it. This is similar to a mixed replacement urn problem where a ball drawn of the fail type is replaced (analogous to associating to an empty region of the image) and a ball of the success type is replaced with a fail type ball (analogous to associating to a region with a detection). In this work there will be two equations derived and proposed as closed-form solutions for the same probability mass distribution of this process. Both of these are presented for three reasons. First is completeness. Second is showing the relation between the continuous complete homogeneous polynomials derived directly from the association behavior and the discrete combinatorial expression. Both are required, as the polynomial expression was used to verify the combinatorial expression. The combinatorial expression was used in this research to evaluate the models as it is easier to optimize computationally and as a result is much faster. Last, the derivation showing that these expressions are equivalent is beyond the scope of this chapter. This probability distribution will be referred to as CombiTron.

Polynomial CombiTron: The polynomial approach is simply multiplying all possible combinations of each probability. [Figure 6.10](#) shows this process in the form of a tree where the probability changes only after association. The polynomial solution has two parts. Firstly, for a given number of associations u the association probabilities can be multiplied up to u , giving the first portion:

$$\prod_{i=0}^{u-1} a_i \quad (6.11)$$

The second portion takes into account all the non-association combinations. Writing out each possible number of associations along

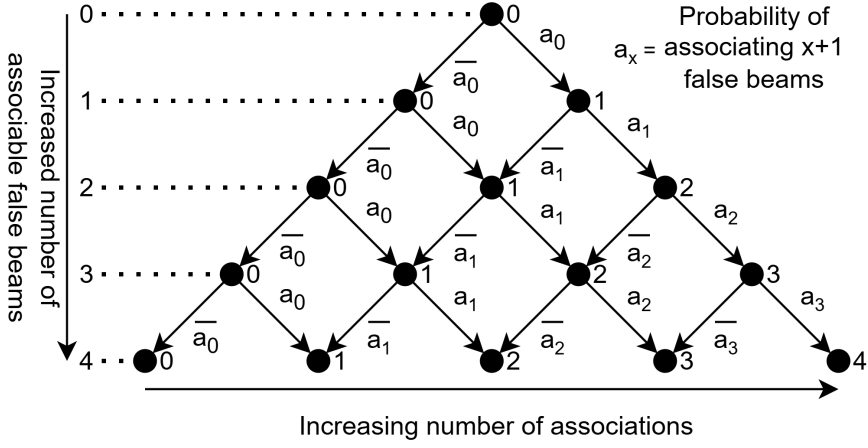


Figure 6.10.: Association probability tree.

the tree shown in Figure 6.10 yields:

6

$$\begin{aligned}
 p(u=4) &= \prod_{i=0}^3 a_i \\
 p(u=3) &= \left(\prod_{i=0}^2 a_i \right) (\bar{a}_0 + \bar{a}_1 + \bar{a}_2 + \bar{a}_3) \\
 p(u=2) &= \left(\prod_{i=0}^1 a_i \right) (\bar{a}_0^2 + \bar{a}_0 \bar{a}_1 + \bar{a}_0 \bar{a}_2 + \bar{a}_1^2 + \bar{a}_1 \bar{a}_2 + \bar{a}_2^2) \\
 p(u=1) &= a_0 (\bar{a}_0^3 + \bar{a}_0^2 \bar{a}_1 + \bar{a}_0 \bar{a}_1^2 + \bar{a}_1^3) \\
 p(u=0) &= \bar{a}_0^4
 \end{aligned} \tag{6.12}$$

When evaluating these paths, it can be seen that the resulting function is always a Complete Homogeneous Symmetric Polynomial (CHSP) of degree $\alpha - u$ (α being the maximum possible associations) with u variables. The definition of CHSPs is:

$$h_k(X_1, X_2, \dots, X_n) = \sum_{1 \leq i_1 \leq i_2 \leq \dots \leq i_k \leq n} X_{i_1} X_{i_2} \dots X_{i_k} \tag{6.13}$$

Combining Eq. 6.11, 6.12 and 6.13 yields:

$$p(u) = h_{\alpha-u}(\bar{a}_0, \bar{a}_2, \dots, \bar{a}_u) \prod_{i=0}^{u-1} a_i \tag{6.14}$$

which is the first closed-form solution. The probabilities are,

$$a_i = \frac{K-i}{N}, \quad \bar{a}_i = \frac{N-K+i}{N} \quad (6.15)$$

where N is the total number of windows, of which K are associable.

Combinatorics CombiTron: From the perspective of multi-beam tracking, there are K associable windows and $N-K$ non-associable windows out of a total N windows at the start of the association process. Associating an FP is denoted as a success within the context of this distribution. From the perspective of urn problems, there might be K balls where the replacement is not allowed and $N-K$ balls where replacement is allowed and N total balls at the start.

Assume a set of size N containing K successes. The ordered set of windows/balls (denoted as W) is as follows, where $*$ simply denotes a success:

$$S_{(W)} = \{W_0^*, W_1^*, W_2^*, \dots, W_K^*, W_{K+1}, \dots, W_N\} \quad (6.16)$$

Considering the Binomial Coefficient, there are $\binom{N}{\alpha}$ ways to select a subset of size α from N without repetition (i.e. uniquely). There are $\binom{N+\alpha-1}{\alpha}$ subsets of size α from N with repetition, i.e. multiset coefficient (also denoted as $\left(\binom{N}{\alpha}\right)$). Logically, the number of unique combinations is less than the number of possible combinations.

This is one of the two motivators for choosing unique associations. When only u unique draws are allowed, then the number of sets of K successes, i.e. the number of unique successful combinations, is $\binom{K}{u}$. If multiple associations were to be allowed, the number of successful combinations would be $\left(\binom{K}{\alpha}\right)$. Since $\left(\binom{K}{\alpha}\right) \geq \binom{K}{u}$, it implies that a filter based on unique associations yields a lower association rate for false positives performance than non-unique associations. The second flows from this effect as well, as the FP accumulation rate is therefore also lower. In 6.2.3 and 6.3, the difference will be discussed further and shown to diverge as noise increases.

Unique association implies that when u successes have been drawn, the remaining set of available windows/balls is of the same size N with a reduced $K-u$ successes. Consequently, the number of combinations of $\alpha-u$ non-uniquely drawn failures is given by the multiset coefficient

$$\binom{N-(K-u)+\alpha-u-1}{\alpha-u} = \binom{N-K+\alpha-1}{\alpha-u} \quad (6.17)$$

The probability of obtaining u unique draws after α random draws can be found by multiplying the number of unique success/association combinations with the possible multiset combinations of non-associations

divided by the total possible multiset combinations of all associations and windows. This results in the probability mass function

$$P(X = u) = \frac{\binom{K}{u} \binom{N-K+\alpha-1}{\alpha-u}}{\binom{N+\alpha-1}{\alpha}} \quad (6.18)$$

with which the mean, variance and program optimization is easier.

Expected Value and Variance of CombiTron: The expected value of the distribution is

$$E(x) = \sum_{u=0}^{\alpha} u P(X = u) = \sum_{u=0}^{\alpha} u \frac{\binom{K}{u} \binom{N-K+\alpha-1}{\alpha-u}}{\binom{N+\alpha-1}{\alpha}} \quad (6.19)$$

which can be re-arranged to

$$= \frac{1}{\binom{N+\alpha-1}{\alpha}} \sum_{u=0}^{\alpha} \binom{K}{u-1} \binom{N-K+\alpha-1}{\alpha-u} \quad (6.20)$$

Observing that $\alpha - u$ can be written as $(\alpha - 1) - (u - 1)$, this can be re-written as

$$= \frac{1}{\binom{N+n-1}{n}} \sum_{u=0}^n K \binom{K-1}{u-1} \binom{N-K+n-1}{(n-1)-(u-1)} \quad (6.21)$$

Taking the identity

$$\sum_{k=0}^n \binom{\alpha}{k} \binom{\beta}{n-k} = \binom{\alpha+\beta}{n} \quad (6.22)$$

yields the expected value of the CombiTron distribution

$$E(X) = \frac{K \binom{N+n-2}{n-1}}{\binom{N+n-1}{n}} \quad (6.23)$$

Using a similar method, the variance can be found to be:

$$\begin{aligned} \text{Var}(X) &= \sum_{u=0}^{\alpha} u^2 P(X = u) - E(X)^2 \\ &= \frac{\sum_{u=0}^{\alpha} u^2 \binom{K}{u} \binom{N-K+\alpha-1}{\alpha-u}}{\binom{N+\alpha-1}{\alpha}} - E(X)^2 \\ &= \frac{K(K\alpha - K + N - 1) \binom{N+\alpha-3}{\alpha-1}}{(N-1) \binom{N+\alpha-1}{\alpha}} - E(X)^2 \end{aligned} \quad (6.24)$$

The expected value will be used in 6.2.3 and 6.2.4 for determining FP performance.

