Portable Optical Ground Stations for Satellite Communication

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This work is based on the unaltered text of the thesis by Kathleen Michelle Riesing submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Aeronautics and Astronautics at the Massachusetts Institute of Technology.
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by

Kathleen Michelle Riesing

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Abstract

Small satellite technical capabilities continue to grow and launch opportunities are rapidly expanding. Several commercial constellations of small satellites for Earth observation and communications are making their way onto orbit, increasing the need for high bandwidth data downlink. Laser communications (lasercom) has the potential to achieve high data rates with a reduction in power and size compared to radio frequency (RF) communications, while simultaneously avoiding the significant regulatory burden of RF spectrum allocation.

Lasercom benefits from high carrier frequencies and narrow beamwidths, but the resulting challenge is to precisely point these beams between transmit and receive terminals. Arcsecond to sub-arcsecond pointing is required from both the space terminal and the ground station. While existing lasercom ground stations have primarily utilized professional telescopes at observatory-class facilities, making optical ground stations more affordable and transportable is a key enabler for expanding lasercom to small satellites and new applications, as well as establishing networks to mitigate the effects of weather.

This thesis focuses on the development of a portable optical ground station utilizing a commercial off-the-shelf (COTS), low-cost telescope. The Portable Telescope for Lasercom (PorTeL) reduces mass and cost by at least 10× compared with existing optical ground stations. To enable the use of a low-cost telescope, several contributions are made to the state-of-the-art approach to optical ground station design, pointing, and tracking. A system architecture is proposed that enables rapid deployment in approximately 30 minutes and that is capable of tracking satellites in low-Earth orbit (LEO) to within arcseconds of accuracy. A novel telescope calibration algorithm is developed that is agnostic to initial mount/telescope orientation and utilizes a star tracker for rapid, automated alignment. This eliminates the need for manual pre-alignment (e.g., leveling of the mount) and provides a generic framework that extends to different mount types. An approach to tracking LEO objects to better than 5 arcseconds RMS using only two-line element sets (TLEs) and low-cost hardware is presented. Pointing and tracking algorithms and performance are validated by using a physical ground station setup to track LEO objects, including the International Space Station (ISS).
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## Nomenclature

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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFRL</td>
<td>Air Force Research Laboratory</td>
</tr>
<tr>
<td>AO</td>
<td>Adaptive optics</td>
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<tr>
<td>APD</td>
<td>Avalanche photodiode</td>
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<tr>
<td>BPSK</td>
<td>Binary phase shift keying</td>
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<tr>
<td>CMOS</td>
<td>Complementary metal–oxide–semiconductor</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial off-the-shelf</td>
</tr>
<tr>
<td>DLR</td>
<td>German Aerospace Center (German: Deutsches Zentrum für Luft- und Raumfahrt)</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree(s) of freedom</td>
</tr>
<tr>
<td>EKF</td>
<td>Extended Kalman filter</td>
</tr>
<tr>
<td>ERS</td>
<td>European Remote Sensing Satellite</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of view</td>
</tr>
<tr>
<td>FSM</td>
<td>Fast-steering mirror</td>
</tr>
<tr>
<td>Gbps</td>
<td>Gigabit per second</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary orbit</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>-------------</td>
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<tr>
<td>INNOVA</td>
<td>IN-orbit and Networked Optical Ground Stations Experimental Verification Advanced Testbed</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>JSpOC</td>
<td>Joint Space Operations Center</td>
</tr>
<tr>
<td>LCRD</td>
<td>Laser Communications Relay Demonstration</td>
</tr>
<tr>
<td>LEO</td>
<td>Low-Earth orbit</td>
</tr>
<tr>
<td>LLCD</td>
<td>Lunar Laser Communication Demonstration</td>
</tr>
<tr>
<td>LLGT</td>
<td>Lunar Lasercom Ground Terminal</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-of-sight</td>
</tr>
<tr>
<td>LUCE</td>
<td>Laser Utilizing Communications Equipment</td>
</tr>
<tr>
<td>Mbps</td>
<td>Megabit per second</td>
</tr>
<tr>
<td>MITLL</td>
<td>Massachusetts Institute of Technology Lincoln Laboratory</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NICT</td>
<td>National Institute of Information and Communications Technology</td>
</tr>
<tr>
<td>NODE</td>
<td>Nanosatellite Optical Downlink Experiment</td>
</tr>
<tr>
<td>OCTL</td>
<td>Optical Communications Telescope Laboratory</td>
</tr>
<tr>
<td>OGS</td>
<td>Optical Ground Station</td>
</tr>
<tr>
<td>OICETS</td>
<td>Optical Inter-orbit Communications Engineering Test Satellite</td>
</tr>
<tr>
<td>OIM</td>
<td>Optics in Motion</td>
</tr>
<tr>
<td>OPALS</td>
<td>Optical PAYload for Lasercomm Science</td>
</tr>
<tr>
<td>OSIRIS</td>
<td>Optical Space Infrared Downlink System</td>
</tr>
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PorTeL Portable Telescope for Lasercom
RF Radio frequency
RMS Root-mean-square
RMSE Root-mean-square error
SOTA Small Optical TrAnspender
SSA Space situational awareness
STAR Lab Space Telecommunications, Astronomy, and Radiation Laboratory
TAOGS Transportable Adaptive Optical Ground Station
TLE Two-line element set
TOGS Transportable Optical Ground Station

**Constants and Variables**

\( \alpha \) Altitude gimbal angle

\( \alpha_{obs} \) Observed (i.e. apparent) elevation angle

\( q_{atm} \) Quaternion rotation through atmospheric refraction, defined by Equations 3.6, 3.8, and B.4

\( q_{NP} \) Quaternion rotation through non-perpendicularity angle, defined by Equation 3.5

\( q_{alt} \) Quaternion rotation through altitude angle, defined by Equation 3.4

\( q_{azi} \) Quaternion rotation through azimuth angle, defined by Equation 3.3

\( q_{CL} \) Quaternion rotation containing closed-loop feedback correction, defined by Equations 4.3, 4.4, and B.4

\( r_{gs} \) Vector location of ground station

\( r_{targ} \) Vector location of target

\( u_{meas} \) Observed unit vector of the target
\( \mathbf{u}_{pmt} \)  Unit pointing vector from telescope to target

\( \mathbf{u}_{tel,CL} \)  Telescope boresight vector updated with closed-loop feedback

\( \mathbf{u}_{tel} \)  Telescope boresight unit vector

\( \mathbf{u}_d \)  Axis of vertical deflection

\( \psi \)  Azimuth gimbal angle

\( 0_{n \times m} \)  \( n \times m \) matrix of zeros

\( \mathbf{I}_{n \times m} \)  \( n \times m \) identity matrix

\( \theta_{cmd} \)  Commanded gimbal angle

\( \theta_{meas} \)  Gimbal angle measured by the encoder

\( \theta_{NP} \)  Gimbal axes non-perpendicularity

\( \theta_{off} \)  Offload angle

\( \theta_{ref} \)  Reference gimbal angle

\( a_d \)  Vertical deflection coefficient

\( \mathbf{H} \)  Jacobian matrix

\( \mathbf{P} \)  Error covariance

\( \mathbf{Q} \)  Process noise covariance

\( \mathbf{R} \)  Measurement noise covariance

\( t_0 \)  Timing offset

\( T_s \)  Settling time

\( \text{ENU} \)  East-north-up reference frame, defined in Section 3.3

\( \text{GIM} \)  Gimbaled reference frame, defined in Section 3.3

\( \text{J2K} \)  J2000 reference frame, defined in Section 3.3

\( \text{MNT} \)  Mount reference frame, defined in Section 3.3

\( \text{OBS} \)  Observed frame, defined in Section 3.3

\( \text{ST} \)  Star camera frame, defined in Section 3.3
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Chapter 1

Introduction

In the last few decades, space-based laser communications (lasercom) has emerged as a transformative technology for scientific, defense, and commercial spacecraft applications. Compared with traditional radio frequency (RF) communications, lasercom offers the potential for higher bandwidth, reduced size and mass of transceivers, and lower power consumption [1]. Lasercom also avoids the significant regulatory hurdles of RF spectrum allocation and provides better link security with narrow beams. As spacecraft generate increasing amounts of data, space-to-ground lasercom can provide high rate downlink capability to overcome a communications bottleneck. Given that one of the major limitations of lasercom is weather, a robust optical ground network is essential.

The small satellite market has emerged as the result of a push for smaller, cheaper, more flexible systems with a rapid development cycle. While multiple efforts have focused on the development of space-based lasercom terminals for these platforms, less work has gone towards alternative approaches to traditional optical ground stations. This chapter motivates the need for a low-cost, transportable ground station for lasercom ground networks and also discusses how a similar system could benefit the space situational awareness (SSA) community. An overview of optical ground station components and considerations is provided, followed by a discussion of major challenges for optical ground stations. The research contributions and roadmap for the thesis are presented in the final section.
1.1 Motivation

1.1.1 Laser Communication for Small Satellites

Small satellites in particular have great potential to benefit from lasercom as they are significantly constrained in size, weight, and power. The small satellite market is currently experiencing a period of rapid growth. Despite launch delays, thousands of small satellites are expected to launch in the next five years [2]. As the number of satellites in orbit grows and their capabilities improve, the amount of data they generate puts pressure on existing RF communications infrastructure.

The communications subsystem has long been a limitation for small satellites. The time required to license a portion of the RF spectrum often takes longer than the entire time to design, build, and test the satellite [3]. The amateur band is becoming overcrowded with small satellites and licensing organizations such as the Federal Communications Commission (FCC) are straining to keep up with increased demand [4].

A recent event has caused conflict over the FCC’s regulation of small satellites. After the FCC denied a license to four picosatellites \((10 \times 10 \times 2.5 \, \text{cm}^3)\) from start-up Swarm Technologies in December 2017, the company launched the satellites anyway, prompting an angry response from the FCC [5]. The FCC considered the picosatellites to be too small to track and therefore a risk, but their decision was not consistent with similarly-sized picosatellites that they had previously allowed. The FCC has proposed a change in small satellite regulation and the resulting uncertainty has disrupted the small satellite market. Ground station licensing and regulation likewise presents a challenge for small satellite operators such as Planet [6], an Earth-imaging company with over 100 operational satellites as of 2018. The company built a ground station in Inuvik, Canada that it is threatening to relocate after two years of waiting for a license [7].

Unlike RF, the lasercom spectrum does not require official allocation due to narrow beams that present little risk of interference. The only restrictions for lasercom frequencies are focused on safety and protection of government assets. The American National Standards Institute provides a metric for maximum permissible exposure. For lasercom downlinks, transmitted power is spread out over a large area and does not approach safety limits, but for uplinks the power is concentrated on the ground. Lasers directed upwards are controlled by the U.S. Air Force’s Laser Clearinghouse, which provides guidelines on reporting laser use to protect space assets. Careful design and precautionary measures such as airplane spotters can avoid safety concerns.
There is strong interest in bringing lasercom to small satellite platforms [8]. Ongoing efforts include The Aerospace Corporation’s Optical Communication and Sensor Demonstration (OCSD) program [9–11], commercial terminals by Sinclair Interplanetary [12] and Microspace [13], the German Aerospace Center’s (DLR) Optical Space Infrared Downlink System (OSIRIS) [14, 15], the National Institute of Information and Communications Technology’s (NICT) Small Optical TrAnsponder (SOTA) [16], and the MIT Space Telecommunications, Astronomy, and Radiation Laboratory’s (STAR Lab) Nanosatellite Optical Downlink Experiment (NODE) [17–20].

NODE is a 1-U (10 cm$^3$) CubeSat module targeting a 10 megabit per second (Mbps) downlink paired with a $\varnothing$28 cm ground station. The NODE module provides data rates competitive with commercial CubeSat radios [21] and provides a scalable communications solution for nanosatellites. If the pointing system of NODE performs as well as expected on-orbit, simply reducing the beamwidth should enable hundreds of Mbps in the next iteration of the terminal. NODE is pictured in Figure 1-1. The accompanying ground station, the Portable Telescope for Lasercom (PorTeL), is the subject of this thesis.

![Figure 1-1: CAD drawing (left) and prototype (right) of the MIT Nanosatellite Optical Downlink Experiment. (Figure credit: Derek Barnes)](image)

Small satellites, as compared to larger spacecraft, have the benefits of rapid development and iteration, low cost, and flexibility. These advantages are fueling the rapid growth of the small satellite market. When designing a lasercom system for small satellites, these benefits should also be expected of the ground segment; however, this is not the standard approach to optical ground stations. A low-cost, portable optical ground station can serve as a testbed for development, an enabling technology to make lasercom more accessible, and a step towards the development of large optical...
ground networks that would both increase throughput and improve weather-limited availability.

1.1.2 Optical Ground Networks

Existing lasercom ground stations are limited in number and are typically built at locations with existing infrastructure, such as astronomical observatories [22]. The limitations imposed by weather are a major challenge for lasercom ground stations. A cloud-free line-of-sight (LOS) between the space and ground terminals is required, which reduces the availability of individual sites. Diversity in ground station locations is essential for link availability.

The initial investment cost can be high for optical ground stations, ranging from $1–5 million for a low-Earth orbit (LEO) to ground link [23]. The initial investment cost makes the development of a diverse ground network challenging. While commercial ground networks exist over RF, no similar option exists for lasercom. Small RF antennas can be purchased off-the-shelf and installed with minimal infrastructure required. Optical ground stations can utilize commercial off-the-shelf (COTS) telescopes and mounts but generally require the construction of a housing facility and custom downstream optics.

Weather is a key consideration for optical ground station location. Optical ground stations have many characteristics in common with astronomical observatories and are sometimes co-located. Desirable characteristics include high altitude, low humidity, few clouds, and low-strength turbulence [22]. An additional consideration is spacecraft visibility, which could be a limitation for locations at extreme latitudes.

Optimal site selection for optical ground stations has long been a topic of study. The Laser Network Optimization Tool (LNOT) [24] has been developed to estimate cloud cover and analyze ground site availability for specific scenarios including LEO, lunar, and deep space. For deep-space optical networks, analysis of satellite imagery shows that greater than 90% availability can be achieved with three to six ground sites [25, 26]. Additional studies have focused on optimal networks for geostationary (GEO) satellites [27, 28], and more recently LEO satellites [29, 30].

LEO networks present unique challenges as compared to GEO or deep-space networks. Because the satellites are much lower, cloud coverage is correlated between all ground locations within view. The availability for a network of three to twenty ground stations can range between 0–8% [30], taking into consideration that a LEO satellite is in view of the ground station substantially less than in the case of deep-space.
Significantly reducing the cost of ground stations and supporting infrastructure as well as the ability to relocate ground stations with relative ease can help mitigate the effects of weather.

While small-aperture ground stations may at first seem to be a limitation on achievable data rates, this need not be the case. Building large telescopes is very costly, and a ground architecture has been proposed to combine the signal of an array of small telescopes to achieve the same size aperture with greater flexibility and lower cost [31]. While data rates only as high as 1 gigabit per second (Gbps) have been developed for small satellite platforms, analysis shows that LEO-to-ground links of hundreds of Gbps to a single small ground station are possible [32]. The ongoing TeraByte InfraRed Delivery (TBIRD) mission at MIT Lincoln Laboratory seeks to demonstrate a 200 Gbps LEO-to-ground link from a CubeSat to a \( \varnothing 40 \) cm ground station [33].

A low-cost, portable optical ground station can complement existing facilities to help alleviate the problem of ground station availability. Stations can be relocated to avoid seasonal weather variation or even to target individual satellite orbits. By using low-cost, COTS technology, many stations can be deployed at the same cost as a single fixed site, or many small apertures can be combined into a large aperture at lower cost. A portable optical ground station can also make lasercom accessible to spacecraft operators who do not have existing infrastructure to support an observatory-class facility.

1.1.3 Communication for Rapid Response

Events such as natural disasters, security crises, or mass gatherings present the need for on-demand communication in unpredictable locations. Near-real-time monitoring can assist in response to these events, but fixed ground stations may not be located nearby and there may be limited infrastructure to support communications. DLR has developed a transportable optical ground station with rapid response applications in mind [34, 35].

In such a scenario, a ground station could be rapidly deployed to receive Earth observation data (e.g. images, thermal maps) in near real-time from aircraft sent out to monitor the area of interest. A communications link could also be used to coordinate on the ground or to receive data from Earth observing satellites. The ability to provide a high-capacity communications link on demand to areas without existing infrastructure can assist in a variety of rapid response scenarios.
1.1.4 Space Situational Awareness

As the number of tracked space objects has multiplied, there is growing interest in utilizing low-cost hardware to actively track space debris and satellites. In 1997, the Air Force Research Lab (AFRL) began investigating the use of small COTS telescopes ("Ravens") as a cost-effective means to improve SSA by supplementing larger assets [36]. The success of this program led to many more Raven-class telescopes, including the Canadian Automatic Small Telescope for Orbital Research (CASTOR) by the Royal Military College of Canada [37], the High Accuracy Network Determination System (HANDS) program at the Air Force Maui Optical and Supercomputing site (AMOS) [38], and the United States Air Force Academy’s Falcon Telescope Network [39]. While Raven-class telescopes initially observed GEO satellite targets, recent efforts have focused on both passive [40, 41] and active [42–45] tracking of LEO targets.

Most SSA telescopes are housed in a permanent facility, but there are advantages to being able to rapidly deploy a telescope to a location with no existing infrastructure. A program at AFRL demonstrated a deployable Raven-class system to track LEO satellites [46]. Deployable systems reduce facilities cost and allow observations of events of interest even when an existing facility is not present. GEO satellites, for example, may never be within range of an existing ground system. The ground station developed in this thesis, while designed with a communications application in mind, is also effective at imaging LEO satellites. It can be deployed rapidly to track from remote locations, making it relevant to SSA applications.

1.2 Ground Station Overview

1.2.1 Atmospheric Effects

To establish an optical link, a clear line-of-sight is required between both terminals. The severity of atmospheric effects ranges from complete link unavailability, as in the case of cloud cover, to milder effects that can be addressed in the design of the terminal. The three major atmospheric effects on beam propagation are absorption, scattering, and refractive-index fluctuations [47]. Absorption and scattering tend to cause signal attenuation, while refractive-index fluctuations (i.e. turbulence) tend to cause irradiance fluctuation and loss of spatial coherence.

The atmosphere has different effects on downlinks and uplinks. In downlinks, the atmosphere is close to the receiver, whereas in uplinks the signal passes through the
atmosphere immediately upon transmission. By the time the downlink reaches the atmosphere it has spread out, so it tends to experience scintillation and changes in angle-of-arrival [47]. The downlink benefits from an aperture-averaging effect.

The uplink experiences scintillation and a more severe beam wander. Since the beam has not spread out significantly as in the case of the downlink, the entire signal can be deflected, typically on the order of a few microradians (sub-arcseconds). These atmospheric effects must be carefully considered in the link budget and the design of the pointing and tracking system.

1.2.2 Components

A block diagram of a generic laser communications link is shown in Figure 1-2. Ground station components typically include a telescope, mount, acquisition sensor, fine tracking sensor and actuator, beacon, and receiver. While the beacon and acquisition sensor are shown on top of the telescope in Figure 1-2, several different architectures are possible. An acquisition telescope may be co-boresighted with the receive telescope, or the acquisition sensor may be downstream of the telescope but with a wider FOV than the tracking sensor. Similarly, the beacon may be mounted to the telescope with a separate aperture or it may use the main aperture. In some cases it may even be desirable to put the beacon on a separate mount.

Telescope

A fundamental design parameter of the ground station is the telescope diameter. A larger telescope will collect more photons, but the desirability of a large aperture also depends on modulation scheme. The most common scheme is intensity modulation, which carries information based on the presence or absence of photons at a given time [48]. However, some lasercom missions utilize coherent communication where the phase of the incoming signal must also be recovered.

In the case of incoherent (i.e. direct) detection, the diameter of the telescope is selected based on the required power at the receiver. The diameter of the telescope goes into the link budget along with other key parameters including transmitter power, path length, and beam divergence [22]. It may be advantageous to split the required collection area into several smaller telescopes, which can avoid the challenges of constructing a single large telescope. This presents its own challenges regarding alignment and the coupling of signal among multiple telescopes. In all architectures, the fundamental design driver is to provide enough aperture to meet a desired link
The desired aperture of a coherent ground station is somewhat more complicated due to atmospheric effects. In this case, there are two different architectures based on whether the aperture is larger than or smaller than the Fried parameter, $r_0$. The Fried parameter has units of length, and is defined as the diameter of a circular area over which the root-mean-square (RMS) wavefront aberration after passing through the atmosphere is 1 radian. For practical purposes, the Fried parameter is the diameter at which a diffraction-limited telescope has approximately the same resolution with or without turbulence [49]. For a telescope with a diameter $D$ where $D/r_0 >> 1$, the atmosphere will cause significant spreading of the signal in the focal plane. A telescope with $D/r_0 << 1$ will be diffraction-limited based on the aperture size.

The Fried parameter depends on location and time of day, but can be something on the order of 10 cm at an astronomical observatory under favorable conditions at a wavelength of 500 nm [49,50]. For coherent ground stations, either the aperture must be reduced below the Fried parameter or adaptive optics (AO) must be used to compensate for atmospheric turbulence. Constraining the aperture presents challenges in the link budget, so generally AO is preferred despite the additional complexity.
Instrumentation

The primary function of the ground station is to collect signal onto a receiver. The design of the ground station optical assembly is mission-specific, but there are key components that ground stations have in common as shown in Figure 1-2. In the case of coherent lasercom or direct detection with preamplification, a wavefront sensor and corrective actuator are usually required.