HYPOTHESIS GENERATION AND LABELING FOR TIME BASED FILTERING

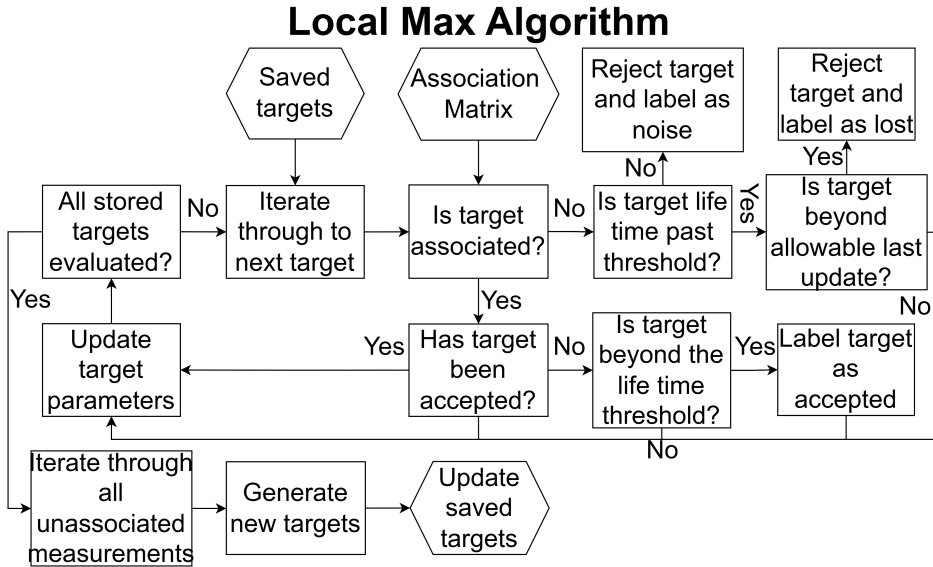


Figure 6.11.: Hypothesis generation and labeling algorithm.

The filtering function performed by hypothesis generation and labeling (hypothesis tracking for short) (HT) is current and retroactive target labeling using past data. As mentioned before, in contrast with MHT, basic parameters such as the life time are used for this process instead of hypothesis tree back propagation. As a result the combined time of the hypothesis generation, association and prediction steps take 2 orders of magnitude less time compared to the image acquisition and sensor processing (see 6.3). An overview of this algorithm step can be found in Figure 6.11. The key metric used to filter is life time in frames; if a target persists longer than the threshold of f frames, it is labeled/accepted as a true beam and if less as noise. Targets persisting shorter than the threshold are labeled as candidate.

The conditions by which noise can be falsely accepted are defined as

$$\begin{aligned}
FP_{HT} &= |\mathcal{T}_{HTfalse}| \\
\mathcal{T}_{HTfalse} &= \{life(\mathcal{T}_{false}) > f\} \subseteq \mathcal{T}_{false} \\
\mathcal{T}_{false} &= H(\mathcal{D} \setminus \mathcal{B}) \subset \mathcal{D} \\
FP_{LMt_i} &= |\mathcal{T}_{LMfalse, t_i}| \\
\mathcal{T}_{LMfalse, t_i} &= \mathcal{D}_{t_i} \setminus \mathcal{B}_{t_i} \subseteq \mathcal{T}_{LMfalse} \\
&= \{\mathcal{T}_{LMfalse, t_i}\}_{i=0}^l \\
\mathcal{D} &= \{D_{t_i}\}_{i=0}^l, \quad \mathcal{B} = \{B_{t_i}\}_{i=0}^l, \quad \mathcal{T} = \mathcal{B} \cup \mathcal{T}_{false} \\
life(\mathcal{T}) &= \Delta t_T = \text{life time of target}
\end{aligned} \tag{6.25}$$

where H is the hypothetical association function. $\mathcal{D}$ is the set of all detections in space and time. Furthermore, $\mathcal{B}$ is the set of all beams in space and time. Note the distinction between Local Max (LM) and HT, as these FPs do not correspond.

Since beams and their windows can overlap, cross, merge and separate, the tracking system needs to be able to handle this. As a result, confirmed beams are given a period within which they are allowed to reappear and continue without re-labeling being necessary. Beyond this time they are labeled as lost. FP must initiate outside of a beam window. However the false beam could merge with a true beam and extend its life.

The analysis of the algorithm will from here be split. Unique associations were used in the experimental demonstration. However, this approach is more laborious for the computational performance evaluation in 6.2.4. Hence, both unique and non-unique associations will be evaluated, starting with multiple associations.

Non-unique Associations Case: The probability of association of FPs over time for consecutive frames at time l since time $l - \Delta l$, assuming the elapsed time is less than the acceptance threshold, i.e. $f < \Delta l$, is

$$\begin{aligned}
P(\mathcal{T}_{false} \in \mathcal{T}_{HTfalse}) &= P(life(\mathcal{T}_{false}) \geq f) \\
&= \sum_{F=l-\Delta l+f}^l P(life(\mathcal{T}_{false}) = F)
\end{aligned} \tag{6.26}$$

Assuming the noise, beam, clutter and interference spatial probability distributions are invariant and independent in space and time, the above equation can be simplified to:

$$\begin{aligned}
P(\mathcal{T}_{false} \in \mathcal{T}_{HTfalse}) &= P(life(\mathcal{T}_{false}) \geq f) \\
&= \sum_{F=f}^l P(life(\mathcal{T}_{false}) = F)
\end{aligned} \tag{6.27}$$

When this is not the case, the constant false alarm rate (CFAR) method can be used spatially and/or temporally. Furthermore, the spatial and temporal invariance of noise over time implies that the method of window placement is irrelevant. Hence the above equation can be simplified as

$$\begin{aligned} P(T_{false} \in \mathcal{T}_{HTfalse}) &= \sum_{F=f}^l \prod_{0}^F P(pixel \in \mathcal{W}(TP + FP)) \\ &= \sum_{F=f}^l P(pixel \in \mathcal{W}(TP + FP))^F \end{aligned} \quad (6.28)$$

and can be further simplified using geometric series identities to

$$\begin{aligned} P(T_{false} \in \mathcal{T}_{HTfalse}) &= \\ &= \frac{(P(pixel \in \mathcal{W}(TP + FP))^{f+1} - P(pixel \in \mathcal{W}(TP + FP))^{l+1})}{1 - P(pixel \in \mathcal{W}(TP + FP))} \end{aligned} \quad (6.29)$$

The identity when l approaches infinity,

$$P(T_{false} \in \mathcal{T}_{HTfalse}) = \frac{P(pixel \in \mathcal{W}(TP + FP))^{f+1}}{1 - P(pixel \in \mathcal{W}(TP + FP))} = q_{nf} \quad (6.30)$$

is useful. Knowing

$$P(pixel \in \mathcal{W}(TP + FP)) = \frac{n}{N_{pixels}} (TP + FP_{LM}) \quad (6.31)$$

q_{nf} is defined as

$$q_{nf} = \frac{\left((1 - p_n) \left(1 - e^{-\frac{nN_B}{N_{pixels}}} \right) + p_n \right)^{f+1}}{(1 - p_n) e^{-\frac{nN_B}{N_{pixels}}}} \quad (6.32)$$

The number of FPs after HT is the number of LM FPs per frame, FP_{LM} , in the past since l which lasted up and until f frames. This is

$$\begin{aligned} FP_{HT} &= (q_{nf} - q_{nl}) FP_{LM} \\ &= (q_{nf} - q_{nl}) p_n \left(\frac{N_{pixels}}{n} - TP \right) \end{aligned} \quad (6.33)$$

The total number of objects tracked is hence

$$\begin{aligned} |\text{active}(\mathcal{T})| &= |\mathcal{B}| + |\text{active}(\mathcal{T}_{\text{false}})| = N_B + \text{FP}_{HT} \\ &= N_B + (q_{nf} - q_{nl})p_n \left(\frac{N_{\text{pixels}}}{n} - \text{TP} \right) \end{aligned} \quad (6.34)$$

This result diverges when the noise increases or the threshold decreases due to the accumulation of false positives due to q diverging.

Unique Associations Case: FP_{HT} can be found in the unique associations by determining the accumulation and attrition rate balance. The association probability, p_{as} , of all N_{targets} tracked targets is determined by the number of threshold excursions, K , produced by the LM step and the total number of windows N . The probability can be expressed using the expected value of the CombiTron distribution as

$$p_{as} = \frac{E(T : N_{\text{targets}}, N, K)}{N_{\text{targets}}} = \frac{1}{N_{\text{targets}}} \frac{K \binom{N+n-2}{n-1}}{\binom{N+N_{\text{targets}}-1}{N_{\text{targets}}}} \quad (6.35)$$

The set of FPs in HT decays due to FPs not being associated for f_{lost} sequential frames. The fraction lost every f_{lost} frames is

$$S_{HT\text{new}} = 1 - (1 - p_{as})^{f_{\text{lost}}} \quad (6.36)$$

The share of FPs that make it through the candidate phase is p_{as}^f . Using Eq. 6.35 and 6.36 to make a balance in the number of FPs over duration l yields

$$\text{FP}_{HT} = E(T) p_{as}^f \frac{1 - S_{HT\text{new}}^{(lf_{\text{lost}}+1)}}{1 - S_{HT\text{new}}} \quad (6.37)$$

with

$$N_{\text{targets}} = N_B + \text{FP}_{LM} + \text{FP}_{HT} \quad (6.38)$$

The number of FPs would hence need to be found recursively through finding a stability point between equations 6.37 and 6.38.

PREDICTION OF NEXT LOCATION/BEHAVIORAL FILTERING

Behavioral filtering helps minimize the window size (see 6.2.3) as well as ensure the highest likelihood of correct association. The result is improved association and minimization of FP_{HT} . Estimation is performed using a simple Kalman filter and previous measurements.

$$\hat{\mathbf{r}}_{T_{D0}:l|l-1} = \mathbf{F}_l \hat{\mathbf{r}}_{T_{D0}:l-1|l-1}, \quad \hat{\mathbf{r}}_{T_{D0}:l|l} = \mathbf{r}_{D0} \quad (6.39)$$

The covariance and dynamic gains were not used in this work due to loop time considerations. This did not impact the performance due to the (near) linear paths of the beams. Implementation, optimization and analysis of a more complex algorithm will be subject of future work.

6.2.4. ANALYSIS OF ALGORITHM LIMITATIONS AND PERFORMANCE

The tracking algorithm limitations and performance will now be analyzed and discussed. Numerous limitations have been identified. These are the related windowing limit, miss limit and noise limit as well as maximum compute. In addition to this the operational regime where tracking precision is maintained, iso-precision operation will be investigated. The combination of these will yield an estimation of the performance envelope for a tracking algorithm which is fully determined by the capabilities of the hardware.

There are roughly three regimes in which the tracking could operate. The first is in a saturated regime, which is when the density of pixels exceeding the threshold in the frame cause the frame to be filled with windows. The limited area within the frame to place windows, places an upper limit to the number of trackable objects and is referred to as the **Windowing limit**. The minimum distance between windows is half a window width between window centers.

$$\text{Windowing Limit} = 2 \frac{N_{\text{pixels}}}{n} \quad (6.40)$$

The threshold exceeding probability at which this occurs, p , is twice the maximum spatial frequency of windows. This is the **Noise limit** and can be expressed as

$$p \geq \frac{2}{n} \rightarrow \text{Noise Limit} = \frac{2}{n} \quad (6.41)$$

The second regime is where the number of pixels above the threshold is sparser, however can also yield full saturation. This regime is related to packing efficiency of randomly placed windows and is beyond the scope of this chapter. However, within this regime there is a configuration where the frame is tiled with windows one window width apart. Subsequently, no additional beams can be tracked. The miss rate is defined as

$$\text{MIS} = \frac{N_B - \text{TP}}{N_B} \quad (6.42)$$

When TP can no longer increase, the miss rate directly increases. Hence, this is referred to as the **Miss Limit**. This is half the windowing limit and serves as an upper bound for the theoretical maximum number of trackable beams. It is expressed as

$$\text{Miss Limit} = \frac{N_{pixels}}{n} = \frac{\text{Windowing Limit}}{2} \quad (6.43)$$

Note that this can only occur in one configuration, meaning that the probability of it occurring is low for randomly wandering beams. In reality, beam and noise density at any given point in time within the frame can be expected to be non-homogeneous and hence there might be some pockets where tracking is possible and pockets where tracking is not possible.

In the third regime is when there is enough sparsity to have sufficient space between the windows and can be expected to start occurring when $p \gg 1 - \frac{2}{n}$. Note that in the first and second regime true positives (TP) cannot be distinguished from false positives (FP). For reliable operation, there should be some margin. The windowing, miss and noise limits primarily affect the sensor processing step and are summarized as

$$FP \approx \begin{cases} 2 \frac{N_{pixels}}{n} & \text{for } p \gg \frac{2}{n} \\ (1 - (1 - p)^n) \left(\frac{N_{pixels}}{n} - TP \right) & \text{for } p \ll \frac{2}{n} \end{cases} \quad (6.44)$$

6

While there are some use cases for the first and second regime and this is modeled in the above equations, this work focuses on the third regime. Hence, after identifying an acceptable noise level on the basis of the above limits, the threshold T can be calculated using

$$T = \mu + \sigma \Phi^{-1}(p^{\frac{1}{n}}) = \mu + \sigma \sqrt{2} \text{erf}^{-1}(2p^{\frac{1}{n}} - 1) \quad (6.45)$$

The **Computational limit** of the MBTA is modeled as adding the duration of each step. Simply put, since local max (LM), association, hypothesis and predictive (AHB) steps are sequentially used, the combined time is the loop time expressed as

$$t = t_{LM} + t_{AHB} \quad (6.46)$$

where t is the loop time, t_{LM} is the LM duration and t_{AHB} is the duration of AHB steps. LM evaluates each pixel for N_{pixels} in the frame and searches in a local window of size n around each pixel exceeding the threshold. This can be noise or beams. Since each beam has a distribution, there is a portion of beam exceeding the threshold with a diameter of d . The resulting equation for the LM duration is

$$t_{LM} = C_o \left(N_{pixels} + n \frac{\pi d^2}{4} TP + np \left(N_{pixels} - \frac{\pi d^2}{4} TP \right) \right) \quad (6.47)$$

with C_o being the time constant needed to evaluate each pixel in the algorithm. Similarly, AHB steps evaluate a matrix with the number of rows equal to the number of tracked targets and column lengths equal to the number of detections. The time can be expressed as

$$t_{AHB} = C_o N_C (TP + FP) (N_B + |active(\mathcal{T}_{false})|) \quad (6.48)$$

with N_C being the constant ratio between C_o and the time needed to evaluate AHB units. N_C was found to equal roughly 9. From this the computational maximum beam capacity can be found to be

$$t = C_o \left(N_{pixels} + n \frac{\pi d^2}{4} TP + np \left(N_{pixels} - \frac{\pi d^2}{4} TP \right) \right) + C_o N_C (TP + FP) (N_B + |active(\mathcal{T}_{false})|) \quad (6.49)$$

Substituting TP with TP_{Climit} and solving for TP_{Climit} such that the total loop time, t , is the input variable yields

$$TP_{Climit} = \frac{\frac{t}{C_o} - N_{pixels}(1 + np) - N_C(N_B + |active(\mathcal{T}_{false})|)FP}{(1 - p)n \frac{\pi d^2}{4} + N_C(N_B + |active(\mathcal{T}_{false})|)} \quad (6.50)$$

6

In operation, $TP \leq TP_{Climit}$ for proper operation. The difference, $TP - TP_{Climit}$, is the buffer the system has for processing clutter and still being capable of achieving loop durations of t . Furthermore, note that the equation is invariant with the life time threshold number of frames. This is due to this parameter being used solely for labeling, while $|active(\mathcal{T}_{false})|$ is the number of tracked false targets. This includes both the targets with life times shorter and longer than the acceptance threshold. It should be kept minimal for timely acceptance of a beam. When a target loop time is inserted in Eq. 6.50, it yields an estimate of the maximum number of TP.

The envelope encompasses a range of precision. Due to the high cost of space hardware, there is a need to minimize the number of transceivers communicating with false beams. It would therefore be useful to determine which part of the performance envelope falls within the required precision. To do this, the **Iso-precision** (iso meaning constant) operation can be evaluated. The precision of the tracking algorithm is defined as

$$PRE = \frac{TP_{HT}}{TP_{HT} + FP_{HT}} \quad (6.51)$$

with PRE being the precision and TP_{HT} the number of true positives. Rearranging the equation to allow for a minimum or target precision yields

$$TP_{HT} \geq \frac{FP_{HT} \text{PRE}}{1 - \text{PRE}} \quad (6.52)$$

In iso-precision operation it is imperative that the noise is scaled back or the threshold raised for a smaller number of beams. However, Eq. 6.33 becomes steeper proportional to the frame cutoff. Increasing the life threshold duration can thus yield an acceptable result.

6.3. RESULTS AND DISCUSSION

In this section, the algorithm will be verified and validated by presenting and discussing the tracking results obtained from both synthetic images and real-time experiments. The modeling and setups are detailed in 6.2.1 and 6.2.2, respectively. An example of the tracks can be seen in Figure 6.14. For brevity, since the tracking results and synthetic images were nearly identical, focus can now be placed on presenting the experimental results.

To demonstrate the alignment between theory and experiment, the following were established as **hypothetical design requirements**:

1. An iso-precision requirement of 90% (i.e. no more than 10% false positives among accepted targets).
2. A compute requirement of 10 ms per loop at 90% precision.
3. A computational resource parameter inverse, $1/C_0$, set at 2.8 Gp/s.
4. Number of beams of 9.

Each experiment ran over 500 frames, totaling approximately 2.2 seconds for the highest noise setting. The results are presented in Figure 6.12 and 6.13.

Examining Figure 6.12, observing that the number of detections in both theory and experiment coincide and approach the Miss Limit, without reaching or exceeding the Window Limit. The theoretical model predicts that while the expected number of detections does not exceed the Miss Limit, certain detection configurations may do so. Consequently, data points above the Miss Limit are consistent with the theory.