The choice of receiver architecture drives the design of the optical assembly. There are three common architectures: direct detection without preamplification, direct detection with preamplification, and coherent detection. The most popular receiver choice is direct detection with a photodiode [51]. Avalanche photodiodes (APDs) can have sensitivities in the photon-counting regime. It is worth noting that high photodiode bandwidth requires low capacitance, which in turn requires a small detector area. This presents a challenge for the ground station to collect signal onto a receiver with a diameter of 200 microns or less. The size of the APD is a key design trade for the system.

Coherent receivers require a local oscillator, and if the telescope is larger than the Fried parameter AO is also typically required. For direct detection, optical preamplifiers such as those in terrestrial fiber systems can greatly improve the sensitivity of receivers [51]. However, this first requires coupling of the signal into a single-mode fiber with a diameter of around nine microns in the case of 1550 nm communications. This again calls for AO to better couple received signal energy into the fiber.

Apart from the receiver, the ground station instrumentation includes sensors and actuators to assist with pointing, acquisition, and tracking. Some ground stations have multiple levels of coarse sensors and actuators to achieve the desired pointing accuracy. The acquisition sensor is commonly a focal plane array or a quadrant detector with a wide field of view (FOV). This sensor is used to spot the signal and steer it into the FOV of the fine sensor. The fine sensor is also usually a focal plane array or quad detector with a narrow FOV. A fast-steering mirror (FSM) is most commonly used for precise tracking. An FSM is a flat tip/tilt mirror with bandwidth in the hundreds or thousands of Hertz. An alternative approach to fine tracking uses a nutation element on the receive fiber paired with a photodiode to measure received power and adjust the fiber LOS [52].
1.3 Ground Station Challenges

1.3.1 Pointing, Acquisition, and Tracking

Lasercom links are efficient compared with RF due to having narrower beams, but a major challenge in lasercom is pointing these beams precisely at a target. Existing systems require error as small as sub-arcsecond (or sub-microradian) [52]. For a ground station, this generally cannot be accomplished by steering the telescope alone and requires a fine pointing stage. The signal is initially acquired with coarse sensors and open-loop pointing of the telescope. The stages of control must be coordinated for handoff and the coarse stage must maintain the signal within the range of the fine stage.

Prior to tracking a satellite, the ground station must be aligned and calibrated. A pointing model is developed which accounts for the orientation of the telescope/mount in inertial coordinates, as well as mechanical properties of the telescope and common sources of error [53]. The pointing model is generated by taking observations of stars or other known celestial objects. This process is examined in depth in Section 3.2.1.

The pointing, acquisition, and tracking steps for a typical lasercom terminal are shown in Figure 1-3. These steps assume that a terminal is closed-loop tracking the signal from an opposing terminal. For satellite-to-ground communications, the initial satellite pointing error is usually larger than the downlink beamwidth. Because more power is available on the ground than on the spacecraft, first contact is usually expected from a wide beacon sent by the ground station. An acquisition procedure ensures each terminal can see the other.

The majority of space lasercom terminals use beacon tracking to locate the ground station. In this approach, the ground station sends up a wide beam towards the spacecraft and the spacecraft corrects its pointing to illuminate the ground station with the downlink. While beaconless tracking reduces system complexity and is particularly appealing for deep space lasercom, it is challenging to implement in practice [54]. Without a beacon, the satellite must point within the accuracy of the downlink beamwidth without receiving any feedback from the ground. In all cases, the ground station closed-loop tracks the downlink.

From the perspective of the ground station, the sequence begins with initial pointing towards the expected location of the spacecraft. Orbital knowledge usually comes from GPS on the satellite, radio ranging, radar, or two-line element sets (TLEs) published by the Joint Space Operations Center (JSpOC). Any error in the spacecraft’s position translates into pointing error. The mispointing induced by position error
Pointing, acquisition, and tracking components:
(1) Open-loop trajectory tracking
(2) Coarse scan
(3) Closed-loop coarse feedback
(4) Closed-loop fine feedback
(5) Link maintenance

Figure 1-3: Pointing, acquisition, and tracking steps for a laser communications terminal. Diagram assumes that the terminal is tracking a beacon, which is most often the case.

gets worse the closer the spacecraft is to the ground station.

Once the spacecraft becomes visible, the ground station enters the acquisition sequence. The ground station open-loop tracks the expected trajectory of the spacecraft and can perform a scan if necessary until a signal is seen. Coarse sensors with a wide FOV, such as cameras or quad cells, are used in the acquisition phase. Once the downlink signal has been detected, the ground station closes its tracking loop and begins using its fine pointing stage. When the ground station is fine tracking onto the receiver, communication can commence.

For bidirectional systems, the alignment of the transmit and receive paths must be maintained over the pass. This can be done by slightly adjusting pointing angle and applying a correction based on received power at the opposing terminal. Alternatively, the system can be designed with self-test capabilities through the use of optical elements to redirect transmitted signal into the receive path for alignment.

Tracking LEO satellites is particularly challenging for optical ground stations. Ground station passes last less than 10 minutes, so rapid acquisition is important to maximize data transmission. Tracking rates for LEO satellites are relatively high: the maximum tracking rate for a LEO satellite in a 400 km orbit is about 1.1 deg/s, which is 264 times faster than 15 arcsec/s sidereal tracking of celestial objects. This challenges the capabilities of a COTS telescope control system.

Altitude-azimuth (altazimuth) mounts are the most common choice for LEO tracking applications. These mounts have one gimbal which provides 360° motion in azimuth and a second gimbal providing 0°–90° (possibly more) in altitude, as shown in
A singularity issue occurs in any two-axis mount. Equatorial mounts, which are a common choice for astronomical observatories, have a singularity aligned with the Earth’s polar axis. Unfortunately for altazimuth mounts, zenith passes also correspond with the shortest link range and the most favorable link conditions. Although high elevation passes are rare, the mount must be capable of fast slews to ensure the link can be maintained near the singularity. Other mount configurations, such as altitude-altitude (alt-alt), can move the singularity to the horizon. This is preferable for satellite tracking but these types of mounts are less common and present some mechanical challenges.

1.3.2 Cost and Transportability

Constructing a transportable optical ground station with a low-cost COTS telescope presents several unique challenges compared with fixed optical ground stations. A transportable ground station must be compact and easily stowed for transport. This makes the design of the optical assembly challenging. Fixed optical ground stations

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1 Depending on the context, altitude is used to refer both to (1) the height of a satellite orbit above the Earth’s surface and (2) the angle between the target and the horizon in a local horizontal frame. When referring to altitude angle, the terms “altitude” and “elevation” are used interchangeably in this thesis. “Altitude” angle will be used primarily to refer to the mount angle and “elevation” angle will be used primarily to refer to the angle of the target (e.g., satellite), although there is no formal distinction.
Figure 1-5: Ground station azimuth slew rate as a function of orbit altitude and maximum elevation of satellite pass. An altazimuth mount tracking near zenith results in very high azimuth rates.

...
class of telescope, a new calibration approach is needed.

1.4 Thesis Contributions and Roadmap

The primary objective of this work is the design and implementation of a portable, low-cost ground station with the following performance metrics: 1) the ground station can be rapidly deployed and calibrated within an hour, 2) the ground station blind pointing accuracy is better than 100 arcseconds RMS, and 3) the ground station can track LEO satellites within 7.4 arcseconds accuracy. The rationale for these requirements is discussed in Section 2.2.3.

The outcome of this thesis is the Portable Telescope for Lasercom (PorTeL), which achieves these performance metrics and demonstrates the feasibility of using an amateur telescope as an optical ground station. Prior “transportable” ground stations that are documented in the literature are transportable via trucks or shipping containers. PorTeL is described as “portable”, meaning that it is compact enough to be physically moved and deployed by 1–2 people and fits in the trunk of a car. PorTeL reduces mass and cost by at least $10 \times$ compared to existing optical ground stations, from hundreds of kilograms to tens of kilograms and from millions of dollars to tens of thousands of dollars. These claims are justified through a review of existing optical ground stations in Section 2.1.

The primary contributions of this thesis are:

1. A system architecture for a low-cost portable optical ground station that tracks LEO satellites
2. A high-fidelity telescope pointing model that is rapidly calibrated using a star tracker with minimal manual input and no assumptions about initial orientation
3. A staged control approach for tracking LEO satellites that enables better than 5 arcsecond tracking using two line element sets (TLEs) and low-cost hardware
4. Experimental validation of contributions #1–3 with the Portable Telescope for Lasercom (PorTeL)

Chapter 1 has motivated the need for a low-cost, portable optical ground station and outlined the contributions of this thesis. Chapter 2 provides background on existing optical ground stations followed by the design and pointing requirements of PorTeL. Chapter 3 describes existing approaches to telescope pointing calibration followed by the derivation of a quaternion-based pointing model that enables
rapid calibration. Chapter 4 discusses existing efforts to track satellites with low-cost hardware and then presents the approach that has enabled better than 5 arcsecond tracking of LEO satellites. Chapter 5 presents the experimental results of this work which include an assessment of the blind pointing accuracy and satellite tracking accuracy of PorTeL, validating that pointing performance requirements have been met. Chapter 6 summarizes the thesis and discusses areas of future work.
Chapter 2

Ground Station Design

This chapter places the Portable Telescope for Lasercom developed in this thesis within the context of existing ground stations. This provides a frame of reference to highlight similarities (such as staged control) and differences (such as cost, mass, and portability). The first part of this chapter reviews existing fixed and transportable ground stations, while the latter portion of the chapter addresses the design of PorTeL.

2.1 Literature Review

2.1.1 Fixed Optical Ground Stations

In this section we focus on three examples of fixed optical ground stations that have supported high-profile lasercom demonstrations. They are the European Space Agency’s Optical Ground Station (ESA-OGS), the NASA Jet Propulsion Laboratory’s (JPL) Optical Communications Telescope Laboratory (OCTL), and the NICT’s IN-orbit and Networked Optical Ground Stations Experimental Verification Advanced Testbed (INNOVA). Additional fixed ground stations that are not discussed in depth, either because they resemble the ground stations discussed or have less detail available in the literature, include DLR’s ground station at Oberpfaffenhofen [55], the Aerospace Corporation’s MOCAM and MAFIOT [10], the MeO optical ground station at Observatoire de la Côte d’Azur (OCA) - GeoAzur [56], the Mynaric/Facebook GS-200 [57], the Chinese Academy of Sciences Optical Ground Station [58], and the NASA Laser Communications Relay Demonstration (LCRD) ground station #2 [59].
ESA-OGS

ESA-OGS is located at the Teide Observatory on Tenerife in the Canary Islands. The facility is pictured in Figure 2-1. ESA-OGS was constructed to support the Semiconductor-laser Inter-satellite Link Experiment (SILEX) [22]. Space-to-ground communication between the GEO telecommunications satellite ARTEMIS and ESA-OGS was first established in 2001 [60]. ESA-OGS has been used extensively in support of lasercom missions including the Laser Utilizing Communications Equipment (LUCE) mission by the Japan Aerospace Exploration Agency (JAXA) launched in 2005 and the French Liaison Optique Laser Aéroportée (LOLA) aircraft-to-space link demonstrated in 2006 [61]. ESA-OGS was one of several optical ground stations utilized in the Lunar Laser Communications Demonstration (LLCD) in 2013, which established lasercom links between a lunar orbiter and Earth [62].

While ESA-OGS originally only supported lasercom links based on intensity modulation, such as on-off keying, it has been retrofitted with adaptive optics to correct atmospheric phase distortion. AO for ESA-OGS was first tested on the Coudé optical bench [63,64], but an assembly is being designed to mount at the Cassegrain focus of the telescope [65,66]. This allows for higher data rates using homodyne binary phase shift keying (BPSK) modulation, which is used by the next-generation lasercom terminals on the European Data Relay System (EDRS) currently being implemented. Initial link acquisition tests between ESA-OGS and two GEO satellites, Alphasat and EDRS-A, were conducted in 2016 [67].

Figure 2-1: The European Space Agency’s Optical Ground Station facility located at the Teide Observatory on Tenerife, Canary Islands, Spain [68].
ESA-OGS has a \( \varnothing 1 \) m Ritchey-Chrétien telescope attached to an English equatorial mount [22], pictured in Figure 2-2. The telescope has a focal ratio of \( f/39 \), which corresponds with a FOV of 2.3 mrad (0.13\(^\circ\)). It has a Coudé path that leads to an enclosed laboratory below the telescope where a \( 5 \times 2 \) m\(^2 \) optical bench contains the receive and transmit optics. An additional assembly is under development to support deep-space lasercom at the range of 0.5 astronomical units [69]. The assembly will mount to a pier at the base of the telescope to bypass Coudé path optical elements and maximize throughput.

![Figure 2-2: The ESA-OGS \( \varnothing 1 \) m telescope on an English equatorial mount [61].](image)

On the Coudé receive path, light from the telescope is collimated and directed onto an FSM that provides steering corrections [22]. A portion of the received signal can be directed onto a wavefront sensor. The remainder of the signal goes through a beam splitter with a pass-through aperture at its center. This aperture is the size of the tracking sensor's FOV, so that if the signal is within the FOV it will pass through; otherwise, the signal is directed to an acquisition sensor with a wider FOV. The signal passing through the beam splitter is directed through an optical isolator for the transmit and receive beams. A final beam splitter divides the signal between the tracking sensor and the receiver/analysis equipment.

The transmitter is a titanium-sapphire laser capable of providing 7 W output power at 847 nm, pumped by an argon laser. A second steering mirror is used for aligning the transmit and receive signals and implementing a point-ahead angle as needed. The transmit signal goes through the optical isolator and couples into the path that the receive signal follows.
During a communications pass, the telescope open-loop tracks the satellite position from known orbital elements. The telescope has an open-loop all-sky pointing accuracy of $\pm 50\, \mu\text{rad} \ (\pm 10\, \text{arcsec})$ [60]. The satellite scans a beacon over its cone of pointing uncertainty and the ground station waits to see a signal on its acquisition sensor. Once the signal is seen, the FSM steers the received signal onto the tracking sensor and the ground station turns on its beacon. If the FSM approaches the edge of its range, it offloads to the telescope mount. When the ground station has locked on to the receive signal, it maintains the signal within four pixels on a tracking sensor which acts as a quadrant detector.

**OCTL**

NASA JPL began construction of OCTL in 1999 to support space-to-ground lasercom missions [70]. OCTL, pictured in Figure 2-3, is located at the Table Mountain Facility in the San Bernardino Mountains in southern California. OCTL conducted a 50 Mbps space-to-ground link with JAXA’s LUCE terminal in 2009 [71]. It was used as one of the ground stations for LLCD to support lunar downlink rates up to 78 Mbps [72]. OCTL was also used for the Optical Payload for Lasercomm Science (OPALS) mission which completed downlinks from the International Space Station (ISS) in 2014.

An adaptive optics system is in the final stages of integration to be used for LCRD [73–75]. LCRD plans to utilize technology from LLCD to establish bidirectional lasercom between a GEO satellite and ground station. Instead of intensity modulation, coherent differential phase shift keying (DPSK) will be used to enable higher data rates. As part of the OPALS project, an adaptive optics system was tested on ISS downlinks to support coupling into single mode fiber [76].

OCTL has a $\varnothing 1\,\text{m}$ telescope attached to a high-speed altazimuth mount with a Coudé room below. The focal ratio of the telescope is $f/76$, corresponding with a diffraction-limited FOV of 500 $\mu\text{rad}$ (103 arcsec) [72]. Co-aligned with the main aperture is a $\varnothing 20\,\text{cm}$, $f/7.5$ Newtonian telescope used for acquisition. This telescope has a FOV of 5 mrad ($0.3^\circ$) and is aligned to well within the FOV of the main telescope. An additional CCD camera with a motorized zoom lens provides a FOV of $34^\circ$ down to $1.7^\circ$ for use in coarse acquisition. Either the wide FOV camera or the acquisition telescope can provide feedback to bring the target within the FOV of the main telescope.

The mount can slew up to 20 deg/s in azimuth and 10 deg/s in altitude, which enables tracking of LEO satellites very close to zenith. OCTL is capable of an all-sky
blind pointing accuracy of 17 µrad (3.5 arcsec) 1-σ and closed-loop tracking capability better than 10 µrad (2 arcsec) RMS [74]. OCTL was able to track OPALS on the ISS to an accuracy of 4.7 µrad (1 arcsec) 1-σ [76].

A mirror along the Coudé path can direct the signal to any of four different optical benches so that simultaneous missions can coordinate time on the telescope. The optical assembly depends on the specific mission, but an FSM is generally used for fine pointing. For LLCD and OPALS, a monostatic configuration was used in which the transmitted signal goes out of the main telescope [72]. In the upgrades to OCTL for use with LCRD, four beacons are coupled into the telescope with a combined divergence of 280 µrad [74]. The AO system consists of two deformable mirrors and a Shack-Hartmann wavefront sensor.

INNOVA

NICT operates several ground stations, which collectively form the IN-orbit and Networked Optical Ground Stations Experimental Verification Advanced Testbed (INNOVA) [77]. The first and largest of these stations is a φ1.5 m telescope constructed in 1988 in Koganei, Tokyo, Japan. Optical links were first demonstrated with the Laser Communication Equipment (LCE) on the Engineering Test Satellite-VI (ETS-VI) from 1994–1996. Laser ranging was conducted with the Reflectometer in Space payload on the Advanced Earth Orbiting Satellite (ADEOS-RIS) from 1996–1997,
the H2A Laser Ranging Equipment (H2A-LRE) and ADEOS-2 satellites from 2002–2003, and the ETS-VIII satellite [78]. LEO-to-ground links were established with the LUCE terminal on the Optical Inter-orbit Communications Engineering Test Satellite (OICETS) in LEO in 2006, followed by a second round of experiments in 2008–2009.

The $\varnothing 1.5$ m telescope has a focal ratio of $f/1.5$ and is driven by an altazimuth mount. The ground station has a Coudé path and detector FOV of 1.5 arcminutes [78]. Mounted within the primary aperture is a $\varnothing 20$ cm guidance telescope with a $0.4^\circ$ FOV. The ground station tracked OICETS to within 2 to 5 arcminutes open-loop and a few arcseconds closed-loop.

For the SOTA experiment, an additional $\varnothing 1$ m telescope was developed nearby in Koganei [79], pictured in Figure 2-4. The telescope is a Cassegrain reflector with a focal ratio of $f/12$. The ground station has multiple focus options, including two Nasmyth foci, two locations on the Coudé path, and a Cassegrain focus. The telescope can closed-loop track LEO satellites to within 10 arcsec. Two additional stations with the same specifications were constructed in Kashima and Okinawa, Japan. These ground stations, along with an additional ground station used for air-to-ground optical communications [80], form the INNOVA testbed [77]. The network enables experiments on site diversity and switching protocol.

![Figure 2-4: NICT's $\varnothing 1$ m optical ground station in Koganei, Japan [81].](image)
2.1.2 Transportable Optical Ground Stations

Existing transportable optical ground stations are described in this section. These include the NASA/MIT Lincoln Laboratory’s Lunar Lasercom Ground Terminal (LLGT), the DLR’s Transportable Optical Ground Station (TOGS), and the Transportable Adaptive Optical Ground Station (TAOGS) by Tesat Spacecom.

LLGT

LLGT was the primary ground terminal developed for LLCD. A 622 Mbps link was established between a lasercom terminal on the Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft and LLGT. The ground station was designed by MIT Lincoln Laboratory and located at the White Sands Missile Range in New Mexico for operations [82]. The ground station was designed to be transportable so that it could be developed near MIT Lincoln Laboratory and then transported to the White Sands location. LLGT has not been in use since the LLCD mission ended with a scheduled crash into the moon in 2014.

The telescope assembly is contained in a clamshell dome and the support equipment is housed in a converted 40 ft shipping container, pictured in Figure 2-5. The telescope assembly consists of four $\varnothing 15$ cm uplink telescopes and four $\varnothing 40$ cm downlink telescopes on an altazimuth mount. Having multiple apertures is a simple way of scaling to a large combined aperture and it provides spatial diversity to mitigate atmospheric effects [83]. Behind each telescope are an FSM and InGaAs focal plane array to allow independent tracking of the downlink with 25 Hz closed-loop bandwidth.

![Figure 2-5: NASA/MIT Lincoln Laboratory’s Lunar Lasercom Ground Terminal pictured in White Sands, New Mexico [84].](image)

The uplink consists of four 10 W optical transmitters with adjustable divergence
angles. The downlink telescopes couple to multi-mode polarization-maintaining fiber which transfer the photons to photon-counting superconducting nanowire arrays [83]. These exotic detectors have demonstrated efficiencies of \( \sim 0.5 \) photon/bit [85] and are critical to the success of LLCD establishing high-rate links at lunar distances.

At the start of a link, the ground and space terminals pointed at each other based on known ephemeris data. After the space terminal saw the ground signal, it corrected its pointing to be seen by LLGT. Both sides of the link would then close in on their targets and initiate communication. This process usually lasted only a few seconds [82].

**TOGS**

DLR developed a transportable ground station to enable near-real-time data transfer from Earth-observing satellites and aircraft [34, 86]. The system was first tested as part of DLR’s VABENE project, in which a 1 Gbps link was established between TOGS and a Dornier 228-212 aircraft [35]. TOGS has also been used to track OPALS on the ISS [55], NICT’s SOTA terminal in LEO [87], and it is the primary ground station for the OSIRIS payload on the BiROS satellite [14].