The tracking capacity approximation for the number of targets diverges as predicted when approaching the Noise Limit in real-world data. However, the improved CombiTron-based model closely follows experimental results even beyond the Miss Limit. Notably, the number

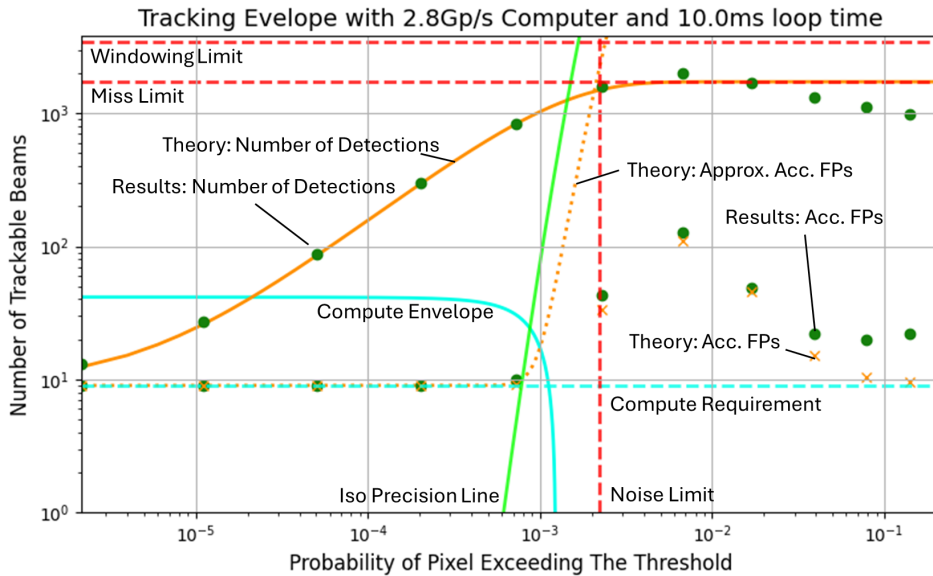


Figure 6.12.: Tracking envelope, theory plotted alongside experimental data.

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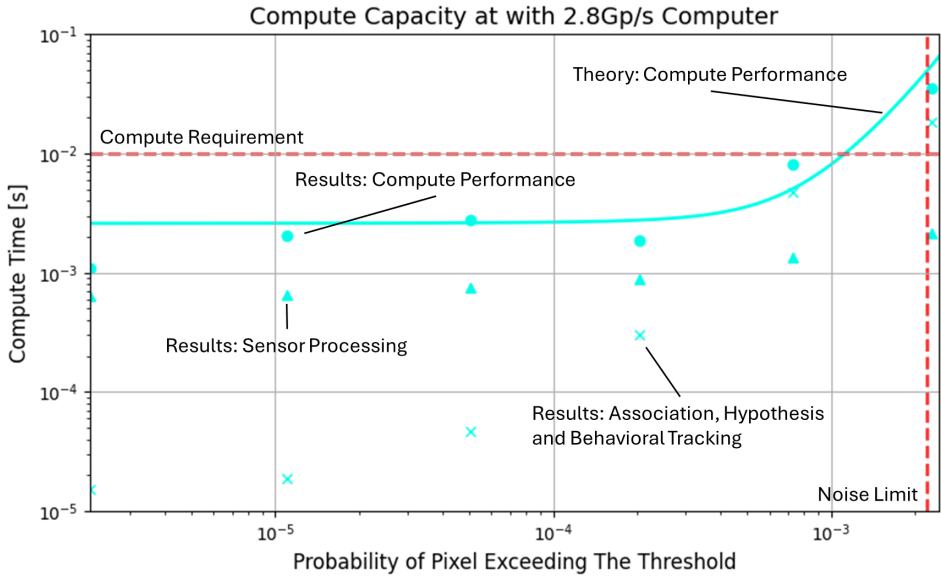
of tracked targets decreases due to persistent targets occupying more time and space, thereby crowding out younger false positives from association.

Figure 6.13 also demonstrates good alignment between theory and experiment. The compute requirement line is crossed beyond the required iso-precision noise level indicated in Figure 6.12, suggesting that compute performance can be predicted and designed for under various noise conditions.

Moreover, at noise levels up to 10^{-3} the loop time remains around 1.5 ms. Of this, the sensor processing is most dominant at 0.8 ms while the association, hypothesis and behavioral (AHB) tracking ranges from 10^{-5} s to 0.5 ms. This discrepancy between these values was verified to be due to overhead in saving data and controlling interfaces. The accumulation of beams causes AHB to be dominant above a noise probability of 10^{-3} . This clearly shows the advantage of temporal AHB tracking over further sensor processing steps.

It is important to note that the data shown does not include interfaces and frame acquisition. Due to the chosen hardware these limitations are more significant.

The **key findings** can be summarized as:



6

Figure 6.13.: The compute capacity as a function of noise, theory plotted alongside experimental data.

1. The tracking envelope results show a close match between theoretical predictions and experimental data, with both approaching but not exceeding the Miss Limit.
2. The CombiTron-based model accurately follows experimental results even beyond the Noise Limit, demonstrating its robustness in high-noise environments.
3. Compute capacity aligns well with theory, allowing for predictable performance under various noise conditions.

Potential sources of error include jitter from the stepper motor gearbox in the experimental setup, interface factors and algorithmic approximations. Future work could focus on mitigating these errors to even further improve the alignment between theory and experiment.

Comparison with Existing Tracking Algorithms: The proposed MBTA can track multiple dynamically moving beams using full frames from image detectors. This improves upon the algorithms presented by Skryja et al.[17] and Wang et al.[5], which employ static target tracking and quad cell detectors respectively.

The demonstrated algorithm latency between 10^{-2} and 10^{-3} s also compares favorably to SBTA's which have control bandwidth

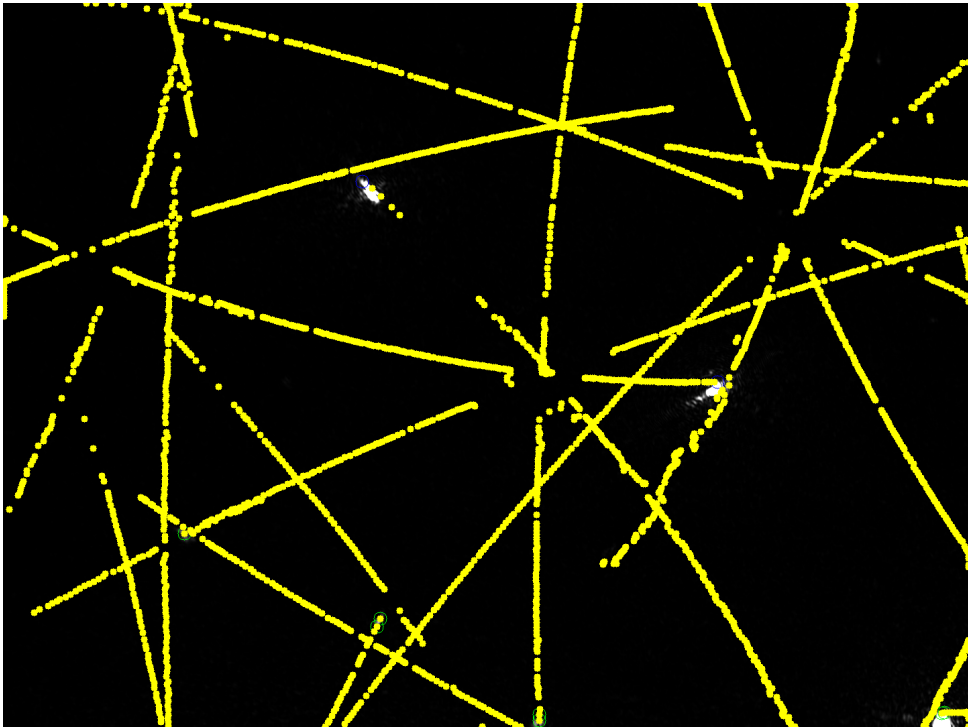


Figure 6.14.: Example tracks from an experiment run.

requirements on the order 100Hz-1kHz.[19, 35, 36, 37, 38, 39] Moreover, the theory and results show that the MBTA adds less overhead than what was reported by employed MTT and neural network algorithms.[24, 26, 27, 28] Future work could investigate bandwidth improvements of SBTAs using the concepts in this work. This could be of particular interest in areas such as high scintillation, diffraction and/or turbulence cell tracking.

Nevertheless, a challenge remains for multi-beam tracking in the need to track full frame. Going to higher bandwidths might be more challenging mainly due to the sensor processing limitations. In this case, looking to improvements such as local region of interesting and having a combination of a slower and faster control loop, as discussed in 6.1, would need to be investigated.

Future research could also focus on refining the algorithm to reduce false positives further and improving computational efficiency. Additionally, exploring the application of this approach in more complex scenarios with dynamic noise levels would be beneficial.

Nevertheless, this algorithm demonstrates the computational load can

be reduced when tracking full frame using temporal tracking techniques over additional image processing techniques.

6.4. CONCLUSION

This chapter addresses the need for a multi-beam tracking algorithm (MBTA) in laser communication terminals by proposing a novel approach that integrates sensor processing techniques from single beam tracking algorithms (SBTAs) with multiple target tracking (MTT) algorithms. The proposed algorithm optimizes computational efficiency by minimizing image processing steps and employing association, hypothesis and behavioral (AHB) tracking over time to filter and estimate target movements accurately.

Comparison of Theory and Experiment: The algorithm was thoroughly detailed, mathematically modeled and its limitations were explored. Theoretical predictions were validated through hardware experiments and simulated images under various noise levels. The results demonstrate a close alignment between theoretical expectations and practical outcomes, confirming the effectiveness of the proposed algorithm.

Implications for Future Work: The control bandwidth achieved by our multi-beam tracking algorithm is comparable to that of existing single beam tracking algorithm requirements, with several key implications:

1. Temporal tracking based on AHB can enhance tracking bandwidth. It could hence be interesting to see if SBTAs can benefit from these insights.
2. Further refinements in the theory and algorithm for multi-beam tracking can improve bandwidth and noise performance. The employed algorithm here has multiple avenues in each step to explore further.
3. Leveraging graphics processing units (GPUs) can significantly improve bandwidth. Furthermore, implementing nested control loops on local regions of interest and global full-frame tracking could further enhance bandwidth per beam.

Final Conclusion: The goal of this research was to determine if and how a multi-beam tracking algorithm could be made which can track multiple dynamically moving beams with an image detector. This work has proven that this is indeed possible through the use of techniques borrowed from SBTAs and MTT, with control bandwidths compatible with single beam tracking algorithms to boot.

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7

CONCLUSION

*When were we at our best? When we were passionate about something.
Not when we were safe.*

Leia Oregana (*Star Wars*)

Each of the previous chapters has tackled an important question for multi-beam laser communication terminals (MBTs). These chapters provide key insight into their respective topics. This concluding chapter will combine these insights and synthesize a bigger picture of multi-beam steering systems. This chapter will begin with a summary of the key findings and subsequently analyze these findings together. Then the research questions discussed at the start of this dissertation will be answered. After this the innovations will be detailed. Lastly, the future research will be suggested to further enhance the field of MBTs in the future.

7.1. SUMMARY

This dissertation investigated multi-beam steering systems for multi-beam laser communication terminals (MBTs). In [Chapter 1](#) it was shown how the rise in data demand and the expansion of networks is projected to accelerate into the future. Radio frequency (RF) based communications are simultaneously approaching a capacity ceiling due to limited spectrum availability. This highlighted the importance of scalable communication solutions relying on optical wavelengths, underlining the need for MBTs. However, literature on MBTs is sparse compared to single beam terminals (SBTs), with only a handful of examples of terminal designs available. In particular, gaps were identified related to the relation between use and design of MBTs as well as understanding of multi-beam steering and tracking systems.

[Chapter 2](#) studied the relationship between use cases and high level parameters related to MBT design. These parameters included the estimates of the total number of users broken down by types, the expected data demands as well as field of view (FoV), average target dwell time in FoV, angular resolution and coverage area. The geometric relation between the FoV, altitude, minimum dwell time and angular resolution was shown and the associated feasible operational altitude ranges were provided. Furthermore, data was given for various orbit regimes relating user number approximations with the aforementioned parameters.

This provided a basis for future chapters and a method for designing and analyzing the operational profiles as well as estimates on MBT utility when applied to a given use case.

[Chapter 3](#) explored the multi-beam steering system functions and associated designs. Presented was an overview of known MBT designs and an analysis with regards to their design choices. Furthermore, systems from adjacent domains were also examined to provide more context with respect to the design options. Subsequently, on the basis of the provided functions, a design options tree and complementary steering mechanism trade-off was presented. Lastly, the most interesting steering system design was motivated and selected for further examination.

This established function flows as well as high level design choice models for MBTs.

[Chapter 4](#) detailed the hardware setup used to demonstrate, verify and validate multi-beam steering and tracking principles. Details of the interfacing and memory management were provided as well as integration of an image detector and a spatial light modulator (SLM). In addition, methods for generating multiple independently moving beams were shown and demonstrated.

This established a testbed and hardware methodologies for researching and demonstrating multi-beam steering systems with hardware.

[Chapter 5](#) investigated the integration of SLMs into a multi-beam steering stage. The main technological challenges, diffraction effects and sys-

tem layout, and their effects on tracking and steering performance were presented. Furthermore, the performance envelopes of SLMs with regard to steering range, resolution and efficiency were provided. A novel phase screen consisting of a phase ramp superimposed with a Fresnel lens (PRFL) was proposed and demonstrated as a solution to these challenges.

These results demonstrated multi-beam steering concepts as well as solutions to technological challenges associated with steering system integration.

Chapter 6 identified bottlenecks for multi-beam tracking when using traditional approaches. It proposed a novel multi-beam tracking algorithm to match the performance of SBT tracking algorithms despite these bottlenecks. This algorithm was extensively studied through mathematical analysis and experimental demonstration. Presented are analytically defined performance envelopes that are demonstrated in experiment.

This not only provided a useful algorithm but also a framework for temporal based tracking techniques within multi-beam laser communication.

In summary, this dissertation provides a considerable advancement in the current understanding of MBT steering systems. It has provided a model for high level design decisions in relation with its use cases. Additionally, considerable advances were made in understanding multi-beam steering using SLMs. Lastly, a new framework for multi-beam tracking has been detailed for tracking multiple beams, computationally outperforming traditional beam tracking techniques.

7.2. ANALYSIS AND DISCUSSION OF CHAPTER FINDINGS AND CONCLUSIONS

The findings and conclusions of each chapter formed the basis for the next chapter. Here, the findings and conclusions of each chapter will be placed in context of the dissertation findings as a whole. This is to create a complete picture.

Chapter 2 discusses parameters related to MBT operations and use cases. The findings and resulting values for FoV, angular resolution, number of beams and dwell times within the FoV are useful to compare to the findings and results from Chapter 5 and Chapter 6. While the theories presented in these chapters are general, some examples were provided. These examples will now be compared and discussed to provide a better overview. A summary of the relevant values of these examples can be found in Table 7.1.

First, the comparison of the number of beams with the number of steerable beams and trackable beams is discussed. Chapter 2 found that the number of potential beams is dependent on the number and types of targets. These can range from single instances up to millions. However,

Findings Chapter 2	Steering Results	Tracking Results
Expected # of Targets: 10-1000	Maximum number of steerable beams: 5184 (for steering area widths of 20 pixels)	Demonstrated target tracking capacity: 1000 (depending on the number of beams, minimum latency and noise levels)
Angular Resolution: 2.8-200 μ rad for 4° FoV	1.7 μ rad for 4° with SLM and beam diameter used	Max intensity: within 1 pixel (48 μ rad for 4° FoV with the detector used) C.G. Tracking: 6-24 μ rad (with the detector used)
Dwell time: 1.1-265 s	Update frequency used SLM: 120 Hz (60 Hz control command frequency)	Demonstrated tracking latency: 0.5-10 ms (depending on the number of beams and noise levels) Demonstrated tracking acquisition time based on tracking latency: 5-100 ms (depending on the number of beams and noise levels) Frame rate used image detector: 227 fps

Table 7.1.: Overview of values found through examples and experiments in the thesis.

between 10-1000 beams were estimated to be the order of magnitude design envelope in context. With the hardware setup demonstrated in [Chapter 4](#) and [Chapter 5](#), when the SLM is fully filled with beams, 5184 individual beams can be theoretically steered. This is more than the 1000 targets (false and true positives) tracked by the tracking algorithm. Both values are within the ranges provided in [Chapter 2](#). This further strengthens the design choice models as well as motivation for the steering sys-

tem layout and steering mechanism selection presented in [Chapter 3](#).

Nevertheless, there is a discrepancy between the steering and tracking with respect to number of possible beams. This discrepancy can in part be explained due to physical hardware parameters such as detector size and number of pixels. The SLM used had a resolution of 1920x1200 pixels while the image detector used has 1440x1080, implying that the SLM can steer 33% more beams of 20 pixels in diameter compared to the image detector, which would be 3888 beams.

However, in the beam tracking algorithm, the capacity is related to the number of windows and not directly the number of beams. These windows encapsulate an area where the beam center (defined as the location of maximum intensity in this case) is expected to reside. Selection of the window size should take into account uncertainty in the estimations. In this case, a window size was selected of 40x40 pixels, yielding the approximately 1000 individually trackable beams according to the miss limit. This is in contrast to steering, where the underlying limit is driven by the ability to individually steer beams. Individually steering beams necessitates that each beam is resolvable, therefore requiring at least one beam diameter separation distance.

Moreover, while operations at higher target densities (both false and true positives) are possible and have been demonstrated, the dynamic beam motions should also be taken into account. As mentioned, the limits stated in [Table 7.1](#) are therefore the miss limits.

Second, the angular resolution ranges for a 4° telescope vary for different altitudes when the ground resolution remains equal. Comparing the steering and tracking results show that it is possible to track and steer at these resolutions. The steering resolution can be further improved by increasing the number of pixels for steering and the beam diameter. However, this also directly decreases the maximum allowable beams. Furthermore, tracking resolution can be further improved through increasing the resolution or resorting to additional image and/or statistical processing steps. This in turn increases the computational load and therefore reduces the maximum number of beams.

Third, the dwell time places a limit on the duration of acquisition and link sustainment phases. However, the particulars of these phases have not been demonstrated nor researched at the level found in [Chapter 4](#), [Chapter 5](#) and [Chapter 6](#). As a result, little can currently be said with regards to the duration of each phase. Nevertheless, what can be compared is the relation with steering and tracking latencies.

The tracking latencies are minimal compared to the steering latencies. When considering the 120 Hz bandwidth of the selected SLM, it is clear that it is not sufficient for jitter compensation. This would also imply that the average rate at which a target moves across the SLM ranges from 11 pixels per frame down to 0.045 pixels per frame at the higher end of the dwell time range. As a result, the SLM update frequency can limit

the lowest altitude and/or FoV in this case. However, SLMs exist that can correct at higher frequencies, showing that this is not a limitation of SLMs in general.[1]

The discussion above shows that there is alignment between the values found in Chapter 2 and the performances discussed in Chapter 4, Chapter 5 and Chapter 6. However, there are still performance aspects of the hardware selected that require further improvement. Nevertheless, these results strengthen the design choice models and mechanism functions discussed in Chapter 3. Additionally, the work presented in this dissertation shows promise for multi-beam terminals.