TOGS has a deployable \( \varnothing 60 \) cm telescope in a Ritchey-Chrétien-Cassegrain configuration with a focal ratio of \( f/2.5 \) [34]. The telescope is supported by an altazimuth mount on a structure with four adjustable legs. The structure has a mass of \( \sim 500 \) kg [88]. The legs can level the mount and compensate for rough terrain. The telescope and mount fold into a truck which provides a means of transportation as well as an operations enclosure. Figure 2-6 shows TOGS in its deployed and folded configurations. To enable rapid calibration, dual-antenna GPS provides initial position and heading information. The mount also contains a tip/tilt sensor.

The optical assembly is mounted behind the telescope. A wide FOV camera is co-aligned with the main aperture to provide coarse feedback [55]. Signal from the telescope is directed by a beam splitter onto a tracking camera and receiver to enable fine pointing. A movable lens allows focus adjustment. TOGS does not employ staged control unlike the other ground stations discussed in this section. When the target is seen on the tracking camera, a correction is applied to the mount. Two 1550 nm, 5 W beacons are co-aligned with the receive telescope to illuminate the target [88].
TAOGS

Tesat Spacecom demonstrated coherent intersatellite laser communications in 2008 between two terminals on LEO satellites, and a modified version of the terminal was placed at ESA’s Tenerife facility to demonstrate space-to-ground coherent communications [50]. A 5.7 Gbps bidirectional link was established with a \( \phi 6.5 \) cm ground aperture and a \( \phi 12.4 \) cm LEO aperture during campaigns in Tenerife and Hawaii. Because the lasercom terminal was designed for intersatellite links using BPSK modulation, the ground terminal size had to be reduced to \( \phi 6.5 \) cm and placed at high altitudes to overcome atmospheric effects [89].

Without adaptive optics the ground station aperture is limited by the Fried parameter, which in turn increases the power required to establish a link. Tesat began developing the larger-aperture TAOGS in partnership with Synopta and DLR. TAOGS has demonstrated 5.7 Gbps communications with LEO satellites and 2.8 Gbps uncoded to GEO satellites [90]. TAOGS consists of an optics container and an operations container as pictured in Figure 2-7.

TAOGS has a receive aperture of \( \phi 27 \) cm and a separate transmit beam that can be adjusted between \( \phi 2 \) cm, \( \phi 3.5 \) cm, and \( \phi 9.5 \) cm. There are two pointing assemblies, one of which contains the receive aperture and can transmit \( \phi 2 \) cm and \( \phi 3.5 \) cm beams. A separate assembly is transmitter-only with a \( \phi 9.5 \) cm beam. A calibration procedure with star sightings is used to calibrate the receive telescope to a pointing accuracy of 50 \( \mu \)rad (10 arcsec), which over time is stable to within 600 \( \mu \)rad (124 arcsec) [90].

TAOGS uses a CMOS camera behind the telescope as an acquisition sensor and an FSM is used for fine steering [91]. A 96-element Shack-Hartmann sensor detects...
the wavefront of the signal and a $12 \times 12$ actuator micro-electro-mechanical (MEMS) deformable mirror applies a correction. A separate mirror is used to implement point-ahead on the transmitted signal.

### 2.1.3 Summary and Research Gap

Table 2.1 summarizes the key parameters of the optical ground stations discussed in Sections 2.1.1 and 2.1.2. While the development costs of these stations are not available in the literature, an estimate is provided by an Interagency Operations Advisory Optical Link Study Group with participants from Centre National d’Études Spatiales (CNES), DLR, ESA, JAXA, Korea Aerospace Research Institute (KARI), and NASA [23]. The group estimated the initial investment costs of a potential $\varnothing 40$ cm ground station for use with LEO satellites to be between $1–5M per site. Part of this cost goes towards weather monitoring, aviation safety systems, and laying the groundwork for wide area communications. PorTeL does not provide any gains in these areas. The remainder of the costs go towards the ground station hardware estimated at $600k and the site facilities which range from $400k–$1M. In these areas PorTeL reduces cost to less than $40k. As a mass estimate, TOGS is about 500 kg excluding the support equipment [88] (in comparison, the NICT’s $\varnothing 1$ m fixed station has a mass of 6800 kg [81]). PorTeL has a mass of $\sim 50$ kg.

PorTeL is at least $10 \times$ less in cost and mass than existing optical ground stations. In other metrics such as pointing and tracking accuracy, environmental robustness, and power collection, existing optical ground stations exceed the capabilities
of PorTeL. The mass and cost comparison primarily suggests that PorTeL targets a tradespace in optical ground station design that has not previously been explored. A low-cost, transportable optical ground station such as PorTeL can fill the gap in this tradespace to address applications such as small satellite lasercom, optical ground networks, and communication for rapid response as discussed in Section 1.1.

Table 2.1: Summary of key parameters of existing optical ground stations. All but LLGT have demonstrated LEO satellite tracking.

<table>
<thead>
<tr>
<th>Name</th>
<th>Org.</th>
<th>Aperture</th>
<th>Mount Type</th>
<th>f-ratio</th>
<th>Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGS</td>
<td>ESA</td>
<td>(\varnothing 1 , \text{m} )</td>
<td>English equatorial</td>
<td>(f/39)</td>
<td>Fixed</td>
</tr>
<tr>
<td>OCTL</td>
<td>JPL</td>
<td>(\varnothing 1 , \text{m} )</td>
<td>Altazimuth</td>
<td>(f/76)</td>
<td>Fixed</td>
</tr>
<tr>
<td>INNOVA</td>
<td>NICT</td>
<td>(3 \times \varnothing 1 , \text{m} ) (1 \times \varnothing 1.5 , \text{m} )</td>
<td>4×Altazimuth</td>
<td>(f/12) (f/1.5)</td>
<td>Fixed (\text{Fixed} )</td>
</tr>
<tr>
<td>LLGT</td>
<td>MITLL</td>
<td>(4 \times \varnothing 40 , \text{cm} ) (4 \times \varnothing 15 , \text{cm} )</td>
<td>1×Altazimuth (co-mounted)</td>
<td>–</td>
<td>Shipping container</td>
</tr>
<tr>
<td>TOGS</td>
<td>DLR</td>
<td>(\varnothing 60 , \text{cm} )</td>
<td>Altazimuth</td>
<td>(f/2.5)</td>
<td>Truck</td>
</tr>
<tr>
<td>TAOGS</td>
<td>Tesat</td>
<td>(1 \times \varnothing 27 , \text{cm} ) (1 \times \varnothing 9.5 , \text{cm} )</td>
<td>2×Altazimuth</td>
<td>–</td>
<td>Shipping container</td>
</tr>
</tbody>
</table>

### 2.2 Portable Telescope for Lasercom

#### 2.2.1 Architecture

The ground station design is intended to be general enough to allow for different telescope and sensor options. The point design is tailored to the requirements of the NODE project, specifically the size of the aperture and the 1550 nm downlink wavelength [20]. However, the approach of using a star camera for rapid alignment as well as the supporting pointing and tracking algorithms are generalizable to any two-axis mount/telescope.

Figure 2-8 shows a block diagram of PorTeL components. The ground station is made up of two separate assemblies, the tracking assembly and the receiver assembly. The tracking assembly consists of an amateur telescope/mount with an attached
star camera and optional guidance camera. The star camera can also function as a guidance camera depending on the downlink wavelength that determines if the detector should be Si or InGaAs. The pointing accuracy of PorTeL, discussed in Section 5.3, is good enough that the target consistently falls within the FOV of the back-end receiver assembly, so a guidance camera is not required. If TLEs are used for orbit determination, however, the resulting error can be larger than the FOV of the receiver assembly and a guidance camera is required.

![Block diagram of the Portable Telescope for Lasercom. The ground station is divided into the coarse stage tracking assembly and the fine stage receiver assembly.](image)

Figure 2-8: Block diagram of the Portable Telescope for Lasercom. The ground station is divided into the coarse stage tracking assembly and the fine stage receiver assembly.

A laptop PC is used to drive the mount. During the calibration process, the laptop processes images from the star camera. The laptop receives encoder feedback from the mount and provides rate commands during tracking.

The receiver assembly does the fine pointing and is mounted behind the telescope. It consists of a fast-steering mirror, tracking camera, and APD receiver. The laptop provides digital tip/tilt commands which are converted to analog voltage to drive the FSM. The downlink signal is split between the tracking camera and the receiver. Tracking camera feedback is processed by the laptop to provide steering commands to the FSM. The laptop is not used to receive communications data, but power measurements from the APD are used to determine its alignment with the tracking camera.

Not included in the block diagram is a beacon uplink, which is still under de-
velopment. An 850 nm uplink beacon is planned for NODE \[92\]. Another effort in STAR Lab has examined using an LED array as a beacon \[93\]. The LED beacon was successfully seen by the AeroCube-5 LEO satellite. An LED array is cheaper and easier to point compared with a laser beacon and avoids some of the regulatory concerns of lasers.

2.2.2 Hardware

Tracking Assembly

The amateur telescope selected for development at MIT is the Celestron CPC1100. As shown in Figure 2-8, the telescope/mount must accept rate commands from external software and provide encoder measurements of the gimbal angles. This makes some popular amateur suppliers unsuitable for this application.

The \( \varnothing 11'' \) (\( \varnothing 28 \text{ cm} \)) Schmidt-Cassegrain telescope comes with an altazimuth mount. The telescope has a focal ratio of \( f/10 \), corresponding with a field of view of 0.6°. Depending on the load, the maximum slew rate of the mount is 4.5 deg/s in each axis. This places a limitation on how close to zenith the mount is able to track (refer to Figure 1-5). For a LEO satellite in a 400 km orbit, such as the ISS, the CPC1100 can track just past 75° at which point the azimuth slew rate saturates.

Mounted to the telescope is an iNova PLB-Mx2 camera used as a star tracker. A \( \varnothing 25 \text{ mm} \) lens with a 35 mm focal length is paired with the camera, resulting in a FOV of 7.8° × 5.9° and a plate scale of 22 arcsec/pixel. The telescope with the star tracker mounted on top is shown on the roof of MIT Building 37 in Figure 2-9.

Receiver Assembly

The receiver assembly contains an FSM, tracking detector, and APD receiver. The FSM is an Optics In Motion (OIM) 1” mirror driven by voice coils with a throw of \( \pm 1.5° \). The bandwidth is >850 Hz with an angular resolution better than 2 µrad.

The receiver is a Voxel RDC1-NJAF APD. This APD has a 200 micron sensor and a bandwidth of 300 MHz. The details of the receiver selection can be found in \[18\] but its key advantages are low noise and high bandwidth.

The infrared (IR) tracking camera is a Sensors Unlimited Micro SWIR 320CSX. It is an InGaAs camera with \( 320 \times 256 \) pixels with a 12.5 micron pitch, resulting in an \( 4.0 \times 3.2 \text{ mm}^2 \) active area. Coupled with the telescope, the full FOV of the detector is 295 × 236 arcsec\(^2\) and the plate scale is 0.92 arcsec/pixel. The camera was selected for its high sensitivity and full-frame readout rate of 60 Hz.
The hardware is mounted to the telescope on an optical breadboard, shown in Figure 2-10. The breadboard attaches to the CPC1100 with custom brackets (designed by Tao Sevigny) that attach to existing mounting holes on the telescope. The FSM is mounted along the boresight of the telescope at a 45° angle which brings the signal into the plane of the optical breadboard. A beam splitter divides the signal between the tracking camera and APD. A segment of the optical breadboard is removed to reduce mass and to make the manual focus adjuster accessible.

One of the major design challenges of the receiver assembly is that it must be compact enough mount on the back of the amateur telescope. It is not possible to have a Coudé or Nasmyth focus that many optical ground stations utilize, so the components must be small and lightweight. Because of the limited space and long focal length (2.8 m) of the telescope, collimating optics are not used. The tracking camera and receiver are placed directly at the telescope’s focus. The primary disadvantage of this design is that the signal does not stay centered on the FSM and the FSM’s range is limited in providing steering corrections.

A basic Zemax model of the telescope and receiver assembly was developed to determine the required pointing accuracy of the telescope. From this model it was determined that at 0.1° off-axis, the signal begins to walk off of the FSM. Beyond 0.15° off-axis, the FSM can no longer steer the signal onto the detector. Therefore,
Figure 2-10: PorTeL receiver assembly mounted behind the telescope. A Thorlabs APD used for testing is shown in the image in place of the Voxtel APD.

the pointing requirement of the tracking assembly is set at $\pm 360$ arcsec $3\sigma$.

**Laptop, GPS, and Battery**

The mount, star camera, FSM, and tracking camera are controlled from a Dell Precision M4800 workstation Laptop with 8 GB of RAM and a 2.80 GHz Quad Core Processor. The PC has four USB interfaces that are all utilized during operation and an ExpressCard slot that is used to interface to the IR camera.

The CPC1100 and iNova camera connect to the PC on serial links over USB. The OIM FSM is driven with a 0–5 V input line in each axis. To produce the analog signal, a custom interface board (designed by Greg Allan) uses an FT4222H USB-to-SPI chip and two AD660BRZ digital-to-analog chips. The PC provides serial over USB input which is converted to the desired analog input to the FSM controller provided by the supplier. An Imperx VCE-CLEX01 frame grabber is used to interface between the PC and the Sensors Unlimited IR camera with Camera Link standard protocol [94].

Two optional accessories may be used with the setup. A GlobalSat BU-353-S4 USB GPS Receiver can be used to provide the latitude and longitude of the ground station position if it is not known *a priori*. The GPS also provides a timing reference to synchronize the PC clock. The program NMEATime2 is used for this purpose, although synchronizing the clock via GPS is not required. The majority of the results from Chapter 5 were acquired without the external GPS reference. If an Internet connection is available, a National Institute of Standards and Technology
(NIST) program can synchronize the PC clock by querying an Internet time server. This approach was used for the majority of satellite tracking experiments.

Another optional accessory is a portable battery to power the setup. A Goal Zero Yeti 400 Portable Power Station can power the setup if dedicated power is not available. The Yeti 400 stores 400 Wh, weighs just under 30 lbs, and has two USB ports, two AC ports, and a 12 V DC port. The maximum power draw of all components apart from the laptop is 40 W. The ground station has been powered by the battery for 3 hours without issue and could run comfortably for several more hours, though longer periods have not been attempted.

**User Interface**

A graphical user interface developed in Visual Studio, shown in Figure 2-11, is used to execute all ground station activity. Software is implemented in a combination of C, C++, and C#. To operate the ground station, the user must initiate connections to the hardware, specifically the CPC1100, the iNova star tracker, the Sensors Unlimited IR tracking camera, and the OIM FSM driver board. The user determines the pixel in the star camera that corresponds with the center of the tracking detector, as described in Section 5.1.1. The selected pixel sets the LOS of the telescope in the star tracker.

The user can elect to do an automated calibration of the pointing model, which will initiate a 10-minute procedure to slew to a series of points, take star camera images, and calculate pointing model parameters (refer to Section 5.2 for an in-depth discussion of the calibration procedure). Once this procedure has been completed, the setup is ready to track objects. The user can request a list of the brightest stars visible based on the current time and position and select one to track.

To track a satellite, the user manually loads a TLE file and requests tracking. The telescope slews to the location that the satellite will appear at 5° above the horizon and waits. When tracking a satellite or star, closed-loop feedback is initiated by the user. For coarse feedback with the star camera, an image is taken every 2 seconds, the brightest object is identified, and a correction is applied to the LOS of the telescope in the star tracker frame to center the object. The user also initiates fine tracking with the FSM. The FSM conducts a spiral scan until the target is seen in the tracking detector. Once it is seen, feedback is automatically applied at 60 Hz. The user may also trigger offloading of the FSM to the telescope to ensure that the coarse stage tracking stays within the range of the fine stage.

In the current version of the software, these controller transitions are all initiated manually. Future work that aims to automate these transitions would be a useful
Automating the process would require a metric to assess that the identified object is the correct target and a process to recover if the target is lost.

**Cost**

Table 2.2 provides a cost overview of PorTeL. The overall hardware cost is $31,400 per station. The most expensive component is the IR tracking detector which makes up nearly half of the cost of the ground station. A less sensitive detector could be used to reduce cost. This may lower the fine control bandwidth if longer integration times are needed, and this trade should be studied based on the detailed link budget.
Table 2.2: PorTeL hardware cost summary.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Celestron CPC1100</td>
<td>$3,000</td>
<td>COTS 11” telescope/mount</td>
</tr>
<tr>
<td>iNova PLB-Mx2</td>
<td>$300</td>
<td>Star camera</td>
</tr>
<tr>
<td>OIM 1” FSM</td>
<td>$3,900</td>
<td>Tip/tilt voice coil driven FSM</td>
</tr>
<tr>
<td>Vooxel RDC1-NJAF APD and W001-0J0D support module</td>
<td>$4,250</td>
<td>InGaAs APD receiver</td>
</tr>
<tr>
<td>Sensors Unlimited</td>
<td>$15,000</td>
<td>InGaAs tracking camera</td>
</tr>
<tr>
<td>Micro-SWIR 320CSX</td>
<td>$2,500</td>
<td>Laptop PC</td>
</tr>
<tr>
<td>Optomechanical accessories</td>
<td>$1,000</td>
<td>Beam splitter, optical breadboard, etc.</td>
</tr>
<tr>
<td>Support electronics</td>
<td>$1,000</td>
<td>Driver boards, cables, etc.</td>
</tr>
<tr>
<td>Goal Zero Yeti 400</td>
<td>$450</td>
<td>Portable power supply</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$31,400</strong></td>
<td></td>
</tr>
</tbody>
</table>

2.2.3 Pointing and Tracking Requirements

The pointing and tracking requirements of PorTeL are summarized in Table 2.3. Figure 2-12 shows a diagram of the requirements and their relationship to the FOV of the receiver assembly components.

Table 2.3: PorTeL pointing and tracking requirements.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Set up of PorTeL, including calibration, shall take less than one hour</td>
<td>Rapid deployment is critical to portability</td>
</tr>
<tr>
<td>2) The open-loop pointing error of the telescope shall be 100 arcseconds RMS or better</td>
<td>The signal must fall within the FOV of the receiver assembly</td>
</tr>
<tr>
<td>3) The closed-loop coarse tracking error of the telescope shall be at most ±360 arcseconds 3-σ</td>
<td>The coarse stage must hold the signal within the FOV of the receiver assembly</td>
</tr>
<tr>
<td>4) The closed-loop combined coarse and fine tracking error shall be at most ±7.4 arcseconds 3-σ</td>
<td>The signal must stay on the receiver</td>
</tr>
</tbody>
</table>

Requirement #1 states that PorTeL must take less than one hour to deploy. This is motivated by the desire for portability, and also because the use of an amateur telescope with incremental encoders demands fast calibration. A one hour setup time allows the telescope to be deployed and repacked in a single night.
Figure 2-12: Diagram of pointing and tracking requirements for PorTeL, drawn to scale. The gray circle shows the receiver assembly FOV which dictates requirement #3. The green rectangle is the tracking camera FOV, and the red circle shows requirement #2. The blue is the receiver assembly FOV which dictates requirement #4.

Requirement #2 states that the open loop pointing accuracy must be 100 arcsec RMS or better. At ±360 arcsec off-axis, the received signal begins to walk off of the FSM. A blind pointing accuracy within 100 arcsec RMS ensures that the target falls within the FOV of the receiver assembly. The FOV of the tracking detector is ±118 arcsec in its smallest axis, so a 100 arcsec RMS blind pointing accuracy ensures that most of the time the signal will be detected immediately and an FSM scan will not be necessary.

Requirement #3 places an upper bound of ±360 arcsec 3-σ on the closed-loop coarse tracking error. The coarse stage must maintain the signal within the FOV of the receiver assembly, which is ±360 arcsec.

Requirement #4 places an upper bound of ±7.4 arcsec 3-σ on the combined coarse and fine tracking error. The area of the APD receiver is 200 microns, and when paired to the telescope its FOV is ±7.4 arcsec. The ground station must hold the signal on the receiver.
Chapter 3

Pointing Model

Telescope control can be split into two segments, “pointing” and “tracking.” Pointing refers to the period before the target is acquired, while tracking describes the period after acquisition. To achieve accurate pointing, a telescope control system relies on a pointing model to determine the gimbal angles that point the telescope towards a desired target whose location is given by an inertial vector. Pointing models for professional-class telescopes enable arcsecond-level pointing, but they assume a fixed initial mount/telescope orientation and take several hours to calibrate. The pointing model developed in this chapter aims to maintain the fidelity of professional software while eliminating orientation assumptions and speeding up the calibration process.

This chapter provides background on telescope pointing control in professional- and amateur-class telescopes. After identifying the relationship between the PorTeL pointing approach and existing approaches, the pointing model, calibration strategy, and mount angle/rate commands to drive the telescope are presented. It may be useful for the reader to refer to Appendices A and B for a description of the vector notation and quaternion conventions used in this chapter.

3.1 Problem Description

The pointing model is at the core of the “virtual telescope” concept. This concept was proposed in the 1970s by the designers of the Anglo-Australian Telescope [95,96], and it allows for modular and user-friendly control system software. A virtual telescope module behaves as a perfect telescope; all the messy transformations and corrections needed to point the physical telescope are contained within it. High-accuracy telescope pointing models include parameters that describe the mount/telescope orientation as well as common static and dynamic mechanical effects.
The block diagram in Fig. 3-1 summarizes the basic pointing problem. Inputs to the pointing model are the current time, location of the telescope, target vector in the inertial frame, and desired vector in the detector frame (e.g., boresight). The pointing model consists of a series of rotations that relate the inertial frame to the detector frame, and the gimbal angles appear within these rotations. If a trajectory is desired, gimbal rates can be determined by differentiating the pointing model equations.

Figure 3-1: Block diagram showing the basic telescope pointing problem of how to generate gimbal commands. The current time, location of the telescope, target vector in the inertial frame, and desired target location in the detector are taken as inputs. The pointing model consists of a series of rotations that relate the inertial frame to the detector frame. Contained in these rotations are the desired gimbal angles, which can be determined analytically.

To point a telescope towards a desired object, the coordinates of the object must first be determined in an Earth-centered inertial or quasi-inertial reference frame (e.g., J2000) [97]. There are several transformations that go into determining the appropriate target coordinates that include precession, nutation, aberration, sidereal time, and refraction through the atmosphere [53]. Positional astronomy libraries such as SLALIB [98] and NOVAS [99] can assist with these transformations. Though the astrometric and detector models that go into producing the target vectors are non-trivial, they are not the focus of this work and we assume the appropriate target vectors have been calculated.

There are two mathematically different approaches to developing the pointing model. A simple approach is to determine the gimbal angles for an ideal telescope and then apply small additive corrections to generate the commanded gimbal angles. This requires linearization of the pointing model. This simplified approach is sufficient for small corrections but ignores the coupling between corrective terms. A more rigorous approach is to pose the full problem in matrix/vector form and solve these equations for the commanded gimbal angles.
3.2 Literature Review

3.2.1 Professional Telescopes

Computer-based telescope pointing has been in use since at least the 1960s, and the basic principles have remained the same over time [100]. Existing software such as TPOINT can develop a pointing model with common error terms based on a series of star observations. TPOINT is used worldwide on professional observatories, including the $\varnothing3.9$ m Anglo-Australian Telescope [95], the $2 \times \varnothing10$ m Keck Telescopes [101, 102], the $2 \times \varnothing8.2$ m Gemini Telescopes [103], the $\varnothing4$ m SOAR Telescope [104], the $4 \times \varnothing8.2$ m Very Large Telescope [105], the Green Bank $\varnothing100$ m Telescope [106], the $66 \times \varnothing12$ m/$\varnothing7$ m Atacama Large Millimeter Array [107], the $\varnothing4.2$ m William Herschel Telescope [108], the $\varnothing4$ m Mayall Telescope [109], the $\varnothing4$ m CTIO Blanco Telescope [110], the $\varnothing4.1$ m Visible and Infrared Survey Telescope for Astronomy [111], and according to [112] the $\varnothing3.5$ m ARC Telescope, the $\varnothing3.5$ m WIYN Telescope, the $\varnothing3.8$ m United Kingdom Infrared Telescope, the $\varnothing76.2$ m Lovell Telescope, the $\varnothing3$ m NASA Infrared Telescope Facility, the $\varnothing6.5$ m Multiple Mirror Telescope, the $2 \times \varnothing6.5$ m Magellan Telescopes, and the $2 \times \varnothing8.4$ m Large Binocular Telescope. Using TPOINT, many telescopes can point with arcsecond-level accuracy.

A revised version of the TPOINT software was proposed by the original developer P. Wallace that condenses the prior versions into a 7-term summary model [53]. The accompanying software framework is described in [104, 113]. While the prior version had many terms which each applied a linear correction [$\Delta Az, \Delta El$] to the commanded mount angles, the revised model is based on a more rigorous matrix/vector formulation. Wallace also provided a very simple pointing model that produces linear corrections based on the seven terms [114]. The pointing model for the $\varnothing120$ ft Haystack antenna, which predates TPOINT, also used a 7-term model with a slightly different formulation [115].

Professional telescopes are usually altazimuth or equatorial mounts, and TPOINT software generalizes to any two-axis gimbal mount as long as the orientation is specified. It is worth noting that the model relies on a concept of nominal orientation. For example, an altazimuth telescope is considered to be nominally level with a zero azimuth angle pointing North. The parameters of the model are linearized and fit based off of this nominal orientation. If the telescope is too far from the nominal orientation it must be physically readjusted.

The pointing model from [53] includes the following seven terms: roll index er-
ror (IA), pitch index error (IB), vertical deflection (VD), optical telescope assembly/pitch non-perpendicularity (CA), roll/pitch non-perpendicularity (NP), and two terms for roll axis misalignment (AW, AN). The transformation chain is shown in Figure 3-2 (from [53]).

![Figure 3-2: The chain of pointing transformations in the pointing algorithm proposed by P. Wallace [53]. The boxes show vectors in intermediate frames while the italics show the transformations between vectors.](image)

There are three key coordinate sets in the chain: the target direction \([\alpha, \delta]\) (i.e. azimuth, elevation), the mount encoder readings \([A, B]\), and the pointing-origin \([x, y]\). Knowing two of these coordinate sets can provide the third. The typical pointing problem is knowing the target direction and the pointing-origin which allows calculation of the desired mount encoder readings. This is the problem formulation shown.
in Figure 3-1, but guiding corrections can be applied at multiple points.

The first two terms are the roll index error (IA) and pitch index error (IB). These terms describe when the true zero position of the pitch and roll axes is perturbed from the nominal orientation. For example, a zero-azimuth reading for an altazimuth mount should correspond with due North, but the zero-azimuth position may point slightly east or west of North. This would be captured in the roll index error (IA) term. Likewise, the zero position of the elevation axis should lie on the horizon. If it is slightly above or below the horizon, this is captured in the pitch index error (IB) term. These terms act as additive corrections to the encoder readings.

The vertical deflection (VD) term captures the tendency of the telescope to droop due to gravity. The deflection is proportional to the cosine of the elevation angle. Since this term is attitude dependent it must be recalculated every few seconds. The optical telescope assembly/pitch non-perpendicularity (CA) corrects the assumption that the pitch axis and the boresight of the telescope are perpendicular, when in reality they may not be. The second non-perpendicularity term is the roll/pitch non-perpendicularity. While the two gimbal axes are nominally perpendicular, they may be slightly misaligned which is captured in this term.

Finally, there are two terms for the roll axis misalignment (AW, AN). For example, an altazimuth telescope should have a level base such that the azimuth gimbal axis points downwards, but it may be tilted towards the North or towards the West. Combined, these seven terms are used in the pointing model to generate desired encoder readings to steer the telescope towards the target. In TPOINT software there are also harmonic terms that can be used to clean up remaining residuals.

To fit the pointing model, it is typical to sight 50–100 stars by either centering them manually or doing a plate-solve to determine where the telescope was pointed on the sky [100]. The measurements are then used to calculate the appropriate terms in the pointing model. This process takes several hours but only needs to be redone on a timescale of weeks.

### 3.2.2 Amateur Telescopes

Amateur telescopes must be calibrated much more often than professional telescopes for two main reasons. First, professional telescopes have dedicated observatories while amateur telescopes are usually deployed in less controlled environments. Second, professional telescopes have absolute encoders (or at least some form of “zero-set”), so that the orientation information is never lost [112]. Many low-cost amateur telescopes
have incremental encoders, so on powering up the telescope there is no information on orientation and the telescope must be realigned.

Many amateur telescopes can be purchased with a built-in computerized alignment procedure. Due to the need for frequent recalibration, the procedure must be easy and quick for the user. The alignment procedures for two major amateur telescope providers, Celestron and Meade, are discussed in this section. While the internal pointing models are not publicly documented, examining the alignment procedure provides some insight into the pointing approach.

The Celestron CPC series provides computerized “Go To” and tracking capabilities for a database of objects [116]. The CPC comes with a GPS to determine position and time. The telescopes have incremental encoders, so the position of the telescope on startup becomes the zero azimuth, zero altitude position.

There are several options available to the user for alignment. The most simple is the One-Star Align, where a single star is identified by the user and centered in the eyepiece (or detector). This measurement constrains two degrees of freedom (DOF) and assumes the telescope is level to constrain the third degree of freedom. This is the minimum amount of information needed to provide mount orientation. Other available procedures include a Two-Star Align and also a SkyAlign procedure. While One-Star and Two-Star Align require that a star be identified by the user, SkyAlign does not require that any stars be user-identified. Given three stars centered in the eyepiece/detector behind the telescope, the software can search a database to identify the stars and provide a unique mount orientation.

Celestron also offers an accessory, StarSense [117], that makes the alignment procedure more autonomous. StarSense is an externally mounted camera with a field of view of $6.88^\circ \times 5.16^\circ$. The telescope slews to a position, takes an image, and automatically matches the stars in the image with a database. The user must manually center a target so that the eyepiece location can be recorded in the StarSense software.

Considering that in all cases only one measurement is required to align, it is likely that the software is only estimating the roll and pitch zero position, and additional star sightings are used to improve the accuracy of this estimate. There may be more complexity to the pointing model internally, but in the simplest case only two degrees of freedom are determined.

The Meade LX200 series provides similar computerized functionality to the Celestron CPC series [118]. As with the CPC series, the encoders are incremental. The LX200 is also equipped with GPS and has additional true-level and true-North sensors. The telescope offers an Auto Align feature. It uses its sensors to find the tip/tilt
of the mount and the direction of magnetic North, and also gets a GPS reading. These
measurements alone are enough to provide an initial mount orientation. The program
then slews to two different stars for the user to center in the eyepiece/detector.

Alternatives to the Auto Align feature are a manual one- or two-star alignment
which does not use sensor information, and therefore requires manual leveling of the
telescope base. This is the same procedure as described with the Celestron mount.
The LX200 series has sensors that the CPC series does not have, and does not assume
that the telescope base must be level. However, the small number of star sightings
indicates that the complexity of the pointing model is limited.

These built-in alignment procedures only take a few minutes. Their accuracy is
hard to assess because they depend on the user. Additionally, when only one or two
stars are selected for alignment, the locations of these stars affect the accuracy of the
procedure. Tests conducted by MIT STAR Lab with a carefully-leveled CPC1100
using the two-star alignment procedure yielded accuracy ranging from 150–800 arc-
sec [119], and performance is only guaranteed by Celestron to within 1200 arcsec
(from personal communication).

While the built-in alignment software for amateur telescopes relies on fairly simple
pointing models, there are software options for higher fidelity models. For example,
Software Bisque provides TheSkyX software that includes telescope models based on
TPOINT [112, 120]. This achieves better accuracy, but has the same drawbacks of
nominal orientation assumptions and time to calibrate.

3.2.3 Research Gap

When developing an optical ground station with a low-cost, COTS telescope, the de-
sired performance is nearly professional-level. The performance of built-in alignment
software for amateur telescopes is not good enough to ensure a lasercom signal can
be detected.

There are also drawbacks to using professional software. The calibration procedure
for professional telescopes is time-consuming, requiring dozens of star sightings. While
this is reasonable for observatories that only need to recalibrate infrequently, it is much
less suitable for an amateur telescope. With incremental encoders, power cycling the
telescope requires recalibration.

The approach of professional software also poses a disadvantage for the portability
of an optical ground station. A rapid calibration procedure that minimizes manual
work such as leveling and alignment is important. A substantial amount of time can
be saved by eliminating assumptions about nominal orientation in software.

In the following sections, an automated, rapid, and high-fidelity calibration procedure for a portable optical ground station is developed. This calibration procedure utilizes an externally mounted star tracker. Star trackers have been used for amateur telescopes, such as Celestron’s StarSense, but their primary purpose is to eliminate the need for user identification of stars rather than improve pointing model fidelity. Star trackers have also been used as a method of low-cost feedback for larger telescopes, such as WIYN [121], but not as the primary means of calibration.

The calibration approach developed in this thesis is based off of the work in [122], but is augmented to include the seven pointing model terms in professional software highlighted by Wallace [53]. There are three key benefits of the pointing model formulation presented in this work compared with existing approaches: 1) the pointing model is tailored for use with a star tracker to greatly speed up calibration while maintaining model fidelity, 2) the pointing model makes no assumptions about the mount type or orientation which minimizes manual set up time, and 3) the gimbal angle and rate commands are derived analytically from the pointing model.

While using a star tracker allows for fast calibration, there are disadvantages to not using the primary aperture. Any misalignment between the star tracker and telescope boresight as a function of attitude is not accounted for unless modeled separately. For very precise pointing this will limit performance. If additional precision is desired, a combination of star tracker measurements and measurements from the detector behind the telescope can be used to fit the pointing model. This will increase the time required to calibrate, but it still retains the benefit of eliminating assumptions about nominal orientation.

3.3 Formulation

The reference frames relevant to the derivation of the pointing model are defined here. They are presented in the order in which they are applied in the pointing model.

1. J2000 (J2K) Frame
   The J2000 frame is an Earth-centered inertial (ECI) frame. The fundamental plane of this frame is the equator, and the \textbf{X} axis points towards the vernal equinox. The \textbf{Z} axis points through the North Pole, and the \textbf{Y} axis forms a right-handed set 90° east of the \textbf{X} axis. These directions are fixed with the mean equator and equinox at 12:00 Terrestrial Time on January 1, 2000.
2. East-North-Up (ENU) Frame

The ENU frame provides local horizontal coordinates. It is centered at the telescope site. The $X$ axis is defined as East, the $Y$ axis as North, and the $Z$ axis forms a right-handed set towards zenith. The transformation from the J2000 frame to the ENU frame changes constantly as the Earth rotates.

3. Mount frame (MNT)

The $Y$ axis is defined by the azimuth gimbal rotation axis. The $Z$ axis is defined as the cross product between the altitude and azimuth gimbal axes at the time the telescope is powered on. The $X$ axis forms a right-handed set.

4. Gimbaled frame (GIM)

The gimbaled frame axes are the mount frame axes rotated through gimbal azimuth $\psi$ and altitude $\alpha$ as read by the encoders. Note that a non-perpendicularity between the azimuth and altitude axes of the gimbals is allowed.

5. Star tracker nominal frame (ST)

The $X$ and $Y$ axes are defined by the $X$ and $Y$ directions in the star tracker focal plane. The $Z$ axis forms a right-handed set. The star tracker is mounted externally to the telescope.

6. Observed frame (OBS)

This frame is the nominal star tracker frame rotated about a vector defined by the cross product of zenith and the telescope boresight. This contains the vertical deflection of the telescope due to gravity as well as the effect of atmospheric refraction.

Each star tracker image yields a quaternion rotation between the J2000 frame and the observed frame. A star camera measurement at time $t$ is given by:

$$
\text{OBS} q_{\text{J2K}}(t) = q_n \otimes \text{OBS} q_{\text{ST}}(t) \otimes \text{ST} q_{\text{GIM}} \otimes \text{GIM} q_{\text{MNT}}(t) \otimes \text{MNT} q_{\text{ENU}} \otimes \text{ENU} q_{\text{J2K}}(t) \quad (3.1)
$$

where $q_n$ is the star tracker measurement noise. Refer to Appendix B for a description of the quaternion conventions and notation used in this section.

The rotation from the J2000 to ENU frame, $\text{ENU} q_{\text{J2K}}(t)$, can be calculated using the International Earth Rotation and Reference Systems Service (IERS) model [97]. The other rotations contain unknown calibration parameters which will be defined.

The rotation from the ENU frame to the mount frame, $\text{MNT} q_{\text{ENU}}$, is unknown and must be estimated fully (3 DOF). The rotation from the mount frame to the gimbaled
frame is given by a rotation through the known azimuth and altitude gimbal angles, ψ(t) and α(t), which can be read out from the encoders. A non-perpendicularity between the gimbal axes is accounted for by introducing a rotation angle $\theta_{NP}$ in the XY plane of the mount frame (1 DOF). Overall, the rotation from the mount frame to the gimbaled frame is given by:

$$\mathbf{GIM}_{MNT}(t) = \mathbf{q}_{NP} \otimes \mathbf{q}_{alt}(t) \otimes \mathbf{q}_{NP}^{-1} \otimes \mathbf{q}_{azi}(t)$$

(3.2)

The azimuth rotation is given by:

$$\mathbf{q}_{azi}(t) = \begin{bmatrix} 0 & \sin(\psi(t)/2) & 0 & \cos(\psi(t)/2) \end{bmatrix}^T$$

(3.3)

The altitude rotation is given by:

$$\mathbf{q}_{alt}(t) = \begin{bmatrix} \sin(\alpha(t)/2) & 0 & 0 & \cos(\alpha(t)/2) \end{bmatrix}^T$$

(3.4)

The non-perpendicularity between the gimbal axes is given by:

$$\mathbf{q}_{NP} = \begin{bmatrix} 0 & 0 & -\sin(\theta_{NP}) & \cos(\theta_{NP}) \end{bmatrix}^T$$

(3.5)

Equations 3.2–3.5 define the rotation from the mount frame to the gimbaled frame, which contains one unknown, $\theta_{NP}$.

The next rotation is from the gimbaled frame to the star tracker frame, $\mathbf{ST}_{GIM}$. This rotation is unknown and must be estimated fully (3 DOF). It is particularly relevant to account for this unknown in the case of telescopes with incremental encoders because the zero position of the telescope is arbitrary upon startup.

The rotation from the star tracker frame to the observed frame is given by a vertical deflection due to gravity followed by a correction for atmospheric refraction. An unknown vertical deflection coefficient, $a_d$, is introduced (1 DOF). Additionally, the term $\mathbf{u}_d$ is introduced, which is the axis about which vertical deflection occurs defined in the star tracker frame. It is given by the normalized cross product of zenith and the telescope boresight:

$$\mathbf{u}_d(t) = \frac{\left( \mathbf{A}^{\text{OBS}}(\mathbf{q}_{ENU}(t)) \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T \right) \times \mathbf{u}_{tel|OBS}}{\left\| \left( \mathbf{A}^{\text{OBS}}(\mathbf{q}_{ENU}(t)) \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T \right) \times \mathbf{u}_{tel|OBS} \right\|}$$

(3.6)
where $\mathbf{u}_{\text{tel}}|_{\text{OBS}}$ is the telescope boresight unit vector as observed in the star tracker. This vector is determined by an inter-camera alignment procedure described in Section 5.1.1.

The rotation from the star tracker frame to the observed frame is described by:

$$
\mathbf{q}_{\text{ST}}^\text{OBS}(t) = \mathbf{q}_{\text{atm}} \otimes \begin{bmatrix}
\sin(a_d \cos(\alpha_{\text{obs}}(t))/2) \mathbf{u}_d(t) \\
\cos(a_d \cos(\alpha_{\text{obs}}(t))/2)
\end{bmatrix}
$$

(3.7)

where $\mathbf{q}_{\text{atm}}$ is the atmospheric refraction and $\alpha_{\text{obs}}(t)$ is the elevation in the local horizontal frame (note that this is not the same as the altitude gimbal reading). To calculate the atmospheric refraction, a simple model developed by Bennett [123] is applied:

$$
\theta_{\text{atm}} = \cot \left( h_a + \frac{7.31}{h_a + 4.4} \right)
$$

(3.8)

where $h_a$ is the apparent altitude in degrees and $\theta_{\text{atm}}$ is the atmospheric refraction in arcminutes. The rotation axis is given by Equation 3.6. Given the rotation axis and angle, $\mathbf{q}_{\text{atm}}$ can be calculated using Equation B.4. A higher fidelity atmospheric refraction model can be used if desired, but it is not necessary to use with the PorTeL telescope as the hardware introduces substantially larger errors.

In summary, the unknowns that must be estimated are $\mathbf{MNTq}_{\text{ENU}}$, $\theta_{\text{NP}}$, $\mathbf{STq}_{\text{GIM}}$, and $a_d$ for a total of 8 DOF. The relationship between these parameters and the parameters in TPOINT software (as described in Section 3.2.1) are shown in Table 3.1. The PorTeL parameters encompass those from the condensed TPOINT model. One additional degree of freedom is included in the $\mathbf{STq}_{\text{GIM}}$ term, which accounts for a rotation of the star tracker about boresight.

Table 3.1: Summary of the eight pointing model degrees of freedom and how they relate to corresponding TPOINT terms. PorTeL pointing model covers the same degrees of freedom as [53] plus one additional degree of freedom in the $\mathbf{STq}_{\text{GIM}}$ term that accounts for a rotation of the star tracker about boresight.

<table>
<thead>
<tr>
<th>PorTeL parameter</th>
<th>TPOINT parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathbf{MNTq}_{\text{ENU}}$</td>
<td>AW, AN, IA</td>
<td>Orientation of mount relative to local horizontal</td>
</tr>
<tr>
<td>$\theta_{\text{NP}}$</td>
<td>NP</td>
<td>Altitude/azimuth gimbal non-perpendicularity</td>
</tr>
<tr>
<td>$\mathbf{STq}_{\text{GIM}}$</td>
<td>IB, CA</td>
<td>Orientation of telescope relative to gimbal frame</td>
</tr>
<tr>
<td>$a_d$</td>
<td>VD</td>
<td>Vertical deflection</td>
</tr>
</tbody>
</table>
3.4 Calibration

3.4.1 Coarse Calibration

Coarse calibration provides an initial state estimate for fine calibration. It utilizes a series of star tracker measurements as modeled in Equation 3.1. For coarse calibration, several assumptions are made. Measurement noise is ignored, vertical deflection is ignored (i.e. the deflection coefficient $a_d$ is assumed to be zero), and the rotation axis non-perpendicularity $\theta_{NP}$ is assumed to be zero such that $\text{GIM} q_{\text{MNT}}$ is known from the encoder output. Under these assumptions, the remaining unknowns in Equation 3.1 are $\text{ST} q_{\text{GIM}}$ and $\text{MNT} q_{\text{ENU}}$, which must be estimated.