7.3. ANSWERS TO THE RESEARCH QUESTIONS

This dissertation aimed to answer four research questions resulting from the gaps identified in Chapter 1. In the subsequent chapters these questions were answered. Provided here is an overview of the research questions and an associated summary of their answers.

1. What is the relation between multi-beam terminals and their use cases?
 - a) How many beams would a multi-beam terminal be expected to handle for different use cases?
 - b) What is the relation between field of view requirements, orbit regime and user type?
 - c) How long is a counter terminal expected to dwell in the field of view?
 - d) How much could a multi-beam terminal impact a multi-domain integrated network?

To answer this question, Chapter 2 analyzed the relationship between use cases and high level parameters related to MBT design. In addition, analysis on different use cases was performed.

To find the expected number of beams for different use cases, estimates were made of the total number of users broken down by types as well as spatial density. These densities were then related to the FoV and orbit through the coverage area. It was found that depending on the target type and orbit, anywhere from single users up to millions can be envisaged. An estimate with regard to the order of magnitude design envelope yielded 10-1000 beams.

For nadir communication for space-to-ground, sea and air as well as high-to-low orbit communications, types such as communication towers and trains were several orders of magnitude more common compared to commercial aircraft and cruise ships. Keeping FoV equal, more beams can be expected for all altitudes when focusing on more abundant types

such as trains and towers. In contrast, sparser types, such as aircraft and cruise ships, will demand more beams only at higher altitudes, where the coverage area is larger.

Another important aspect for nadir communication is the target dwell time within the FoV. Both acquisition and communication phases must occur within the dwell time. The FoV and altitude both increase the dwell time through the cross distance. This implies that there is a feasible altitude range for operations, where the minimum altitude is either limited by dwell time or FoV and the maximum altitude by the minimum ground resolution. Dwell times for a 4° FoV were found to be between 1.1 s in LEO up to 80 s in GEO.

When a minimum dwell time was set at 10 s and the ground resolution set to 100 m, the altitude range found was between 1305 km and 13,300 km for an FoV of 4° and 450 km to 13,300 km for 12°. This shows the influence of FoV, dwell time and angular resolution on the altitude range. Furthermore, when the dwell time was increased to 240 s, it was found that there was no overlapping range for the angular resolution and dwell time for a 4° FoV. For 12° this was 7410 km to 13,300 km, illustrating the importance of overlapping ranges for FoV, dwell time and angular resolution.

Lastly, for multi-domain networks it was found that the substitution of SBTs with MBTs yielded improvements in the reduction of the number of components, latency and capacity. However, the network performance gains were shown to approach an asymptote, illustrating that adding beams yields diminishing marginal returns. Furthermore, investigation into inter-satellite communication for constellations similar to Starlink, shows that the horizon and satellite spacing influence the maximum number of satellites within the FoV.

2. What are the functions and design options for a space borne multi-beam steering system?
 - a) What are the functions of a multi-beam laser communication terminal?
 - b) How do the functions for a single beam laser communication terminal differ from those of a multi-beam laser communication terminal?
 - c) What are the design options for a multi-beam steering system?
 - d) How can a high level design for a multi-beam steering system be selected?

To answer this question, [Chapter 3](#) first analyzed the functions of MBTs. It was found that the beams undergo similar phases of acquisition, link sustainment and termination as SBTs. However, within the context of multiple beams, additional steps of filtering and labeling are required in

tracking. Furthermore, each beam must be steered individually by the system, implying resource allocation and parallel beam management.

The starkest contrast between SBTs and MBTs is found on the terminal level. Multiple beams enter, exist and exit each phase in parallel. An important system function is to maintain resources, labeling and filtering of false beams. Furthermore, the termination phase offers the opportunity to re-distribute these resources.

Design options of both MBTs and SBTs as well as adjacent domains of inter-building laser communication, LiFi and 3D MEMS optical cross connects were analyzed. This was in order to determine design options for multi-beam steering systems. These design options were analyzed within the domain context and application. Subsequently, these options and applications were compared to existing literature on MBTs. Patterns were found, discussed and organized. The result was a design options tree, which acts as a design choice model for steering system layouts. When used, simple yes and no questions answered on the basis of the use case will lead to a high level steering system design. Furthermore, design options for the steering mechanisms were compared and contrasted in a trade-off table. This table also allows selection of the steering mechanism based on the use case and desired function.

3. What are the characteristics of integrating an SLM based multi-beam steering system?

- a) What are the operational drawbacks of SLMs and how can these be compensated?
- b) What is the angular steering resolution performance envelope of an SLM within a multi-beam steering system?
- c) What is the total angular steering range performance envelope of an SLM within a multi-beam steering system?
- d) How can multiple beams be mapped from the counter terminals to the transceivers?
- e) What is a viable SLM based multi-beam steering system layout?
- f) Can steering and steering system layouts be validated in the lab?

To answer this question, [Chapter 5](#) investigated and demonstrated the effects of SLM based beam steering and the detailed steering system layout which can accommodate such mechanisms. The main drawbacks of SLM steering originate from two main areas: diffraction effects and non-modulated beams (NMBs).

As a result of discrete pixelation, SLMs act as diffraction gratings causing diffraction orders. Additionally, not all the light incident on the SLM is modulated due to cover layers. These diffraction orders and NMB not only decrease efficiency, they also yield beam copies which make beam

tracking more complex. A novel method was proposed which used a phase screen consisting of a phase ramp and Fresnel lens (PRFL). In combination with deliberate defocus immediately before the SLM, it allowed diffraction and NMB to be separated from the modulated beam or removed altogether from the image detector. This simplifies tracking in hardware with little to no computational overhead. This concept was demonstrated experimentally using the hardware setup determined and detailed in [Chapter 4](#).

The SLM steering resolution and range envelopes were also determined. The steering resolution was found to be proportional to the beam diameter as a function of the number of pixels as well as the level of discretization of the phase modulation range of each pixel. It was found that μrad level steering could be achieved with 10-bit discretization and at around 15-20 pixels diameter.

The pixel size was the determining factor in the steering range. It was found that diffraction effects and aliasing caused efficiency to decrease with increased steering angle. It was found that steering beyond the aliasing angle caused the steered diffraction order to no longer be the largest. This effectively yielded steering reversal. The efficiency at this angle was found to be 40%. This was experimentally demonstrated, with the SLM used verifying the steering range of 2.25° . Both the steering range and resolution performances were found to be comparable to FSMs.

The steering system layout found most promising in [Chapter 3](#) on the basis of [Chapter 2](#) was selected. It was found that phase ramp (PR) steering made spatial decoupling of the transceivers from the targets challenging. This was due to conjugate plane positioning. However, it was found that through PRFL, each beam could be given a tailored optical system dynamically created by SLMs. Through individually focusing and steering beams, it allowed for locally decoupling the correct transceiver from the target. This was validated on a single beam and its diffraction orders in the lab.

4. How can multiple individually moving beams be tracked in a noisy environment?
 - a) What are the limitations of single beam tracking methods when applied to multi-beam tracking?
 - b) How can multiple beam tracking performance in space match single beam tracking performance requirements?
 - c) How can the tracking performance envelope of this multiple beam tracking method be quantified with regard to noise and computational load?
 - d) Can the tracking principles and theory be demonstrated in the lab?

To answer this question, [Chapter 6](#) investigated and demonstrated multi-beam tracking algorithms. SBT tracking algorithms were found to be limited in two aspects: First, there were no built-in multiple beam tracking mechanisms. Second, SBT tracking algorithms found in literature heavily rely on computationally expensive image processing made possible using region of interest.

Due to beams moving throughout the FoV, full frame processing is needed to determine the location of all the beams in the FoV. This makes image processing computationally expensive. In contrast, multiple target tracking relies heavily on statistical processes applied temporally. On this basis, a novel multi-beam tracking algorithm was proposed which utilizes temporal tracking techniques to filter noise.

This algorithm used motion patterns over time to predict false and true positives. As a result, only probable false detections are to be filtered out. This implies that the algorithm scales with the number of detections rather than the number of pixels. In turn, the computational load is reduced compared to image processing.

The algorithm performance envelope was derived analytically through combinatorics and probabilistic analysis. This defined the theoretical behavior in relation to noise. Additionally, fundamental limits with regards to noise, number of beams and computational loads were determined analytically.

The resulting algorithm was used to track multiple independently moving beams in the presence of noise. In [Chapter 4](#), the experimental setup was determined and detailed. These beams were generated by moving diffraction gratings with respect to each other. The beams were subsequently collimated and projected via a steering mechanism onto the image detector. This made it possible to experimentally demonstrate the algorithm in a representative lab environment.

It was found that using the selected hardware, as predicted, up to 1000 targets (false positives and true positives) could be tracked in accordance with the miss and windowing limits. Furthermore, the latency per frame ranged from 0.5 ms in low noise conditions up to 10 ms in higher noise conditions while tracking full frame. Lastly, the theoretical limits of the system were all verified.