The $i^{th}$ star camera measurement in the form of $\text{OBS} q_{\text{J2K},i}$ is multiplied by known transformations into the form $\text{ST} q_{\text{ENU},i}$. Given an $i^{th}$ and $j^{th}$ measurement, they can be used to estimate $\text{ST} q_{\text{GIM}}$ with the following:

$$\text{ST} q_{\text{ENU},i} \otimes \text{ST} q_{\text{ENU},j}^{-1} = \text{ST} q_{\text{GIM}} \otimes \text{GIM} q_{\text{MNT},i} \otimes \text{GIM} q_{\text{MNT},j}^{-1} \otimes \text{ST} q_{\text{GIM}}^{-1} \quad (3.9)$$

Using the quaternion property in Equation B.5, Equation 3.9 can be written as:

$$\text{ST} q_{\text{ENU},i} \otimes \text{ST} q_{\text{ENU},j}^{-1} = \begin{bmatrix} A^\text{(ST} q_{\text{GIM})} & 0 \\ 0 & 1 \end{bmatrix} \text{GIM} q_{\text{MNT},i} \otimes \text{GIM} q_{\text{MNT},j}^{-1} \quad (3.10)$$

By pairing star tracker measurements to calculate the quaternions in Equation 3.10, the problem transforms into one of attitude determination given a set of vector measurements. A method such as QUEST [124] can then be applied to estimate $\text{ST} q_{\text{GIM}}$.

Similarly, $\text{MNT} q_{\text{ENU}}$ can be estimated with the following:

$$\text{ST} q_{\text{ENU},i}^{-1} \otimes \text{ST} q_{\text{ENU},j} = \begin{bmatrix} A^\text{(MNT} q_{\text{ENU})} & 0 \\ 0 & 1 \end{bmatrix} \text{GIM} q_{\text{MNT},i}^{-1} \otimes \text{GIM} q_{\text{MNT},j} \quad (3.11)$$

These coarse estimates of $\text{ST} q_{\text{GIM}}$ and $\text{MNT} q_{\text{ENU}}$ are used to proceed to fine calibration.

3.4.2 Fine Calibration

Fine calibration uses a nonlinear least squares approach with the initial state supplied by coarse calibration. There are eight unknown parameters to be estimated. The error
state is given by:

\[ \delta x = [\delta a_d \quad ST\delta Q_{\text{GIM}} \quad \delta \theta_{NP} \quad MNT\delta Q_{\text{ENU}}]^T \quad (3.12) \]

The error quaternion, defined in Equation B.6, can be determined using the star tracker measurements from Equation 3.1:

\[ \text{OBS} \delta q_{J2K,i} = q_{n,i} \otimes \text{OBS} (\delta q \otimes \hat{q})_{\text{ST},i} \otimes \text{ST} (\delta q \otimes \hat{q})_{\text{GIM}} \otimes \text{GIM} (\delta q \otimes \hat{q})_{\text{MNT},i} \]
\[ \quad \cdots \otimes \text{MNT} \delta q_{\text{ENU}} \otimes \text{GIM} \hat{q}_{\text{MNT},i} \otimes \text{ST} \hat{q}_{\text{GIM}} \otimes \text{OBS} \hat{q}_{\text{ST},i} \quad (3.13) \]

Using Equation B.5, Equation 3.13 can be rewritten as:

\[ \text{OBS} \delta q_{J2K,i} = q_{n,i} \otimes \text{OBS} \delta q_{\text{ST},i} \otimes \begin{bmatrix} A(\text{OBS} \hat{q}_{\text{ST},i}) & 0 \\ 0 & 1 \end{bmatrix} \text{ST} \delta q_{\text{GIM}} \]
\[ \quad \cdots \otimes \begin{bmatrix} A(\text{ST} \hat{q}_{\text{GIM}}) & 0 \\ 0 & 1 \end{bmatrix} \text{GIM} \delta q_{\text{MNT},i} \]
\[ \quad \cdots \otimes \begin{bmatrix} A(\text{GIM} \hat{q}_{\text{MNT},i}) & 0 \\ 0 & 1 \end{bmatrix} \text{MNT} \delta q_{\text{ENU}} \quad (3.14) \]

The vector portion of the error quaternion is then approximated to first order as:

\[ \text{OBS} \delta Q_{J2K,i} \approx q_{n,i} + \text{OBS} \delta Q_{\text{ST},i} + A(\text{OBS} \hat{q}_{\text{ST},i}) \text{ST} \delta Q_{\text{GIM}} \]
\[ \quad \cdots + A(\text{GIM} \hat{q}_{\text{MNT},i}) \text{GIM} \delta Q_{\text{MNT},i} + A(\text{OBS} \hat{q}_{\text{MNT},i}) \text{MNT} \delta Q_{\text{ENU}} \quad (3.15) \]

In this equation, \text{ST} \delta Q_{\text{GIM}} and \text{MNT} \delta Q_{\text{ENU}} are components of the state, but \text{OBS} \delta Q_{\text{ST},i} and \text{GIM} \delta Q_{\text{MNT},i} must be related back to the state components.

Equations 3.2–3.5 define the rotation between the mount frame and the gimbaled frame. With these equations, and again utilizing Equation B.5, the error quaternion \text{GIM} \delta q_{\text{MNT},i} is given by:

\[ \text{GIM} \delta q_{\text{MNT},i} = \delta q_{NP} \otimes \begin{bmatrix} A(\hat{q}_{NP} \otimes q_{alt,i} \otimes \hat{q}_{NP}^{-1}) & 0 \\ 0 & 1 \end{bmatrix} \delta q_{NP}^{-1} \quad (3.16) \]

The vector portion of the error quaternion from Equation 3.16 can be approximated...
to first order as:

$$GIM \delta Q_{MNT,i} \approx (I_{3 \times 3} - A(\hat{q}_{NP} \otimes q_{alt,i} \otimes \hat{q}_{NP}^{-1})) \delta Q_{NP}$$  \hspace{1cm} (3.17)$$

Finally, $\delta q_{NP}$ must be related to $\delta \theta_{NP}$ from the state. This relationship is given by:

$$\delta q_{NP} = \begin{bmatrix} 0 & 0 & \sin(-\delta \theta_{NP}/2) & \cos(-\delta \theta_{NP}/2) \end{bmatrix}^T$$  \hspace{1cm} (3.18)$$

To first order, the vector portion of $\delta q_{NP}$ can be approximated as:

$$\delta Q_{NP} \approx \begin{bmatrix} 0 & 0 & -\delta \theta_{NP}/2 \end{bmatrix}^T$$  \hspace{1cm} (3.19)$$

Combining this result with Equation 3.17 yields the overall approximation:

$$GIM \delta Q_{MNT,i} \approx \frac{1}{2} (A(\hat{q}_{NP} \otimes q_{alt,i} \otimes \hat{q}_{NP}^{-1}) - I_{3 \times 3}) \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T \delta \theta_{NP}$$  \hspace{1cm} (3.20)$$

Returning to Equation 3.15, $OBS \delta Q_{ST,i}$ must be related to the state components. Equations 3.6 and 3.7 describe the rotation from the star tracker frame to the observed frame. Following the form of Equation B.1, the error quaternion from the star tracker to the observed frame at the $i^{th}$ measurement is as follows:

$$OBS \delta q_{ST,i} = \begin{bmatrix} \sin(\delta a_d \cos(\alpha_{obs})/2) u_{d,i} \\ \cos(\delta a_d \cos(\alpha_{obs})/2) \end{bmatrix}$$  \hspace{1cm} (3.21)$$

The vector component is approximated as:

$$OBS \delta Q_{ST,i} \approx \frac{1}{2} \cos(\alpha_{obs}) u_{d,i} \delta a_d$$  \hspace{1cm} (3.22)$$

Overall, combining Equations 3.15, 3.20, and 3.22 yields a linearization of the form:

$$OBS \delta Q_{J2K,i} = H_i \delta x_i + Q_{n,i}$$  \hspace{1cm} (3.23)$$

where $H_i$ is a matrix of partial derivatives, $\delta x_i$ is the state correction. The matrix $H_i$ is composed of:

$$H_i = \begin{bmatrix} \partial OBS \delta Q_{J2K,i} / \partial \delta a_d \\ \partial OBS \delta Q_{J2K,i} / \partial q_{GIM} \\ \partial OBS \delta Q_{J2K,i} / \partial \delta \theta_{NP} \\ \partial OBS \delta Q_{J2K,i} / \partial \delta Q_{MNT,i} \end{bmatrix}$$  \hspace{1cm} (3.24)$$
with partial derivatives given by:

\[
\frac{\partial \text{OBS} \delta Q_{\text{J2K},i}}{\partial \delta a_d} \approx \frac{1}{2} \cos(\alpha_{\text{obs}}) u_{d,i} \tag{3.25}
\]

\[
\frac{\partial \text{OBS} \delta Q_{\text{J2K},i}}{\partial \delta \theta_{\text{NP}}} \approx \frac{1}{2} \Lambda(\text{OBS} \hat{q}_{\text{GIM},i}) \left( \Lambda(\hat{q}_{\text{NP}} \otimes \hat{q}_{\text{alt},i} \otimes \hat{q}_{\text{NP}}^{-1}) - I_{3x3} \right) \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T \tag{3.27}
\]

Multiple measurements can be combined into an iterative nonlinear least squares process. For \( n \) measurements, the measurement errors are related to state errors as:

\[
\begin{bmatrix}
\text{OBS} \delta Q_{\text{J2K},1} \\
\vdots \\
\text{OBS} \delta Q_{\text{J2K},n}
\end{bmatrix} = \begin{bmatrix} H_1 \\ \vdots \\ H_n \end{bmatrix} \delta x_k + \begin{bmatrix} Q_{n,1} \\ \vdots \\ Q_{n,n} \end{bmatrix} \tag{3.29}
\]

This equation is of the form:

\[
\delta y_k = H \delta x_k + \omega \tag{3.30}
\]

where \( k \) is the iteration number and the covariance of \( \omega \) is a diagonal matrix of measurement noise with covariance \( R \). Using iterative least squares, the state update is given by:

\[
\delta x_k = (H^T R^{-1} H)^{-1} H^T R^{-1} \delta y_k \tag{3.31}
\]

The quaternions \( \text{ST} \hat{q}_{\text{GIM}} \) and \( \text{MNT} \hat{q}_{\text{ENU}} \) are updated with a quaternion product and the state components \( \hat{\theta}_{\text{NP}} \) and \( \hat{a}_d \) are updated additively. Iterations continue until the estimate converges.

### 3.5 Gimbal Angle and Rate Commands

The primary goal of the pointing model is to determine how to provide angle and rate inputs to the mount to look at a desired target. In this section, gimbal angle and rate commands are derived based on the pointing model formulation from Section 3.3.
Let $u_{\text{pnt}|J2K}$ be the unit pointing vector from the telescope to the target in the J2000 frame. This pointing vector is given by:

$$u_{\text{pnt}|J2K} = \frac{r_{\text{targ}|J2K} - r_{gs}|J2K}{\|r_{\text{targ}|J2K} - r_{gs}|J2K\|}$$

(3.32)

where $r_{\text{targ}|J2K}$ is the target location in the J2000 frame and $r_{gs}|J2K$ is the ground station location in the J2000 frame.

The pointing model can be applied to image a target in the detector behind the telescope as follows:

$$u_{\text{tel}|OBS} = A(\text{OBS}q_{ST} \otimes \text{ST}q_{\text{GIM}} \otimes \text{GIM}q_{\text{MNT}} \otimes \text{MNT}q_{\text{ENU}} \otimes \text{ENU}q_{J2K}) u_{\text{pnt}|J2K}$$

(3.33)

The gimbal angles appear in both $\text{OBS}q_{ST}$, which determines the vertical deflection of the telescope, and $\text{GIM}q_{\text{MNT}}$, which executes the gimbal rotation. A simplifying assumption is made that $\text{OBS}q_{ST}$ can be evaluated based on the target azimuth and elevation which can be determined from $u_{\text{pnt}|\text{ENU}}$. This assumption essentially states that the vertical deflection from the undeflected position is approximately the same as the vertical deflection would be at the desired location. Since the deflection should be less than a degree in elevation for a reasonable telescope and deflection is proportional to the cosine of the elevation angle, this is justified.

This assumption allows the problem to be simplified greatly. The gimbal angles only appear in the $\text{GIM}q_{\text{MNT}}$ transformation, so Equation 3.33 can be presented as:

$$u_{\text{tel}|\text{GIM}} = A(\text{GIM}q_{\text{MNT}}) u_{\text{pnt}|\text{MNT}}$$

(3.34)

where $u_{\text{pnt}|\text{GIM}}$ and $u_{\text{pnt}|\text{MNT}}$ are determined by rearranging and multiplying frame the transformations from Equation 3.33.

Combining Equations 3.34 and 3.2 and rearranging yields:

$$A(q_{NP}^{-1}) u_{\text{tel}|\text{GIM}} = A(q_{alt} \otimes q_{NP}^{-1} \otimes q_{azi}) u_{\text{pnt}|\text{MNT}}$$

(3.35)

For notational simplicity, let:

$$a = A(q_{NP}^{-1}) u_{\text{tel}|\text{GIM}}$$

(3.36)

and

$$b = u_{\text{pnt}|\text{MNT}}$$

(3.37)
Using the definitions from Equations 3.3–3.5 to multiply out Equation 3.35 gives the set of equations:

\[ a_1 = \cos(\theta_{NP}) \cos(\psi)b_1 + \sin(\theta_{NP})b_2 - \cos(\theta_{NP}) \sin(\psi)b_3 \]  
(3.38)

\[ a_2 = (-\sin(\theta_{NP}) \cos(\alpha) \cos(\psi) + \sin(\alpha) \sin(\psi)) b_1 + \cos(\theta_{NP}) \cos(\alpha)b_2 \]  
... + (\sin(\theta_{NP}) \cos(\alpha) \sin(\psi) + \sin(\alpha) \cos(\psi)) b_3 \]  
(3.39)

\[ a_3 = (\sin(\theta_{NP}) \sin(\alpha) \cos(\psi) + \cos(\alpha) \sin(\psi)) b_1 - \cos(\theta_{NP}) \sin(\alpha)b_2 \]  
... + (-\sin(\theta_{NP}) \sin(\alpha) \sin(\psi) + \cos(\alpha) \cos(\psi)) b_3 \]  
(3.40)

where \( a_i \) denotes the \( i^{th} \) element of vector \( a \) and likewise with vector \( b \).

To solve Equations 3.38–3.40 for the gimbal angles, a useful relationship is presented. Given an equation of the form:

\[ u \cos(\theta) + v \sin(\theta) = w \]  
(3.41)

applying the Pythagorean trigonometric substitution for \( \sin(\theta) \), rearranging, squaring the equation, and applying the quadratic formula yields two solutions for \( \cos(\theta) \):

\[ \cos(\theta) = \frac{uw \pm [2u^2w^2 - 2(u^2 + v^2)(v^2 + w^2)]^{1/2}}{u^2 + v^2} \]  
(3.42)

Equation 3.38 can be rearranged into the form of Equation 3.41, so \( \cos(\psi) \) can be calculated with Equation 3.42. This yields four possible solutions for the azimuth angle \( \psi \). Multiplying Equation 3.39 with \( \cos(\alpha) \) and subtracting Equation 3.40 multiplied by \( \sin(\alpha) \) yields an equation in the form of Equation 3.41 which can be solved for \( \cos(\alpha) \), with \( u, v, \) and \( w \) given by:

\[ u = a_2 \]  
(3.43)

\[ v = -a_3 \]  
(3.44)

\[ w = -\sin(\theta_{NP}) \cos(\psi)b_1 + \cos(\theta_{NP})b_2 + \sin(\theta_{NP}) \sin(\psi)b_3 \]  
(3.45)

Equation 3.45 depends on the azimuth angle, which has four possible solutions. This yields eight possible solutions for \( \cos(\alpha) \), and 16 possible solutions for the elevation angle \( \alpha \). If there are angle restrictions such as \( 0 < \alpha < \pi/2 \) they can be applied to reduce the solution set. The correct solution set for the gimbal angles can be determined by testing each set against Equation 3.35.
By differentiating Equations 3.38–3.40, the desired gimbal rates can be determined to track a target. This applies to both celestial objects and non-celestial objects such as satellites. It is assumed that $\mathbf{r}_{\text{pat}}|_{\text{MNT}}$ has been calculated by taking into account the trajectory of the target and Earth rotation. The rate of change of the target in the detector behind the telescope can be specified in calculating $\mathbf{r}_{\text{tel}}|_{\text{GIM}}$. The rate of change of atmospheric refraction is assumed to be negligible. Setting $\mathbf{r}_{\text{tel}}|_{\text{GIM}} = 0$ will maintain the target in a fixed location in the detector. The equations resulting from this differentiation are:

$$
\dot{a}_1 = -\cos(\theta_{NP}) \sin(\psi) \dot{\psi} b_1 - \cos(\theta_{NP}) \cos(\psi) \dot{\psi} b_3 + \cos(\theta_{NP}) \cos(\psi) \dot{b}_1 \\
\cdots + \sin(\theta_{NP}) \dot{b}_2 - \cos(\theta_{NP}) \sin(\psi) \dot{b}_3 
$$

$$
\dot{a}_2 = \left( \sin(\alpha) \cos(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) + \cos(\alpha) \sin(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) \right) b_1 \\
\cdots + \left( \cos(\alpha) \cos(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) - \sin(\alpha) \sin(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) \right) b_3 \\
\cdots - \cos(\theta_{NP}) \sin(\alpha) \dot{b}_2 + (\sin(\alpha)) \sin(\psi) - \sin(\theta_{NP}) \cos(\alpha) \cos(\psi)) \dot{b}_1 \\
\cdots + \cos(\theta_{NP}) \cos(\alpha) \dot{b}_2 + (\sin(\theta_{NP}) \cos(\alpha) \sin(\psi) + \sin(\alpha) \cos(\psi)) \dot{b}_3
$$

$$
\dot{a}_3 = \left( \cos(\alpha) \cos(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) - \sin(\alpha) \sin(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) \right) b_1 \\
\cdots + \left( -\sin(\alpha) \cos(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) - \cos(\alpha) \sin(\psi) \left( \sin(\theta_{NP}) \dot{\psi} + \dot{\alpha} \right) \right) b_3 \\
\cdots - \cos(\theta_{NP}) \cos(\alpha) \dot{b}_2 + (\cos(\alpha)) \sin(\psi) + \sin(\theta_{NP}) \sin(\alpha) \cos(\psi)) \dot{b}_1 \\
\cdots - \cos(\theta_{NP}) \sin(\alpha) \dot{b}_2 + (-\sin(\theta_{NP}) \sin(\alpha) \sin(\psi) + \cos(\alpha) \cos(\psi)) \dot{b}_3
$$

Equation 3.46 can be solved for the azimuth gimbal rate:

$$
\dot{\psi} = \frac{-\dot{a}_1 + \cos(\theta_{NP}) \cos(\psi) \dot{b}_1 + \sin(\theta_{NP}) \dot{b}_2 - \cos(\theta_{NP}) \sin(\psi) \dot{b}_3}{\cos(\theta_{NP}) \sin(\psi) b_1 + \cos(\theta_{NP}) \cos(\psi) b_3}
$$

(3.49)

Multiplying Equation 3.47 by $\cos(\alpha)$ and subtracting Equation 3.48 multiplied by $\sin(\alpha)$ yields a solution for the elevation gimbal rate:

$$
\dot{\alpha} = \frac{\cos(\alpha) \dot{a}_2 - \sin(\alpha) \dot{a}_3 - \sin(\theta_{NP}) \left( \sin(\psi) \left( \dot{\psi} b_1 + \dot{b}_3 \right) + \cos(\psi) \left( \dot{\psi} b_3 - \dot{b}_1 \right) \right)}{\sin(\alpha) b_1 + \cos(\alpha) b_3}
$$

(3.50)

Using Equations 3.49 and 3.50, the mount can be commanded to follow a target trajectory.
Chapter 4

Satellite Tracking

Dynamic tracking of fast-moving objects challenges a telescope control system substantially more than static pointing. Tracking rates for LEO satellites can be as high as 1.1 deg/s for a 400 km orbit. Due to the keyhole problem, azimuth slew rates can exceed 10 deg/s for passes near zenith. The quality of the telescope/mount hardware plays a key role in successfully tracking LEO satellites, which makes low-cost COTS telescopes particularly challenging to use in this context.

Chapter 3 described the PorTeL pointing model and how angle and rate commands are generated. This chapter covers the control strategy and how these commands are executed. In this chapter, the approaches of existing optical ground stations to the tracking of LEO satellites are reviewed. Tracking LEO satellites with COTS hardware has been an area of focus in space situational awareness and these efforts are described. The tracking approach of PorTeL and its context in terms of existing work is then presented.

4.1 Problem Description

The tracking problem can be split into open-loop and closed-loop segments. Open-loop tracking refers to the phase before the target is seen and known orbital elements provide a desired tracking trajectory. Closed-loop tracking refers to the phase where observations of the target provide feedback to improve tracking.

There are two general approaches to open-loop tracking. The first is to generate a series of angle commands for the telescope using the orbital elements and the telescope pointing model. The desired trajectory results from following this series of waypoints. However, tracking via waypoints requires an internal controller to execute the angle commands, which for amateur telescopes can have significant overshoot or
other performance deficiencies.

The second approach is to drive the gimbal rate directly to produce the desired trajectory. Given a pointing model of the form in Figure 3-1, desired gimbal rates can be determined by differentiating the model. As in the case of generating angle commands, the equations must be implicitly solved for the desired rates. The TPOINT model discussed in Section 3.2.1 does not explicitly provide these equations. Solving for gimbal rate directly from the pointing model increases accuracy and avoids instability due to cross-coupling of terms or inaccurate approximations near zenith.

Once the target is seen, detector measurements can be used to improve tracking. This begins the closed-loop tracking phase. Closed-loop tracking corrections can be applied at multiple points in the pointing model, as discussed by Wallace [53]. Small angular offsets are commonly used to apply corrections, but it is important to note that in most cases this does not address the root cause of an error. In the case of an encoder indexing error, applying an angular offset is the appropriate correction for all orientations. Any other source of error, however, is dependent on orientation. When tracking LEO satellites a large swath of sky is covered in a matter of minutes, so angular corrections must to be updated. If possible, it is better to address the root cause of the pointing error, though in some cases this can be very challenging to identify.

4.2 Literature Review

4.2.1 Optical Ground Stations

Optical ground stations typically have a fine pointing system that does closed-loop tracking of the downlink signal. In some cases, open-loop tracking by the mount is sufficient to stay within the range of the fine pointing system such that closed-loop telescope tracking is not required. This reflects the high quality of the telescope/mount hardware.

It is useful to look at the tracking strategies of the optical ground stations described in Section 2.1. ESA-OGS tracks a satellite open-loop and only offloads when the fine pointing system reaches the edge of its range [22]. Likewise, OCTL tracks open-loop with a repeated angular offset to offload the fine pointing system [76]. NICT’s $\phi 1.5$ m optical ground station open-loop tracked the LEO satellite OICETS with 60 arcsec average error, mostly due to ephemeris error, and closed-loop tracked OICETS to within 10 arcsec [125]. TOGS begins with open-loop tracking and then
applies closed-loop corrections to the mount by a series of angular offsets calculated from image centroids [34]. Similarly, TAOGS begins with an open-loop trajectory and applies angular offsets once the signal is acquired.

The optical ground stations described in Section 2.1, with the exception of TOGS, all employ a staged control approach. A fast-steering mirror with high bandwidth is used to compensate for residual telescope tracking error. The open-loop tracking performance of the telescope is sufficient to stay within the range of the fine stage with periodic desaturation.

4.2.2 Amateur Telescopes

The desire for space situational awareness has led to interest in more affordable ways to observe space. AFRL introduced the concept of small, low-cost telescopes called “Ravens” for observing space objects [36]. Initially these telescopes were used for GEO tracking but more recently have been used for LEO targets.

Software Bisque offers TheSkyX [120] package which contains TPOINT for calibration as well as satellite tracking software. As a result, Software Bisque Paramount mounts and the accompanying software package are a popular choice for Raven-class systems, including the original AFRL Ravens [36]. Other Ravens using this platform include CASTOR [37], the Falcon Telescope Network [39], systems developed by the Pacific Northwest National Laboratory [43] and J.T. McGraw and Associates [41], and a deployable system developed by AFRL [46]. For these platforms, calibration is conducted by sighting tens to hundreds of stars that are used by TPOINT for a parameter fit. TheSkyX software contains TLEs for many space objects and the user can select a satellite to track from a virtual display of the sky. The system can be set up in a single night [46].

An effort at RC Optical Systems also using TheSkyX software successfully adapted a mid-size COTS telescope to track LEO objects [42]. TPOINT software is used for precision pointing and tracking onto a camera with a 0.39° × 0.39° FOV. The effort relies on TLEs from JSpOC for orbit prediction. A separate telescope with a FOV of 1.28° × 0.85° is used for acquisition, and it was found that open-loop tracking was sufficient to maintain the satellite within the main camera FOV in most cases. Nonlinear least squares is used to fit Keplerian elements from observed position during tracking.

Other Raven-class systems rely on the amateur telescope calibration described in Section 3.2.2. A Celestron Nexstar 6SE Mount is used to track LEO satellites in a
project at the United States Air Force Academy [44]. Alignment is done with built-in software by sighting Polaris, and Heavenscape Satellite Tracker software is used to track satellites. The camera used in this project has a 12° FOV, so tracking accuracy is not a major concern.

The Virginia Tech Optical Satellite Tracking Telescope (VTOST) combines a narrow FOV Celestron CGE Pro 1400 Computerized Telescope with a large FOV camera for acquisition and tracking of satellites [45,126]. When not in use, the mount remains powered to avoid having to perform realignment. Tracking relies on TLEs to generate angle commands for open-loop pointing, which is the driving motivation for the large FOV acquisition camera. Closed-loop pointing updates are provided by analyzing streaks in the camera and generating angular corrections that result in a series of discrete angular steps.

There are some important differences between using amateur telescopes for space surveillance and lasercom that are worth noting. For space surveillance the pointing requirements are generally less stringent. Since the goal is to image a target, a large focal plane array can be used to maximize the FOV. The object must remain within a FOV on the order of tenths of a degree or more, whereas a lasercom receiver has a FOV on the order of thousandths of a degree or less. Most systems developed for space surveillance are also intended to be fixed, so they do not address transportability or rapid calibration.

4.2.3 Research Gap

In developing a tracking approach for a portable optical ground station with an amateur telescope, there are several gaps in current approaches. While most existing tracking is based on an open-loop trajectory of angle commands, this forces a reliance on the internal controller of the amateur telescope, which can have large overshoot or other deficiencies.

Tracking commands for existing systems are based around the pointing models discussed in Section 3.2, which make assumptions about the nominal orientation of the telescope. To eliminate these assumptions, open-loop slew commands are generated by differentiating the pointing model (see Section 3.5) and using known orbital elements.

Small satellites commonly rely on publicly-available TLEs for orbit determination, but these can suffer from large error for LEO satellites [127]. These errors contribute significantly to tracking error, which tends to grow the longer they are propagated.
However, it has been observed that the error is predominantly confined to the in-track component [127–129]. To eliminate this error in real-time, an extended Kalman filter (EKF) is used to estimate a timing offset, $t_0$, which compensates for open-loop trajectory error. In existing software such as TheSkyX, a timing offset can be adjusted manually by the user to address this issue. By implementing an EKF, this process is automated based on real-time measurements.

Bringing these aspects together enables better than 5 arcsecond RMS pointing using low-cost, COTS hardware and TLEs on a system that can be deployed and calibrated within 30 minutes. In terms of speed of deployment and accuracy at a given cost, PorTeL contributes to the state-of-the-art.

4.3 Approach

The overall tracking approach consists of three phases: acquisition, coarse tracking, and fine tracking. A state diagram of these phases is shown in Figure 4-1. The coarse stage tracking assembly and fine stage receiver assembly each have their own set of control elements that are executed during each phase (for the description of the tracking and receiver assemblies, refer back to Section 2.2.1).

**Coarse Stage:**
1. Open-loop TLE tracking
2. Closed-loop feedback with coarse guidance camera and telescope
3. EKF estimating timing error
4. Offloading FSM to telescope

**Fine Stage:**
1. FSM scanning
2. Closed-loop feedback with FSM and tracking camera

![State diagram of the satellite tracking approach implemented in PorTeL software. The approach contains six elements of coarse and fine control that are split into three phases: acquisition, coarse tracking, and fine tracking.](image_url)

Figure 4-1: State diagram showing the satellite tracking approach implemented in PorTeL software. The approach contains six elements of coarse and fine control that are split into three phases: acquisition, coarse tracking, and fine tracking.

In the acquisition phase, the telescope open-loop tracks the expected trajectory...
of the satellite while the FSM executes a spiral scan to search for a signal. Both the
course guidance camera and tracking camera behind the telescope are in a mode of
continuous capture.

Once a signal is detected in the coarse guidance camera, the system transitions into
the coarse tracking phase. On top of the open-loop expected trajectory, corrections
are applied to telescope pointing using feedback from the guidance camera. An EKF
to estimate timing offset is also initiated which updates the open-loop trajectory.
During this phase the FSM is still scanning for a signal.

Once a signal is seen in the tracking camera, the system transitions to the fine
tracking phase. The coarse stage follows the open-loop expected trajectory which is
adjusted based on the EKF timing error estimate. Coarse guidance corrections are
turned off and replaced with continuous offloading of the FSM to the telescope. This
ensures that the FSM does not saturate and also provides much smoother feedback
to avoid the discontinuous steps of coarse feedback.

4.3.1 Coarse Stage

Open-loop

In the acquisition phase, the coarse stage tracks open-loop. TLEs are used for orbit
determination. At each timestep, the satellite is propagated using the Standard
General Perturbations Model 4 (SGP4) [130, 131], which provides the position and
velocity of the satellite. The reference gimbal angles and rates are calculated from
the equations in Section 3.5.

Once the reference gimbal angles and rates to follow the satellite trajectory are
known, an input rate command to the mount is generated. The mount controller is
given by:

\[ \dot{\theta}_{cmd} = \dot{\theta}_{ref} + \frac{1}{T_s}(\theta_{ref} - \theta_{meas}) \]  

(4.1)

where \( \dot{\theta}_{cmd} \) is the commanded gimbal rate, \( \dot{\theta}_{ref} \) is the reference gimbal rate, \( T_s \) is the
settling time, \( \theta_{ref} \) is the reference gimbal angle, and \( \theta_{meas} \) is the gimbal angle measured
by the encoder. Rate commands are generated for each gimbal.

The settling time was selected to be 0.6 s in azimuth and 1 s in altitude through
hardware-in-the-loop simulated satellite tracks. At these gains the control error is
below 10 arcsec and no instability has been observed, though there is a discussion of
the altitude gain in Section 5.4.2. During open-loop tracking, the mount controller
executes at a rate of 5 Hz. The open-loop reference trajectory is used in every phase of tracking.

**Closed-loop**

Once the target is acquired in the coarse guidance camera, the acquisition phase transitions into the coarse tracking phase. The mount commands are generated following Equation 4.1 as in the open-loop phase, but closed-loop feedback is applied by updating the telescope boresight vector.

The gimbal angle and rate reference commands are calculated based on the boresight vector of the telescope in the observed frame of the star tracker, $\mathbf{u}_{\text{tel}|\text{OBS}}$ (refer to Equation 3.33). Closed-loop corrections can be applied by updating the LOS based on the observed satellite position:

$$\mathbf{u}_{\text{tel,CL}|\text{OBS}} = A(q_{\text{CL}}) \mathbf{u}_{\text{tel}|\text{OBS}}$$  \hspace{1cm} (4.2)

where $\mathbf{u}_{\text{tel,CL}|\text{OBS}}$ is the new LOS vector and $q_{\text{CL}}$ is the rotation in the observed frame that contains the closed-loop correction. The updates are stored in a quaternion so that the corrections can be cleared and $\mathbf{u}_{\text{tel}|\text{OBS}}$ remains intact.

Let $\mathbf{u}_{\text{meas}|\text{OBS}}$ be the unit vector of the target observed from the star tracker. To calculate the update quaternion, the rotation axis and angle are determined. The axis is given by:

$$\mathbf{u}_{\text{CL}} = \frac{\mathbf{u}_{\text{meas}|\text{OBS}} \times \mathbf{u}_{\text{tel}|\text{OBS}}}{||\mathbf{u}_{\text{meas}|\text{OBS}} \times \mathbf{u}_{\text{tel}|\text{OBS}}||}$$  \hspace{1cm} (4.3)

The angle is given by:

$$\theta_{\text{CL}} = \sin^{-1} (||\mathbf{u}_{\text{meas}|\text{OBS}} \times \mathbf{u}_{\text{tel}|\text{OBS}}||)$$  \hspace{1cm} (4.4)

The update quaternion $\delta q_{\text{CL}}$ is then calculated using Equation B.4.

At each timestep $k$, the closed-loop correction is updated by:

$$q_{\text{CL},k} = \delta q_{\text{CL}} \otimes q_{\text{CL},k-1}$$  \hspace{1cm} (4.5)

A correction is applied whenever a measurement is available from the coarse guidance camera, which takes images at 0.5 Hz during a satellite track. After each satellite pass, $q_{\text{CL}}$ is cleared by default since the errors are generally specific to the conditions of the pass (e.g. on-sky location, TLE error, telescope lead/lag).
Extended Kalman Filter for Timing Offset

During the coarse and fine tracking phases, an extended Kalman filter estimate of timing offset is used to update the satellite trajectory in real-time. This compensates for in-track TLE error and also any timing biases in the ground station. The EKF addresses the root cause of a major source of tracking error, which results in better tracking than repeatedly applying angular offsets. The derivation of the EKF is provided here.

The state dynamics are given by:

$$\frac{d}{dt} t_0 = \eta$$  \hspace{1cm} (4.6)

where \( t_0 \) is the timing offset, and \( \eta \) is white process noise with a variance of \( Q \). Timing offset is modeled as a constant since the drift over a pass duration <10 minutes is negligible.

The measurement from the guidance camera is given by:

$$u_{meas|OBS} = A(OBSq_{J2K}) u_{pnt|J2K}$$  \hspace{1cm} (4.7)

where \( u_{meas|OBS} \) is the unit vector of the observed target in the star tracker frame, and \( OBSq_{J2K} \) is determined from the pointing model. The inertial pointing vector, \( u_{pnt|J2K} \), was defined in Equation 3.32 and is reproduced here for reference:

$$u_{pnt|J2K} = \frac{r_{targ|J2K} - r_{gs|J2K}}{||r_{targ|J2K} - r_{gs|J2K}||}$$  \hspace{1cm} (4.8)

Differentiating the measurement with respect to the timing offset and applying the chain rule yields:

$$\frac{\partial u_{meas|OBS}}{\partial t_0} = \frac{\partial u_{meas|OBS}}{\partial u_{pnt|J2K}} \frac{\partial u_{pnt|J2K}}{\partial r_{targ|J2K}} \frac{\partial r_{targ|J2K}}{\partial t_0}$$  \hspace{1cm} (4.9)

Each of these derivatives can be determined individually. The first chain rule term is easily determined from Equation 4.7:

$$\frac{\partial u_{meas|OBS}}{\partial u_{pnt|J2K}} = A(OBSq_{J2K})$$  \hspace{1cm} (4.10)

Differentiating Equation 4.8 to first order provides the second chain rule term.
For notational simplicity, let:

\[ r_{\text{pnt}} = r_{\text{targ}}|_{J2K} - r_{\text{gs}}|_{J2K} \]  

(4.11)

The second chain rule term is given by:

\[
\frac{\partial u_{\text{pnt}}|_{J2K}}{\partial r_{\text{targ}}|_{J2K}} = \left| r_{\text{pnt}} \right|^{-3} \begin{bmatrix}
    r_{\text{pnt},2}^2 + r_{\text{pnt},3}^2 & -r_{\text{pnt},1}r_{\text{pnt},2} & -r_{\text{pnt},1}r_{\text{pnt},3} \\
    -r_{\text{pnt},1}r_{\text{pnt},2} & r_{\text{pnt},1}^2 + r_{\text{pnt},3}^2 & -r_{\text{pnt},2}r_{\text{pnt},3} \\
    -r_{\text{pnt},1}r_{\text{pnt},3} & -r_{\text{pnt},2}r_{\text{pnt},3} & r_{\text{pnt},1}^2 + r_{\text{pnt},2}^2
\end{bmatrix}
\]  

(4.12)

where \( r_i \) denotes the \( i^{th} \) element of \( r \).

The third chain rule term, \( \frac{\partial r_{\text{targ}}|_{J2K}}{\partial t_0} \), is simply the velocity at time \( t + t_0 \). The equations for the EKF are given as follows. For the propagation step,

\[
t_{0,k}^- = t_{0,k-1}^+ \\ P_k^- = P_{k-1}^+ + Q_k
\]

(4.13)

(4.14)

where \( P \) is the estimate of the error variance. The variance of the process noise \( Q_k \) was selected to be 0.05 to keep the filter from closing. For the update step, the Jacobian is given by:

\[
H = \frac{\partial u_{\text{meas}}|_{\text{OBS}}}{\partial t_o}
\]

(4.15)

as calculated above.

The update equations are:

\[
K_k = P_k^- H_k^T \left( H_k P_k^- H_k^T + R \right)^{-1} \\ t_{0,k}^+ = t_{0,k}^- + K_k (u_{\text{meas}}|_{\text{OBS}} - \hat{u}_{\text{meas}}|_{\text{OBS}}) \\ P_k^+ = (1 - K_k H_k) P_k^-
\]

(4.16)

(4.17)

(4.18)

The measurement noise covariance \( R \) is a diagonal matrix with values of 20 arcsec in the cross-boresight axes, \( x \) and \( y \), and 200 arcsec in the boresight axis of the coarse guidance camera. The EKF update rate is 0.5 Hz as each new guidance camera image is available.
Fine Stage Offloading

During the fine tracking phase, the coarse stage stops executing closed-loop commands from the coarse guidance camera and instead transitions to offloading of the FSM. An additional term is added to the mount controller from Equation 4.1 to offload the FSM:

$$
\dot{\theta}_{cmd} = \dot{\theta}_{ref} + \frac{1}{T_s} (\theta_{ref} - \theta_{meas} + \theta_{off})
$$

(4.19)

where $\theta_{off}$ is the offload angle.

The offload angle is updated at 60 Hz with the fine control loop. The angle is updated by:

$$
\theta_{off,k} = \theta_{off,k-1} + g\theta_{FSM,k}
$$

(4.20)

where $g$ is the gain and $\theta_{FSM,k}$ is the FSM angle at the current timestep. The gain $g$ was determined by testing in the lab to provide rapid offloading without excessive overshoot. The gain is set to $4.5 \times 10^{-4}$ in azimuth and $2.25 \times 10^{-4}$ in altitude.

4.3.2 Fine Stage

Calibration of Gains

Prior to tracking, the gain between the FSM input voltages and the motion of the centroid on the tracking detector must be calculated. This allows the FSM to drive the centroid to the desired location in the tracking detector. The centroid vector $c$ is given by:

$$
c = \begin{bmatrix} x \\ y \end{bmatrix}^T
$$

(4.21)

where $(x, y)$ is the pixel location in the tracking detector. The input voltage vector $v$ is given by:

$$
v = \begin{bmatrix} v_x \\ v_y \end{bmatrix}^T
$$

(4.22)

where $(v_x, v_y)$ are the FSM input voltages.

The change in centroid location is modeled as linear to the change in input voltage:

$$
\Delta c = M \Delta v
$$

(4.23)

where $M$ is the gain matrix that must be determined. Let $m$ be the vector of the components of $M$:

$$
m = \begin{bmatrix} M_{1,1} & M_{1,2} & M_{2,1} & M_{2,2} \end{bmatrix}^T
$$

(4.24)
The FSM input voltages are zeroed, a source is centered in the tracking detector, and an initial centroid \( c_0 \) is measured. The FSM is then commanded to several tip/tilt angles and the resulting centroids are measured. Least squares is used to determine the gain matrix. For the \( i^{th} \) measurement, the FSM is commanded to a new tip/tilt position with voltages \( v_i \) resulting in a new centroid \( c_i \). For \( n \) measurements, the overall centroid measurement vector \( y \) is given by:

\[
y = \begin{bmatrix} (c_1 - c_0)^T & \cdots & (c_n - c_0)^T \end{bmatrix}^T
\]

Assuming a linear relationship between the input voltage and output centroid, the Jacobian is given by:

\[
H = \begin{bmatrix}
    v_1^T & 0_{1 \times 2} \\
    0_{1 \times 2} & v_2^T \\
    \vdots & \vdots \\
    v_n^T & 0_{1 \times 2} \\
    0_{1 \times 2} & v_n^T
\end{bmatrix}
\]

The gain matrix is then estimated with the least squares formula:

\[
m = (H^T H)^{-1} H^T y
\]

It is convenient to perform this calibration at the same time as the inter-camera alignment procedure described in Section 5.1.1. The gain should be recalibrated every time the receiver assembly and tracking assembly are decoupled.

**Acquisition and Tracking**

During the acquisition phase, the FSM is scanning for a signal. A spiral scan is used that is defined by a radial rate \( \dot{r} \) and angular rate \( \omega \). The full tip/tilt range of the FSM is scanned and when the edge or center is reached, the scan reverses radial direction. The rates are selected so that the start of each spiral is out of phase with the prior spiral, resulting in fuller coverage over time. Figure 4-2 shows the sample points for 20 seconds of scanning with \( \dot{r} = 2 \) V/s and \( \omega = 3.5 \) rad/s.

Scanning continues until the target is seen, at which point the fine tracking phase begins. The FSM controller drives the centroid to the origin at each step using the gain matrix calculated from Section 4.3.2. The FSM controller is given by:

\[
v_k = v_{k-1} + M^{-1} (c - c_{ref})
\]
Figure 4-2: FSM spiral scan after 20 seconds with $\dot{r} = 2$ V/s and $\omega = 3.5$ rad/s. The voltage range of the FSM is $[-10, 10]$ V in each axis, corresponding with $\pm 1.5^\circ$.

where $v_k$ is the updated tip/tilt voltage, $c$ is the measured centroid, and $c_{\text{ref}}$ is the reference centroid. The fine control loop is executed at 60 Hz when a tracking detector image becomes available. If the target is lost, the FSM automatically returns to scanning until the target reappears.
Chapter 5

Operation and Results

The Portable Telescope for Lasercom was designed to meet the following performance metrics: 1) the ground station can be rapidly deployed and calibrated within an hour, 2) the ground station blind pointing accuracy is better than 100 arcseconds RMS, and 3) the ground station can track LEO satellites within 7.4 arcseconds accuracy.