7.4. INNOVATIONS

The PhD project yielded the following innovations:

1. **Study of potential use cases and scenarios** for MBTs and their associated counter terminal availability, dwell time as well as the relations with FoV and altitude.
2. **Identification of multi-beam terminal functions.**

3. **Development of design options choice model** which allows for high level design choices.
4. **Comparison of multi-beam technology with adjacent domains** for design inspiration and lessons.
5. **Development of experimental setup and methodologies for hardware demonstration of multi-beam terminals** including interface management and methods to emulate multiple beams moving individually.
6. **Reduction in tracking complexity when steering using SLMs using PRFL** through in-phase screen separation of diffraction and non-modulated beams.
7. **Characterization of multi-beam steering performance envelope when using SLMs**, with relations for steering resolution, number of beams capacity, steering efficiency as well as steering angle.
8. **Characterization and development of multi-Beam steering system layout using dynamically tailored optical trains through PRFL**, which allows separation and individual steering of multiple beams at scale.
9. **Analysis and characterization of computationally efficient multi-beam tracking algorithm based on temporal multiple target tracking techniques** such that the computational load is proportional to the number of tracked targets and not the number of pixels.
10. **Mathematical characterization and modeling of tracking algorithm performance** which can be used to model the algorithm performance and size the tracking hardware.
11. **Definition of tracking performance envelope and identified limits** to predict and help design tracking.
12. **Increase of multi-beam steering system TRL levels** from 1-2 (basic research level) to 3-4 (technology development and research into feasibility with lab demonstrations).

7.5. FUTURE RESEARCH

This project made significant advancements in the field of multi-beam steering. However, several areas remain unexplored.

Firstly, the development of wide FoV telescopes. Current advancements of wide FoV telescopes show promise. However, these advancements focus on providing wide FoVs for flat image planes. FoVs on the order of 45° would likely require a different approach.

In relation to this, integration of higher resolution image detectors and SLMs would be required as well. As the FoV increases, the resolution required for tracking and steering also increases. As a result, future image detectors, SLMs and their associated algorithms require further research.

Once this step has been achieved, more accurate estimates can be made with regard to the quality of service and the link budget. Furthermore, the limitations from the optical design can help narrow down higher likelihood use cases, allowing for true feasibility studies and accurate market research. Nevertheless, the innovations in the coming years could open more possibilities.

Second, with respect to the work done in this thesis, there are a few places where further research can be done. Starting with the control and integration aspects. While this work has been started, a full demonstration of a (two) stage steering system with closed control loop still has to be performed. This would undoubtedly provide additional insights and advance the field further. This would also raise the TRL level further. Additionally, the setup can be further upgraded to include expected power levels, wavelengths, more advanced SLMs and the inclusion of transceivers. This would allow direct analysis and research into optimization of form factor, thermal loads and system steering performances. The acquisition phase is currently underexplored as well.

Thirdly, the current multi-beam tracking algorithm borrows from multiple target tracking. However, multiple target tracking algorithms as a field include many diverse concepts. This implies that multi-beam tracking algorithms can be made more complex and effective by taking on board more aspects. In particular, beam behavior can be further exploited as well as the statistical analysis on clutter. For example, in practice the trajectories of the beams are potentially known beforehand. Additionally, the precision can be further improved by allocating local regions of interest and subsequently locally performing additional image processing steps.

Next, as mentioned before, the SLM has a number of strengths and a number of weaknesses. One such drawback is that the majority of SLMs available are based on liquid crystal technologies. This poses polarization limitations and generates reflection problems. Further research and development to create MEMS mirror based SLMs would address the shortcomings.

Finally, steering multiple beams can be used in each phase of the beam life cycle. Each part of this cycle needs to be further researched. This is particularly the case for the acquisition phase.

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A

APPENDIX: MULTI-BEAM TERMINAL USE CASES

A.1. FIELD OF VIEW

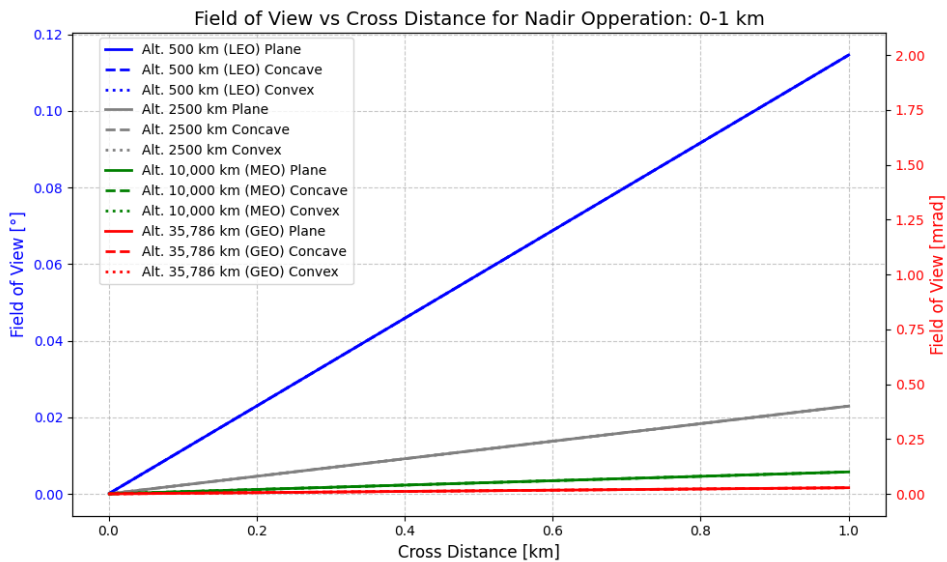


Figure A.1.: Field of view vs the cross distance of the projected field of view with different methods for cross distances between 0 and 1 km.

A.2. ANGULAR AND SPATIAL RESOLUTIONS

A

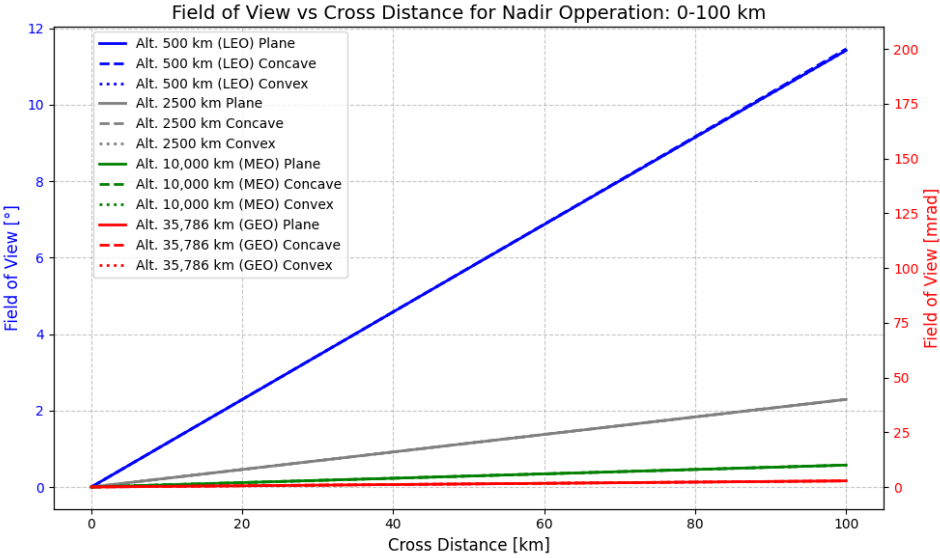


Figure A.2.: Field of view vs the cross distance of the projected field of view with different methods for cross distances between 0 and 100 km.

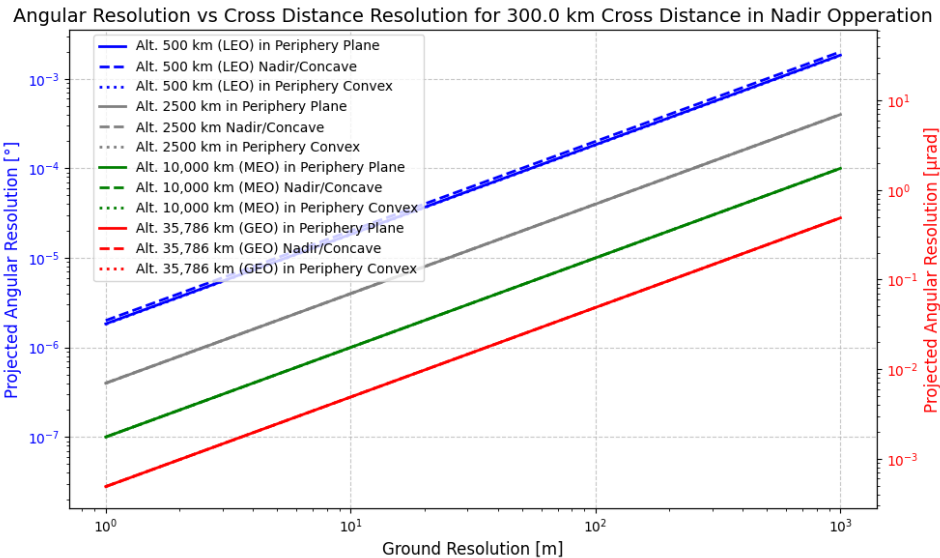


Figure A.3.: Angular vs spatial resolution with 30 km cross distance.