This chapter presents the experimental results that justify these claims. The operation of the ground station is described, followed by results from calibration of the pointing model developed in Chapter 3 and an assessment of the blind pointing accuracy of PorTeL through star observations. The satellite tracking approach described in Chapter 4 is tested by tracking several LEO satellites.

5.1 Ground Station Deployment

5.1.1 Physical Setup

PorTeL can be deployed in approximately 30 minutes from a state of storage to ready-to-track, meeting the first requirement of the system (see Table 2.3). Two manual steps are required: the telescope must be physically assembled and then an inter-camera alignment procedure must be performed. Figure 5-1 summarizes the manual and automated steps to deploy and calibrate the telescope.

The physical assembly of the telescope takes approximately 10 minutes. The CPC1100 telescope must be mounted on the tripod provided by Celestron. The back-end receiver assembly must be coupled to the telescope with two custom brackets that screw into four existing mounting holes on the telescope. The star tracker also has a custom bracket that screws into two existing mounting holes. The necessary cables must be connected to power and to the laptop.
Figure 5-1: Block diagram showing the PorTeL deployment steps from telescope setup to ready-to-track. Manual steps are shown in blue and automated steps are shown in green. The calibration steps take approximately 10 minutes plus an additional 15 minutes to set up the telescope. The entire process takes less than 30 minutes.

The second manual step is to do an inter-camera alignment. The purpose of the inter-camera alignment procedure is to identify the location of the telescope boresight in the star tracker. This allows the star tracker to be used to guide a signal through the main aperture. A distant source (e.g., a bright terrestrial light or a star) is centered in the tracking detector behind the telescope and imaged with the star tracker. The centroid of the target in the star tracker provides a unit vector in the star tracker observed frame, $\mathbf{r}_{tel|OBS}$, that represents the boresight of the telescope. It takes approximately 5 minutes to identify and center a source. This procedure can also be done during the daytime using any identifiable feature such as the corner of a building.

5.1.2 Test Locations

When disassembled, the ground station can be transported manually in a case for short distances or by car for longer distances. Test results that are presented in Sections 5.3 and 5.4 were acquired from three diverse locations, shown in Figure 5-2. The primary testing location is on the roof of MIT Building 37, located in Cambridge, Massachusetts at a latitude and longitude of (42.360689°N, 71.093197°W) and an elevation of roughly 30 m above sea level. Standard wall plugs are available on the roof to provide power. Challenges of testing on the MIT Building 37 rooftop include strong winds, significant ambient light from downtown Cambridge and Boston, and many passing aircraft.

Boston weather significantly limits testing opportunities during the winter. To overcome this issue, the ground station was packed into a 2018 Subaru Crosstrek
(in the compact sport utility vehicle class) and transported to two testing locations in the southeastern United States. The first location was on a large field in The Villages, Florida, located at a latitude and longitude of (28.927986°N, 81.951836°W) and an elevation of 23 m. No power is available at this location, so a portable battery is used. Wind at this location was minimal and some ambient light was present from the residential surroundings. The tripod was placed directly on the grass which likely introduced some error as the tripod may have shifted over time. The second testing location was on a driveway in Hendersonville, North Carolina. The elevation of this location is about 950 m and the latitude and longitude are (35.312461°N, 82.523574°W). During the testing period, this location experienced mild wind and very little ambient light was present. A portable battery was used to power the setup.

5.2 Calibration of Pointing Model

The pointing model developed in Chapter 3 must be calibrated at the beginning of each test period. In this section, the full results of a single calibration are presented. Calibration results vary somewhat from night to night depending on clouds, wind,
temperature, humidity, testing location, and other factors, but the results of this run are representative of the typical performance given a clear sky.

The results presented in this section were acquired on February 14, 2018 between the hours of 23:48–23:59 UTC from the roof of MIT Building 37 as pictured in Figure 5-2. The calibration procedure took a total of 11 minutes. To calibrate the pointing model, 24 star tracker images were taken at points equidistributed across the sky above 20° elevation. Figure 5-3 shows the locations of the calibration points on a 2-D projection of the sky.

![Calibration points on 2-D proj. of unit hemisphere](image)

Figure 5-3: The 24 calibration points from PorTeL software projected on a bird’s-eye view of a unit hemisphere. The calibration points are approximately equidistributed above 20° elevation and are numbered in the order in which they are executed.

Images were taken with a 300 ms exposure and star identification (ID) was performed on each image using a correlation-based pattern matching algorithm developed by Yoon et al. [132,133]. An image is excluded from the calibration set if fewer than six stars are identified or if the ID score (as described in [133]) is below a threshold of 30, determined empirically. A sample star image is shown in Figure 5-4 which was taken from the calibration set on 2/14/18.
Figure 5-4: Sample star tracker image from 2/14/18. Stars identified are marked in green, unidentified stars are marked in red, and the brightest star is marked in yellow. In this image, 13 stars are identified and the image residual is 2.4 arcseconds RMS.

Table 5.1 summarizes the results of the star tracker images. The azimuth and altitude measured by the encoders are listed, followed by the number of stars identified and the star ID RMS residual. Once the stars are identified, their vector is known in the J2000 frame from a star catalog. The vectors of each star in the star tracker observed frame are determined from the image, and QUEST [124] is used to estimate a rotation between the two frames. Using this estimate, the predicted vectors in the star tracker are compared to the measured star vectors to calculate the residuals, as described in [122]. The RMS of the residuals provide a metric to assess the accuracy of each image measurement, which ranges from 2–8 arcseconds within this data set.

The final two columns of Table 5.1 show the azimuth and elevation residuals of each image within the overall pointing model. Three images (#7, #9, and #11) are excluded from the pointing model calibration due to low star ID scores. Image #8 appears to be an outlier, but it has a strong identification score and it is more likely that the calibration is skewed slightly by the exclusion of images #7 and #9 near it (refer to Fig. 5-3). The accuracy of the overall calibration was 27 arcseconds RMS in azimuth and 37 arcseconds RMS in altitude.

Residuals from the 21 images included from calibration are shown in Figure 5-5. A trend can be seen between altitude and rotation about the star tracker Z axis, but otherwise the residuals do not contain any clear trends. Rotation of the star tracker about the Z axis only has a small coupling to the telescope line-of-sight (if the star tracker and telescope were co-aligned perfectly, there would be no coupling), so residuals in the Z axis are of less importance than the other axes.
Table 5.1: Results from star tracker images for pointing model calibration taken on 2/14/18 between the hours of 23:48–23:59 UTC. Azimuth and altitude are listed for each image followed by the number of stars identified, the residual of the star ID, and the azimuth and altitude residuals in the pointing model calibration.

<table>
<thead>
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<th>#</th>
<th>Azi (deg)</th>
<th>Alt (deg)</th>
<th>Stars ID'd</th>
<th>ID RMS res. (asec)</th>
<th>Azi cal. res. (asec)</th>
<th>Alt cal. res. (asec)</th>
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<td>29.37</td>
<td>12</td>
<td>4.3</td>
<td>-38</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>45.21</td>
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<td>2.2</td>
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<td>-46</td>
</tr>
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<td>3</td>
<td>70.29</td>
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<td>3.5</td>
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<td>4</td>
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</tr>
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<td>8</td>
<td>3.3</td>
<td>11</td>
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</tr>
<tr>
<td>6</td>
<td>109.70</td>
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<td>12</td>
<td>2.8</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>134.78</td>
<td>38.48</td>
<td>11</td>
<td>3.6</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>8</td>
<td>167.06</td>
<td>29.37</td>
<td>12</td>
<td>3.8</td>
<td>136</td>
<td>-201</td>
</tr>
<tr>
<td>9</td>
<td>161.30</td>
<td>52.50</td>
<td>9</td>
<td>3.7</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>10</td>
<td>136.26</td>
<td>73.61</td>
<td>13</td>
<td>6.3</td>
<td>-7</td>
<td>-13</td>
</tr>
<tr>
<td>11</td>
<td>43.73</td>
<td>73.60</td>
<td>6</td>
<td>2.9</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>12</td>
<td>18.69</td>
<td>52.52</td>
<td>10</td>
<td>2.6</td>
<td>23</td>
<td>-37</td>
</tr>
<tr>
<td>13</td>
<td>347.06</td>
<td>29.37</td>
<td>12</td>
<td>3.3</td>
<td>-23</td>
<td>1</td>
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<tr>
<td>14</td>
<td>314.78</td>
<td>38.50</td>
<td>12</td>
<td>2.2</td>
<td>-38</td>
<td>-13</td>
</tr>
<tr>
<td>15</td>
<td>289.70</td>
<td>53.84</td>
<td>12</td>
<td>4.2</td>
<td>-11</td>
<td>13</td>
</tr>
<tr>
<td>16</td>
<td>282.87</td>
<td>31.48</td>
<td>8</td>
<td>2.3</td>
<td>-36</td>
<td>26</td>
</tr>
<tr>
<td>17</td>
<td>257.12</td>
<td>31.48</td>
<td>9</td>
<td>2.6</td>
<td>-31</td>
<td>41</td>
</tr>
<tr>
<td>18</td>
<td>250.29</td>
<td>53.84</td>
<td>13</td>
<td>2.4</td>
<td>-4</td>
<td>31</td>
</tr>
<tr>
<td>19</td>
<td>225.21</td>
<td>38.50</td>
<td>10</td>
<td>5.3</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>20</td>
<td>192.93</td>
<td>29.37</td>
<td>13</td>
<td>8.0</td>
<td>28</td>
<td>53</td>
</tr>
<tr>
<td>21</td>
<td>198.69</td>
<td>52.52</td>
<td>13</td>
<td>3.0</td>
<td>33</td>
<td>52</td>
</tr>
<tr>
<td>22</td>
<td>223.73</td>
<td>73.61</td>
<td>8</td>
<td>4.6</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>23</td>
<td>316.26</td>
<td>73.61</td>
<td>10</td>
<td>5.1</td>
<td>-6</td>
<td>-16</td>
</tr>
<tr>
<td>24</td>
<td>341.30</td>
<td>52.52</td>
<td>11</td>
<td>3.7</td>
<td>-2</td>
<td>-3</td>
</tr>
</tbody>
</table>

Overall RMS 27 37

*Excluded due to low star identification score
Figure 5-5: Residuals from pointing model calibration in the star tracker frame plotted against azimuth and altitude. Data acquired on 2/14/18 between the hours of 23:48–23:59 UTC.

The pointing model parameters determined from the calibration are summarized in Table 5.2. The parameters indicate that the initial telescope setup was imperfect: the starting elevation was \(-1.24^\circ\) and the mount was mis-leveled by \(1.06^\circ\). These errors can be conveniently identified and corrected in software rather than manually.

The vertical deflection coefficient is negative, indicating that the telescope tends to pitch up when it is near the horizon. This is likely due to a mass imbalance caused by instrumentation on the back of the telescope, which exacerbates an imbalance already observed with no instrumentation. A counterbalancing weight has been added to the front of the telescope but this approach is imprecise. The calibration also shows that there is a non-perpendicularity of \(0.19^\circ\) between the gimbal axes.

While a single calibration set is presented here, the calibration procedure has been conducted with this telescope over two dozen times with similar results and stable estimates for the non-perpendicularity and vertical deflection coefficient.
Table 5.2: Pointing model parameter values as calculated from calibration. Data acquired on 2/14/18 between the hours of 23:48–23:59 UTC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ST \hat{q}_{GIM} )</td>
<td>[ \begin{bmatrix} 0.00365 \ -0.0102 \ -0.9999 \ 0.0052 \end{bmatrix} ]</td>
<td>Rotation between gimbaled frame and star tracker frame determines telescope “zero” position, which is at an ENU azimuth of ( 298.8^\circ ) and elevation of (-1.24^\circ)</td>
</tr>
<tr>
<td>( MNT \hat{q}_{ENU} )</td>
<td>[ \begin{bmatrix} 0.1670 \ -0.6877 \ 0.6834 \ -0.1794 \end{bmatrix} ]</td>
<td>Rotation between mount frame and ENU frame, indicating that the mount is mis-leveled by ( 1.06^\circ )</td>
</tr>
<tr>
<td>( \hat{a}_d )</td>
<td>(-8.59 \times 10^{-4})</td>
<td>Vertical deflection coefficient resulting in maximum deflection of 177 arcseconds on horizon</td>
</tr>
<tr>
<td>( \hat{\theta}_{NP} )</td>
<td>(0.19^\circ)</td>
<td>Gimbal axis non-perpendicularity</td>
</tr>
</tbody>
</table>

5.3 Star Pointing Results

To test the accuracy of the calibration procedure, 15 bright stars were measured through the main aperture between 00:14–00:42 UTC on 2/15/18 (the same night as the calibration was conducted). Table 5.3 lists the pointing accuracy for these stars based on their location in the tracking detector behind the telescope. The telescope tracked the stars at sidereal rate for each measurement. The results are treated as a measurement of pointing accuracy rather than tracking accuracy because the observations were less than a minute each.

The pointing accuracy was 53 arcsec RMS in azimuth and 66 arcsec RMS in altitude, meeting the requirement that the blind pointing accuracy be better than 100 arcsec RMS overall (refer to Table 2.3). Every star was visible in the tracking detector behind the telescope with no feedback required, which was the motivation behind the blind pointing requirement. The open-loop pointing of the telescope is sufficient to capture the target unless large errors are introduced by another source, such as orbital error from TLEs.

As expected, these errors are worse than the 27 arcsec RMS and 37 arcsec RMS error of the calibration procedure. There are two potential causes of the decreased accuracy. First, there is a penalty for calibrating with the star tracker rather than the main aperture. There can always be some motion between the boresights of the two
Table 5.3: Star pointing results for 15 stars acquired between the times of 00:14–00:42 UTC on 2/15/18. The star’s common name as well as the local East-North-Up azimuth and altitude angles are listed with the pointing errors in each axis.

<table>
<thead>
<tr>
<th>#</th>
<th>Star Name</th>
<th>ENU Azi</th>
<th>ENU Alt</th>
<th>Azi err.</th>
<th>Alt err.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sirius</td>
<td>166°</td>
<td>29°</td>
<td>32</td>
<td>-45</td>
</tr>
<tr>
<td>2</td>
<td>Betelgeuse</td>
<td>180°</td>
<td>55°</td>
<td>-35</td>
<td>-47</td>
</tr>
<tr>
<td>3</td>
<td>Aldebaran</td>
<td>219°</td>
<td>58°</td>
<td>-18</td>
<td>-98</td>
</tr>
<tr>
<td>4</td>
<td>Procyon</td>
<td>141°</td>
<td>46°</td>
<td>-22</td>
<td>-24</td>
</tr>
<tr>
<td>5</td>
<td>Rigel</td>
<td>193°</td>
<td>38°</td>
<td>-49</td>
<td>-63</td>
</tr>
<tr>
<td>6</td>
<td>Pollux</td>
<td>114°</td>
<td>63°</td>
<td>-45</td>
<td>37</td>
</tr>
<tr>
<td>7</td>
<td>Mirach</td>
<td>288°</td>
<td>35°</td>
<td>-39</td>
<td>-92</td>
</tr>
<tr>
<td>8</td>
<td>Scheat</td>
<td>290°</td>
<td>19°</td>
<td>30</td>
<td>-59</td>
</tr>
<tr>
<td>9</td>
<td>Dubhe</td>
<td>38°</td>
<td>42°</td>
<td>55</td>
<td>73</td>
</tr>
<tr>
<td>10</td>
<td>Menkar</td>
<td>237°</td>
<td>35°</td>
<td>-7</td>
<td>-70</td>
</tr>
<tr>
<td>11</td>
<td>Algieba</td>
<td>90°</td>
<td>30°</td>
<td>89</td>
<td>52</td>
</tr>
<tr>
<td>12</td>
<td>Almach</td>
<td>290°</td>
<td>47°</td>
<td>-32</td>
<td>-13</td>
</tr>
<tr>
<td>13</td>
<td>Wezen</td>
<td>163°</td>
<td>19°</td>
<td>113</td>
<td>-28</td>
</tr>
<tr>
<td>14</td>
<td>Rho Persei</td>
<td>269°</td>
<td>68°</td>
<td>-64</td>
<td>-101</td>
</tr>
<tr>
<td>15</td>
<td>Mirfak</td>
<td>299°</td>
<td>62°</td>
<td>-63</td>
<td>-96</td>
</tr>
</tbody>
</table>

Overall RMS 53 66

Instruments due to flexure, thermal variation, etc. Second, the calibration set was 21 images for the entire sky, so it is expected that accuracy would reduce at locations far from the calibration points.

In Figure 5-6, the errors for each star are plotted against the ENU azimuth and altitude of the observation. A correlation can be seen between the altitude error and the ENU azimuth. This could indicate a small error in the fit of the calibration parameters. There could also be a shift in the mount orientation over time due to the fact that it is not rigidly mounted on a concrete pier, for example. The pointing accuracy of 1–2 arcmin is good for this class of telescope\(^1\), and the primary benefit of this approach is rapid setup that avoids manual pre-alignment. In comparison, the built-in calibration procedure for the CPC1100 tested on a different night with careful manual deployment yielded accuracies from 2–14 arcmin per star [119].

\(^1\)From personal communications with Celestron support, the guaranteed accuracy of the CPC1100 with two-star alignment is ±20 arcminutes.
Figure 5-6: Star pointing error plotted against ENU azimuth and altitude of the observation. Data acquired between the times of 00:14-00:42 UTC on 2/15/18.

5.4 Satellite Tracking Results

PorTeL is designed to track an optical downlink at a wavelength of 1550 nm to be compatible with the NODE module [20]. Because an on-orbit optical downlink is not yet available to test with PorTeL, pointing and tracking performance is validated using large LEO satellites that reflect sunlight and are often visible to the naked eye. This restricted testing to times around twilight, when it is dark on the ground but satellites are illuminated overhead. In these tests, the star tracker is used in place of an IR coarse guidance camera. The majority of testing is conducted by tracking the International Space Station (ISS), but other large satellites and rocket stages are also used.

5.4.1 Coarse Tracking

Coarse tracking refers to the phase in which closed-loop guidance camera feedback is available to the telescope, but the fine stage receiver assembly is not active (refer to Figure 4-1). During fine tracking, closed-loop feedback from the guidance camera is disabled and the coarse stage transitions to a continuous offloading of the fine stage. As a result, less data has been collected of coarse tracking alone, but several passes
at low to moderate elevation (maximum 50°) have yielded an accuracy of around 60 arcsec RMS [122, 134].

The results of a high elevation dataset are presented in Figure 5-7. The Chinese space laboratory Tiangong-2 was tracked on February 18, 2018 starting at 23:46 UTC from MIT.

Figure 5-7: Tiangong-2 pass data collected on 2/18/18 with coarse tracking. The plot on the top left shows the reference and measured gimbal angles for the pass with a peak elevation of 78°. The plot on the top right shows the reference and commanded slew rates for the pass, which shows that the azimuth slew rate was saturated for a portion of the pass. The plot on the bottom left shows the EKF estimate of the timing offset, which was nearly 3 seconds. The plot on the bottom right shows the azimuth and altitude coarse tracking error.

Tiangong-2 is in a 383 × 387 km orbit and the pass had a maximum elevation of 78°. This low orbit, high elevation pass resulted in a maximum required azimuth slew rate of 5.9 deg/s, and the maximum slew rate of the CPC1100 mount is limited to around 4.5 deg/s depending on the load. The plot in the top right of Figure 5-7
shows the azimuth rate saturated and took approximately 20 seconds to recover.

A notable aspect of the pass was the significant timing offset estimate. The bottom left plot of Figure 5-7 shows that the offset was nearly 3 seconds, which is attributable to a combination of TLE error and hardware timing error. If not compensated for, this would lead to an error of nearly 3.5° at the peak of the pass. This was one of the most significant timing offsets observed, but offsets of several tenths of a second are frequently present. Using an EKF to compensate for these errors improves the coarse tracking performance, particularly at high elevation.

The bottom right plot of Figure 5-7 shows the coarse tracking error. For this pass, the error was 58 arcsec RMS in azimuth and 215 arcsec RMS in altitude for an error of 223 arcsec RMS overall. A significant portion of the error is due to the recovery delay after the azimuth axis saturates.

When PorTeL enters the fine tracking phase, the coarse stage transitions to continuous offloading of the fine stage. During continuous offloading, the coarse error is often worse than in the coarse tracking phase. The reason for this is that during fine tracking, the most important aspect of the coarse stage tracking is that it be smooth. The magnitude of the coarse stage error is not as relevant as its spectral characteristics, as long as it stays within the range of the fine stage. This is the primary motivation for transitioning to continuous offloading.

### 5.4.2 Fine Tracking

**Results Summary**

PorTeL can track LEO satellites to better than 5 arcsec RMS during fine tracking. Figure 5-8 shows an image of the ISS taken by the IR camera during fine tracking. Table 5.4 summarizes data from nine satellite passes. Six of the nine passes tracked the ISS, one tracked the European Remote Sensing satellite ERS-2, one tracked the Russian intelligence satellite Cosmos 1455, and one tracked the Russian Resurs-O1-3 rocket body.

The orbits ranged from 400–650 km, and the maximum elevation of the passes ranged from 16° to 80°. The maximum elevation in Table 5.4 refers to the maximum elevation of the sunlit portion of the pass. In some cases, the maximum elevation of the entire pass was higher than the value in Table 5.4, but this portion could not be observed. The root-mean-square error (RMSE) and percentages of time within the pointing requirement provided in Table 5.4 refer to the duration of a pass where fine tracking was possible. They exclude periods of time where, for example, the maximum
slew rate exceeded the mount’s capability and the target was lost. Depending on the orbit, this can occur on passes above approximately 75° altitude. The maximum slew rate of the mount is 4.5 deg/s, and tracking limitations can be determined from Figure 1-5 as a function of maximum pass elevation and orbit altitude.

In seven of the nine passes, the signal stayed on the detector for >95% of the pass. In all passes, the tracking was better than 5 arcsec RMS. The two passes where <95% tracking onto the receiver was achieved were an 80° maximum elevation pass of ERS-2 on 1/23/18 and a 65° maximum elevation ISS pass on 1/24/18. In the case of the ERS-2 pass, the high elevation caused the azimuth slew rate to saturate which induced additional error. The SL-16 R/B pass on 3/26/18 also caused saturation in the azimuth rate though the ground station quickly recovered.

The other pass that fell below 95% time within the pointing requirement was the ISS pass on 1/24/18. The maximum elevation of the full pass was 83°, but fine tracking was only maintained until 65° elevation. In this case, the FSM saturated in the azimuth axis as the mount could not keep up with offloading. As a result of this pass, the offloading gain in the azimuth axis was increased to enable faster offloading in the future. Apart from this pass, the third requirement from Table 2.3, that the coarse stage error must not exceed the range of the fine stage, was met in all other passes.

A challenge of tracking large satellites is that the centroids are much larger than what would be expected from a lasercom downlink. NODE has an aperture of \( \varnothing 2.54 \text{ cm} \) and can be approximated as a point source. The Rayleigh criterion provides
Table 5.4: Summary of satellite tracking performance data acquired between 1/19/18 and 3/26/18. Date, location of test, satellite target, orbit of satellite, maximum elevation observed during pass, RMS tracking error, and percentage of time within the requirement (signal within the receiver area) are listed. Locations correspond with those described in Section 5.1.2.

<table>
<thead>
<tr>
<th>Date</th>
<th>Place</th>
<th>Target</th>
<th>Orbit</th>
<th>Max el.</th>
<th>RMSE (arcsec)</th>
<th>Met req.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/19/18</td>
<td>FL</td>
<td>ISS</td>
<td>403 × 408 km</td>
<td>23°</td>
<td>1.9</td>
<td>100.0%</td>
</tr>
<tr>
<td>1/21/18</td>
<td>FL</td>
<td>Cosmos 1455</td>
<td>502 × 525 km</td>
<td>42°</td>
<td>3.1</td>
<td>97.8%</td>
</tr>
<tr>
<td>1/21/18</td>
<td>FL</td>
<td>ISS</td>
<td>403 × 408 km</td>
<td>16°</td>
<td>2.8</td>
<td>99.2%</td>
</tr>
<tr>
<td>1/23/18</td>
<td>NC</td>
<td>ERS-2</td>
<td>498 × 504 km</td>
<td>80°</td>
<td>4.9</td>
<td>88.9%</td>
</tr>
<tr>
<td>1/23/18</td>
<td>NC</td>
<td>ISS</td>
<td>403 × 408 km</td>
<td>25°</td>
<td>4.1</td>
<td>95.1%</td>
</tr>
<tr>
<td>1/24/18</td>
<td>NC</td>
<td>ISS</td>
<td>403 × 408 km</td>
<td>65°</td>
<td>4.3</td>
<td>93.8%</td>
</tr>
<tr>
<td>1/25/18</td>
<td>NC</td>
<td>ISS</td>
<td>403 × 408 km</td>
<td>18°</td>
<td>3.0</td>
<td>98.7%</td>
</tr>
<tr>
<td>2/27/18</td>
<td>MA</td>
<td>ISS</td>
<td>403 × 408 km</td>
<td>64°</td>
<td>4.2</td>
<td>95.4%</td>
</tr>
<tr>
<td>3/26/18</td>
<td>MA</td>
<td>SL-16 R/B*</td>
<td>635 × 644 km</td>
<td>79°</td>
<td>3.9</td>
<td>95.3%</td>
</tr>
</tbody>
</table>

*NORAD ID: 23343

the approximate angular resolution of a point source as $\theta = 1.22\lambda/D$ where $\lambda$ is the wavelength and $D$ is the diameter of the aperture. For a 1550 nm wavelength and a $\varnothing 28$ cm aperture, the angular resolution is 1.4 arcsec.

The ISS has dimensions of $109 \times 73$ m². Considering the longest dimension of the ISS, at a distance of 1500 km it spans 15 arcsec and directly overhead at 400 km it spans 56 arcsec. The angle of the ISS and other large satellites is very large relative to tracking errors of a few arcseconds. A point source would produce a smaller, more stable centroid, and it is possible that some of the error from tracking is due to the large footprint of the target. This effect should be assessed when a more suitable target becomes available.

The fourth requirement from Table 2.3, that the signal must stay on the receiver, was not completely met, though seven of the nine passes had >95% of the pass on the receiver. To improve this metric further, suggestions are provided in Section 6.3.

**Sample Pass**

To look in more detail at the tracking performance, the full results of one of the passes from Table 5.4 is presented. The ISS pass on February 27, 2018 tracked the ISS through a peak elevation of 64°. The pass angles as well as the coarse and fine tracking error are shown in Figure 5-9. The maximum coarse error is 225 arcsec
in azimuth and 175 arcsec in altitude, and the RMSE is 106 arcsec in azimuth and 57 arcsec in altitude. As noted in Section 5.4.1, the coarse error during fine tracking is actually worse than during coarse tracking. While the error is larger, the corrections are smoother, resulting in better tracking with the fine stage.

![Gimbal angles and tracking error plot](image)

**Figure 5-9:** Plot of gimbal angles and coarse/fine tracking error for an ISS pass on 2/27/18. Maximum elevation of the pass is 64°. Oscillations can be seen in the coarse altitude tracking error which limit overall performance.

As can be seen in the bottom plot in Figure 5-9, there is some oscillation in the coarse altitude axis. While an attempt was made to adjust the gain in that axis to reduce oscillations, testing opportunities were limited and further adjustments to gain should improve performance in this axis. The oscillations become particularly problematic at high elevation passes and are a significant driver of error. There are two potential improvements to help this issue: first, continued tuning of the gains in Equations 4.19 and 4.20 could help to reduce oscillations, and second, the receiver assembly mass could be reduced. The motors driving the altitude axis are challenged
by the increased rotational inertia, while the azimuth axis still performs well with the increased load.

Figure 5-10 shows the FSM offload angles plotted with the slew rates for the pass. It can be seen that the offload angles correlate negatively with the slew rate. In this case, the telescope was leading the ISS from the start of the pass. Looking across other passes, errors are not always in a consistent direction (i.e. sometimes leading, sometimes lagging) [134]. This is consistent with a timing error that was not fully compensated for with the EKF.

![Offload angles and slew rates for ISS pass on 2/27/18](image)

Figure 5-10: Azimuth and altitude slew rates plotted with FSM offload angles for an ISS pass on 2/27/18. The offload angles correlate negatively with the slew rate, indicating that the open-loop trajectory is leading the satellite.

A limitation on EKF performance is the time delays in communication with the mount. The interface with the mount is serial over USB, which results in imprecise timing. The delay for a request for encoder angles varies by approximately ±20 ms, which directly limits the accuracy of the EKF. The offload angles from the FSM were not incorporated as measurements for the EKF, but this is a possibility for future work. An observation of a target with the knowledge of the fine stage correction provides a direct measurement of the coarse stage error. This can be used as a residual assuming that control error is small compared to the errors in the estimated angles to the target. Given that control errors measured in the lab have been <10 arcsec, this is likely the case.
Performance Drivers and Limitations

A key performance driver for fine tracking has been a transition to continuously offloading the fine stage, as described in Section 4.3.1. Initially the coarse and fine stages were operated independently and the coarse stage continued to receive feedback from the coarse guidance camera at a rate of 0.5 Hz. During the 2 seconds between corrections the coarse stage drifted significantly and then executed a large correction step. This step response was hard for the fine stage to keep up with and resulted in large errors fine tracking. Figure 5-11 shows an example pass before and after offloading was initiated. Continuous offloading is necessary to keep the signal on the receiver.

![Tracking accuracy of ISS on detector, 1/19/18](image)

Figure 5-11: Tracking error relative to the receiver area during an ISS pass on 1/19/18 with offloading and without offloading the FSM. Offloading significantly improves tracking accuracy.

The EKF estimating timing error also helped to offset cases where timing errors were very large, as described in Section 5.4.1. While large timing offsets were not always observed, if a large error is present, closed-loop tracking performs poorly without a correction to the reference trajectory. The benefit of the EKF is that it addresses the root cause of the error, rather than trying to correct it with a series of angular offsets.

Regarding limitations of PorTeL, it was initially hypothesized that an increase in fine tracking error at high elevation angles was due to the keyhole problem that
results in azimuth slew rate saturation. To determine if this was the case, all the tracking data from the passes listed in Table 5.4 was combined and analyzed. The data was binned based on the azimuth rate and the failure rate (time in which the fine tracking is outside of the receiver area) within each bin was calculated. The same procedure was conducted for altitude rate, and the results are shown in Figure 5-12. In each bin there are at least \( N > 100 \) sample points, though the number of samples in each bin varies.

![Failure rate vs. slew rate](image)

Figure 5-12: Failure rate of ground station tracking as a function of azimuth and altitude slew rates. A data point is considered a failure if it falls outside of the receiver area. Data from nine satellite passes is binned by slew rate and the fraction of time that the pointing requirement is not met is calculated. Failure rate correlates strongly with altitude rate.

While the failure rate generally increases with both azimuth and altitude rate and it is important to note that azimuth and altitude rates are correlated, the highest failure rates result from large altitude slew rates. This is consistent with the oscillations that are observed in the coarse altitude axis as in Figure 5-9. It is hypothesized that this is driving the increase in tracking error at high elevation. Again, this points to reducing the mass of the receiver assembly as an important step to improve tracking.

While the peak azimuth slew rate occurs at the maximum elevation of the pass, the peak altitude slew rate occurs twice along the trajectory, once before and after the maximum elevation. The largest tracking errors are observed at these points of maximum altitude slew. While the azimuth axis slew rate is at risk of saturating due to the keyhole problem, the altitude axis is producing more error until azimuth saturation occurs.
Figure 5-13 shows the maximum slew rates in azimuth and altitude as a function of maximum pass elevation for a satellite in a 400 km orbit. The slew rate in the altitude axis increases more modestly with maximum elevation of the pass. Above 0.7 deg/s in altitude the failure rate exceeds 20%, so improving performance in this axis should be the focus of future development of PorTeL.

![Graph showing maximum slews rates in azimuth and altitude as a function of maximum elevation of pass for a 400 km orbit. The keyhole problem results in large azimuth slew rates at high elevation.]

Figure 5-13: Azimuth and altitude slew rates as a function of maximum elevation of pass for a 400 km orbit. The keyhole problem results in large azimuth slew rates at high elevation.
Chapter 6

Conclusion

6.1 Summary

Laser communications is rapidly transitioning from early stage demonstrations to a backbone technology for future communications. Compared with RF, lasercom offers the potential for lower size, weight, and power due to its efficient, narrow beamwidths. The key challenges of lasercom systems are the need for precise pointing and compensating for unavailability due to weather.

There has been a push in space-based laser communications, and space systems in general, to move towards smaller, cheaper, and more flexible systems. This is evidenced by the rapidly growing small satellite market and a number of efforts to build lasercom systems for small satellites. While miniaturization and cost-reduction has advanced for space lasercom terminals, much less focus has been given to designing a ground station with similar aims. The need for a robust network to overcome weather constraints makes development of a low-cost, flexible ground station particularly important.

This thesis represents one approach to fill that gap. The Portable Telescope for Lasercom (PorTeL), the outcome of this thesis, demonstrates the feasibility of using an amateur telescope as an optical ground station. With low-cost, COTS components, PorTeL achieves the following objectives: 1) it can be rapidly deployed and calibrated within 30 minutes, 2) its blind pointing accuracy is better than 100 arcseconds RMS, and 3) it can track LEO satellites to within 5 arcseconds RMS. These objectives have been validated with a physical ground station setup used to track stars and LEO satellites.

PorTeL is compact enough to be physically moved and deployed by 1–2 people and fits into the trunk of a car. PorTeL reduces mass and cost by at least $10 \times$, from
hundreds of kilograms to tens of kilograms and millions of dollars to tens of thousands of dollars, compared to existing optical ground stations. Small, low-cost apertures can complement large, fixed optical ground stations as lasercom expands its reach.

6.2 Contributions

The primary contributions of this thesis are restated below. Subpoints within each contribution provide additional detail.

1. A system architecture for a low-cost portable optical ground station that tracks LEO satellites

   - The ground station is described as “portable”, meaning that it can be manually moved and deployed. Existing transportable ground stations have used trucks or shipping containers for transport.
   - Many low-cost COTS telescopes have incremental encoders, which makes rapid calibration essential. The approach of using a star tracker with a high-fidelity pointing model enables accurate pointing from low-cost telescopes.
   - A small, lightweight back-end optical assembly was developed that attaches directly to a COTS telescope without a need to modify the existing mount.

2. A high-fidelity telescope pointing model that is rapidly calibrated using a star tracker with minimal manual input and no assumptions about initial orientation

   - A quaternion-based approach enables straightforward use of star tracker measurements in a mathematically rigorous formulation.
   - The pointing model encompasses the major parameters from professional software, yet takes minutes rather than hours to calibrate.
   - The elimination of initial mount and telescope orientation assumptions means that no manual pre-alignment, such as leveling or zeroing, is required. The software functions with any two-axis mount and it is not necessary to specify the mount type.

3. A staged control approach for tracking LEO satellites that enables better than 5 arcsecond tracking using two line element sets (TLEs) and low-cost hardware
To enable use of TLEs despite sometimes significant in-track error, an extended Kalman filter (EKF) was developed to estimate a timing offset.

- Tracking angles and rates are derived analytically from the pointing model.
- Continuous offloading of the fine stage by the coarse stage improves tracking to the accuracy required for lasercom.

4. Experimental validation of contributions #1–3 with the Portable Telescope for Lasercom (PorTeL)

- Testing was conducted in multiple diverse locations and PorTeL was transported and deployed from a car.
- PorTeL was able to track a signal from a LEO satellite accurately enough to hold it on a receiver, demonstrating its potential for use with a lasercom downlink.

6.3 Future Work

Areas for further development of PorTeL are listed below. Some of the areas expand on work in this thesis, while others are remaining work that will enable use of PorTeL as an operational ground station.

- **Beacon design:** The design of the uplink beacon was not addressed in this thesis. NODE was designed with the expectation that the ground station provides a wide beacon that the satellite sees and uses to correct its pointing so that the ground station detects it. It is not expected that the initial pointing of the satellite is sufficient for ground station detection, so a beacon is essential. While preliminary link budgets have been conducted [92], the beacon should be redesigned based on the open-loop pointing capabilities of the ground station. The open-loop pointing performance of PorTeL is overall 85 arcseconds RMS. Additional error is introduced if TLEs are used to track the satellite. Tradeoffs between beamwidth, power, scanning, acquisition time, and monostatic/bistatic architectures must be considered.

- **Receiver assembly:** As mentioned in the discussion of satellite tracking results, it is hypothesized that the receiver assembly mass is a current bottleneck on the performance. The current version of the receiver assembly uses a threaded aluminum optical breadboard, which allows components to be moved
around easily during development. Once the layout is finalized, as-is or with modifications, a custom tray and shroud should be constructed to hold the components and minimize mass. Mechanical stiffness and thermal response should be considered. Additionally, a more precise alignment of the back-end optical components is necessary. While rough alignment was sufficient to assess pointing performance, it is necessary to align more precisely to minimize optical losses.

- **Embedded platform:** PorTeL currently runs off of a laptop PC with an operator in the loop. This requires the operator to be physically located with the platform. The ground station should be configured for remote operations by replacing the laptop with a compact processor. The software currently runs within a Windows framework. While this enabled easy development of a user interface, it is not a sustainable framework for real-time control. Tracking performance would likely improve by porting the software to another framework such as real-time Linux.

- **Autonomous operation:** Current operation of the ground station requires significant operator input. All controller functions are initiated by the operator, and there is still substantial reliance on operator oversight to ensure the software is correctly identifying and tracking the target. The performance of PorTeL has stabilized significantly from earlier phases of development, and it would benefit from additional work towards automating operator tasks.

- **Controller improvements:** There are multiple ways to improve the existing fine and coarse control. The simplest modification to the coarse stage control is to continue gain tuning as discussed in Section 5.4.2. The first suggestion to reduce altitude axis oscillation is to lightweight the receiver assembly, but if it continues to be an issue, a derivative controller term may be considered to dampen the oscillations. Simple improvements to the fine stage control include adding a feedforward term during offloading to the coarse stage, and also adaptively windowing the tracking detector for faster readout rates. However, it is recommended that this be pursued only after transitioning to a better real-time framework.

- **Environmental robustness:** This thesis only assessed the performance of PorTeL at night directly after performing a calibration. Testing was conducted over a wide span of temperatures, roughly 20° to 80° F, but the amount of
thermal shift within the setup was not rigorously characterized. This should be assessed along with calibration stability over time, particularly with respect to the potential for daytime operations. The effect of wind and potential mitigation strategies should also be investigated. Experience indicates that winds up to around 15 mph are manageable, albeit with reduced performance. This should be more formally characterized and temporary enclosures should be considered.

- **Daytime operations:** Due to time constraints, exploration of daytime operations was not considered in this thesis. The design of the ground station (e.g., aperture size, APD) was based on a link budget assuming daytime operation, so with a tight optical filter daytime communication should be possible. At the moment, however, calibration is only possible at night. The simplest solution is to calibrate at night and assess whether or not the setup is stable enough for the calibration to remain valid during daytime, perhaps with a small enclosure. If calibration during daytime is required, stars with bright IR signatures will have to be sighted individually and modification to the existing software will be required. A hybrid approach could calibrate at night and then sight a few IR stars individually during the day to fine-tune the parameters. More careful consideration of daytime operations is needed.

- **Validation with a lasercom link:** From its conception, the goal of PorTeL has been operational use with an on-orbit lasercom terminal. The performance of PorTeL should be validated through a communications link with an on-orbit terminal, NODE or other, once it becomes available.
Appendix A

Vector Notation

This appendix describes the vector notation used throughout the thesis. Vectors are denoted with bold font (e.g., \( \mathbf{v} \)). Vectors in general are written in the following format:

\[ \mathbf{v}_{\text{desc.}} |_{\text{FRAME}} \]  

(A.1)

where the subscript \( \text{desc.} \) contains descriptive identifying information and \( |_{\text{FRAME}} \) explicitly notes the frame in which the vector is defined. Unit vectors are distinguished by \( \mathbf{u} \).
Appendix B

Quaternion Conventions

This appendix outlines the quaternion conventions, notation, and important relationships that are used in this work.

The vector and scalar components of a quaternion \( q \) are represented as:

\[
q = \begin{bmatrix} Q \\ q \end{bmatrix}
\]  
(B.1)

with the vector component \( Q \) appearing before the scalar component \( q \).

With this convention, multiplication of quaternion \( p \) by quaternion \( q \) is given by:

\[
p \otimes q = \begin{bmatrix} pQ + qP - P \times Q \\ pq - P \cdot Q \end{bmatrix}
\]  
(B.2)

The notation used for the direction cosine matrix corresponding to a quaternion is \( A(q) \), which can be calculated by:

\[
A(q) = \begin{bmatrix}
q^2 + Q_0^2 - Q_1^2 - Q_2^2 & 2(Q_0Q_1 + qQ_2) & 2(Q_0Q_2 - qQ_1) \\
2(Q_0Q_1 - qQ_2) & q^2 - Q_0^2 + Q_1^2 - Q_2^2 & 2(Q_1Q_2 + qQ_0) \\
2(Q_0Q_2 + qQ_1) & 2(Q_1Q_2 - qQ_0) & q^2 - Q_0^2 - Q_1^2 + Q_2^2
\end{bmatrix}
\]  
(B.3)

Given a rotation angle \( \theta \) and a unit vector rotation axis \( u \), the corresponding quaternion \( q \) can be calculated by:

\[
q = \begin{bmatrix} \sin(\theta/2)u \\ \cos(\theta/2) \end{bmatrix}
\]  
(B.4)
A relationship between two quaternions \( p \) and \( q \) that is frequently used in this thesis is given by:

\[
q \otimes p \otimes q^{-1} = \begin{bmatrix} A(q) & 0 \\ 0 & 1 \end{bmatrix} p
\]  \hspace{1cm} (B.5)

The current estimate of a quaternion has an error of \( \delta q \) such that the true quaternion \( q \) is given by:

\[
q = \delta q \otimes \hat{q}
\]  \hspace{1cm} (B.6)

where \( \hat{q} \) is the quaternion estimate.

Finally, while it is not done in this appendix, in most cases quaternions are written to explicitly note the reference frames as \( ^Aq_B \), which represents a rotation from frame B to frame A.
Bibliography


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