Angular Resolution vs Cross Distance Resolution for 300.0 km Cross Distance in Nadir Operation

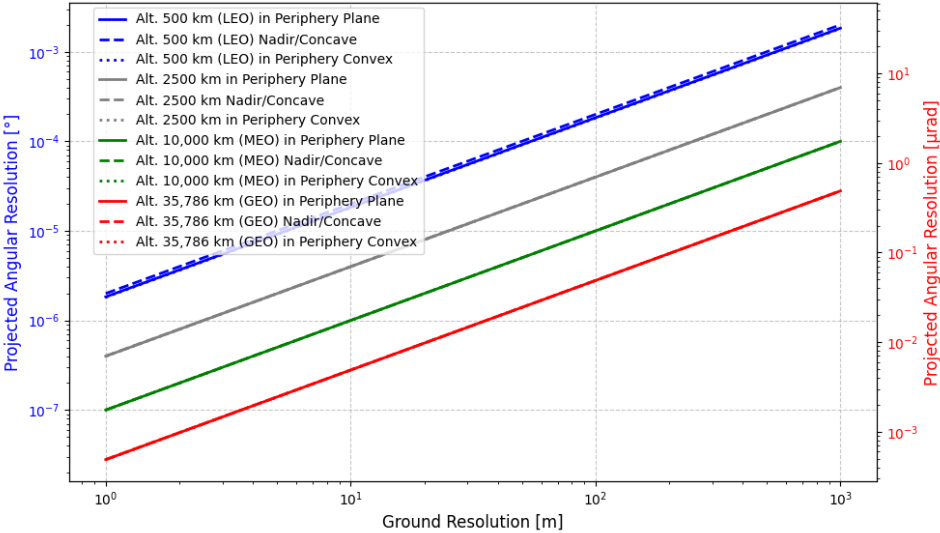


Figure A.4.: Angular vs spatial resolution with 300 km cross distance.

B

APPENDIX: DESIGN OF MULTI-BEAM STEERING SYSTEMS

LITERATURE TABLES

Overview of multi-beam systems found in literature										
Application\Design Choice	Transmitter selection	Large Mirrors (B<M)	FSMs and MMAs (B<M)	MMAs and SLMs (B>M)	Closed loop control	Open loop control	No control	Multiple steering Stages	Single steering stage	No Steering
Broadcasting										
Point-to-point	AWGR, VCSEL, COG, DORA	OPMP, OPMPW, SD/TDMA E, IRF	MPFSO, MBLCS, LOXC, LLR, TTMEIS	SLMOIC, MBTS	OPMP, OPMPW, MPFSO, MBLCS, SLMOIC, MBTS, MBLCS2	SD/TDMA E, IRF, LOXC, COG, LLR, TTMEIS	AWGR, VCSEL, DORA	OPMP, OPMPW, MBTS, LOXC, LLR, TTMEIS	SD/TDMA E, IRF, MPFSO, MBLCS, SLMOIC, COG, MBLCS2	AWGR, VCSEL, DORA
Static targets	AWGR, VCSEL, COG	SD/TDMA E, IRF	LOXC, LLR, TTMEIS	SLMOIC	SLMOIC	SD/TDMA E, IRF, LOXC, COG, LLR, TTMEIS	AWGR, VCSEL	LOXC, LLR, TTMEIS	SD/TDMA E, IRF, MPFSO, MBLCS, SLMOIC, COG	
Moving targets	DORA	OPMP, OPMPW	MPFSO, MBLCS	MBTS	OPMP, OPMPW, MPFSO, MBLCS, MBTS, MBLCS2		DORA	OPMP, OPMPW, MBTS	MBLCS2	DORA
Target density greater than steering system	AWGR, VCSEL, DORA						AWGR, VCSEL, DORA			AWGR, VCSEL, DORA
Target density smaller than steering system resolution	COG	OPMP, OPMPW, SD/TDMA E, IRF	MPFSO, MBLCS, LOXC, LLR, TTMEIS	SLMOIC, MBTS	OPMP, OPMPW, MPFSO, MBLCS, SLMOIC, MBTS, MBLCS2	SD/TDMA E, IRF, LOXC, COG, LLR, TTMEIS		OPMP, OPMPW, MBTS, LOXC, LLR, TTMEIS	SD/TDMA E, IRF, MPFSO, MBLCS, SLMOIC, COG, MBLCS2	
Duplex		OPMP, OPMPW, SD/TDMA E, IRF	MPFSO, MBLCS, LOXC, LLR, TTMEIS	MBTS	OPMP, OPMPW, MPFSO, MBLCS, MBTS, MBLCS2	SD/TDMA E, IRF, LOXC, LLR, TTMEIS		OPMP, OPMPW, MBTS, LOXC, LLR, TTMEIS	SD/TDMA E, IRF, MPFSO, MBLCS, MBLCS2	
Non-duplex	AWGR, VCSEL, COG, DORA			SLMOIC	SLMOIC	COG	AWGR, VCSEL, DORA		SLMOIC, COG	AWGR, VCSEL, DORA

Table B.1.: Overview of systems placed into design choices table. [Table B.2](#) can be used to cross reference which system was selected.

System:	Acronym:	Institution:	References:
One-Point to Multi-Point laser communication system	OPMP	Changchun University	[1, 2, 3, 4]
SD/TDMA experiment	SD/TDMA E	Graduate School of Global Information and Telecommunication Studies Department of Science Japan Women's University	[5]
One-Point to Multi-Point laser communication system wedge version	OPMPW	Changchun University	[6]
FSO link via Intelligent Reflecting Surfaces	IRF	Purvanchal University	[7]
MULTI-POINT FREE SPACE OPTICAL COMMUNICATION SYSTEM	MPFSO	X Development	[8]
MULTI-BEAM LASER COMMUNICATIONS SYSTEM AND METHOD	MBLCS	Lockheed Martin Corporation	[9]
high port count arrayed waveguide grating router (AWGR)	AWGR	TU Eindhoven	[10]

Continued on next page

System:	Acronym:	Institution:	References:
multiple-input multiple-output (MIMO) optical wireless communication (OWC) link based on vertical cavity surface emitting laser (VCSEL) arrays	VCSEL	University of Strathclyde	[11]
optical interconnect using a liquid-crystal spatial light modulator	SLMOIC	Cambridge University	[12]
Multi-Beam laser communication terminal	MBTS	Delft University of Technology	[13]
large optical cross-connects (OXC)	LOXC	Lucent Technologies	[14]
Cognitive multi-user free space optical communication testbed	COG	University of Oklahoma	[15]
Lucent LambdaRouter	LLR	Lucent Technologies	[16]
microelectromechanical systems (MEMS) two-axis tilt mirror arrays	TTMEMS	NTT Microsystem Integration Laboratories	[17]
MULTI-BEAM LASER COMMUNICATIONS SYSTEM AND METHOD	MBLCS2	Lockheed Martin Corporation	[18]
Deployable Optical Receiver Array Cubesat	DORA	Arizona State University	[19]

Table B.2.: Previous systems and their sources.

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C

APPENDIX: HARDWARE SETUP

The following are implementations of converting two 10-bit mono images into one 8-bit RGB image. The 8-bit RGB images are provided to the SLM for display.

High level Python implementation:

```
R = ((Mono1 >> 7) << 5) + (Mono2 >> 7);
G = ((Mono1 >> 4) & 0b0111) << 5 + ((Mono2 >> 4) & 0b0111);
B = (Mono1 & 0b1111) + (Mono2 & 0b1111);
RGBImage = np.stack(R,G,B)
```

Linear C implementation:

```
#include <stdint.h>

typedef struct {
    uint8_t r;
    uint8_t g;
    uint8_t b;
} RGBPixel;

void convertMonoToRGB(const uint16_t* mono1, ...
    const uint16_t* mono2, RGBPixel* rgb, ...
    size_t width, size_t height) {
    for (size_t i = 0; i < width * height; i++) {
        uint16_t m1 = mono1[i];
        uint16_t m2 = mono2[i];

        uint8_t r = ((m1 >> 7) << 5) + (m2 >> 7);
        uint8_t g = ((m1 >> 4) & 7) << 5 + ((m2 >> 4) & 7);
        uint8_t b = (m1 & 15) + (m2 & 15);

        rgb[i].r = r;
        rgb[i].g = g;
        rgb[i].b = b;
    }
}
```


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LIST OF PUBLICATIONS

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4. J. Spaander, R. Saathof, E. Gill, and J. Guo. "Tracking Algorithm for Multi-Beam Laser Communication Terminals". In: (May 2026). doi: [10.1364/opticaopen.32125477.v1](https://doi.org/10.1364/opticaopen.32125477.v1).
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The moments that matter burn into your heart while others fade in the mist.

James Fraser (*Outlander*)

The performance analysis of the multi-beam tracking performance relies heavily on combinatorics, the area of mathematics which explores counting. I used it to assess the probability of various combinations of outcomes related to tracking multiple beams. I used it to answer questions such as: How sure can I be that a detection is correct? How well does my system filter noise? How many beams does my system miss? When studying this field of mathematics, the sheer number of possible outcomes, even for a small number of events, quickly dawned on me. Adding just a few more beams here and a bit more noise there can mean the difference between my computer taking microseconds and thousands of years. Large and small differences (tricks and optimizations) can change outcomes very significantly.

Having made it to this stage in my career, it would be easy to say that it was my hard work that led me here. While I undeniably did work hard, the reality is that the people around me have made the difference, both at work and outside it.

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