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THESIS

SATELLITE TRACKING WITH TELESCOPE AND SOFTWARE

by

Laura G. Anderson

September 2019

Thesis Advisor: Charles M. Racoosin
Second Reader: James A. Horning

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Space is becoming increasingly congested and contested as small satellites, to include CubeSats, are launched in greater numbers. The Space Systems Academic Group at the Naval Postgraduate School purchased an advanced commercial-off-the-shelf (COTS) telescope from Meade Instruments (model LX600) with the goal of tracking CubeSats and as an educational tool for postgraduate students. This thesis specifies a plan, based on research and proof-of-concept testing, for NPS to create an automated (closed-loop) optical telescope system capable of detecting and tracking CubeSats in low Earth orbit. Satellite tracking will be a new capability for NPS, and will allow for future work in multiple areas, to include orbit determination, space situational awareness, and laser communications. This thesis recommends additional equipment, dedicated software, and permanent staging of the telescope system in order to attain a closed-loop satellite tracking system with an optical telescope.

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SATELLITE TRACKING WITH TELESCOPE AND SOFTWARE

Laura G. Anderson
Lieutenant Commander, United States Navy
BS, Worcester Polytechnic Institute, 2009

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Approved by: Charles M. Racoosin
Advisor

James A. Horning
Second Reader

James H. Newman
Chair, Department of Space Systems Academic Group

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ABSTRACT

Space is becoming increasingly congested and contested as small satellites, to include CubeSats, are launched in greater numbers. The Space Systems Academic Group at the Naval Postgraduate School purchased an advanced commercial-off-the-shelf (COTS) telescope from Meade Instruments (model LX600) with the goal of tracking CubeSats and as an educational tool for postgraduate students. This thesis specifies a plan, based on research and proof-of-concept testing, for NPS to create an automated (closed-loop) optical telescope system capable of detecting and tracking CubeSats in low Earth orbit. Satellite tracking will be a new capability for NPS, and will allow for future work in multiple areas, to include orbit determination, space situational awareness, and laser communications. This thesis recommends additional equipment, dedicated software, and permanent staging of the telescope system in order to attain a closed-loop satellite tracking system with an optical telescope.

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LIST OF ACRONYMS AND ABBREVIATIONS

1U	one unit (CubeSat)
3U	three unit (CubeSat)
AFOV	apparent field of view (eyepiece)
Alt-az	altitude-azimuth
CCD	charge coupled device
CLI	command line interface
CMOS	complementary metal oxide semiconductor
COTS	commercial off-the-shelf
FOV	field of view
GEM	German equatorial mount
GEO	geostationary Earth orbit
GPS	global positioning system
GUI	graphic user interface
ISS	International Space Station
LEO	low Earth orbit
LOS	line of sight; loss of signal
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
NPS	Naval Postgraduate School
SATCAT	satellite catalog
SATCOM	satellite communications
Smallsat	small satellite
SSA	space situational awareness
SSAG	Space Systems Academic Group
STK	Systems Tool Kit
TFOV	true field of view (telescope)
TLE	two line element
USSTRATCOM	United States Strategic Command

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I. INTRODUCTION

Observing objects in outer space has been done with the naked eye for thousands of years, but new technology is changing how we view and utilize space. Recently, there has been increased interest, investment, and development by numerous entities across the globe toward expanding into space. In the United States, commercial companies are announcing ambitious plans for launching thousands of small satellites into low Earth orbit (LEO) within the next decade for communications networks, as well as for photography (Koziol 2019). This poses a challenge to space observers that want to track and view such small objects using commercial off-the-shelf (COTS) equipment. One type of small satellite, called a CubeSat, is growing in popularity due to its modular design and affordable-to-create size; it is a 10 cm by 10 cm by 11 cm cube-shaped satellite that can be combined with another CubeSat to create a bigger (but still small) satellite. CubeSats have been constructed by schools and universities for space-based experiments, and are increasingly capable due to technological miniaturization advancements. They are easily and inexpensively launched into orbit, and are enabling a new era of space usage and experimentation.

CubeSats are small and fast-moving, presenting a challenge to the agencies within the U.S. Department of Defense that are tasked with the complex problem of tracking all satellites orbiting Earth. The simplest and most direct means of keeping track of on-orbit satellites is visually, usually with a ground-based optical telescope. Detecting, acquiring, and tracking CubeSats with an optical telescope system is a capability achieved by many companies, organizations, universities, and even amateur astronomers—but is not a current capability of the Naval Postgraduate School (NPS). NPS is currently pursuing such a capability for the Space Systems Academic Group (SSAG). This capability could be incorporated into “hands-on” lab work associated with a number of space systems courses, and would greatly expand the areas of research available to the SSAG. Many organizations and astronomers have open-loop telescope systems, which involve predicting the path of the satellite across the sky, while fewer have closed-loop systems. Closed-loop systems, the gold standard for tracking, are able to detect the location of an object relative to a point in the field of view (FOV), and calculate corrective actions needed to maintain pointing at the object: the software part of the system receives feedback (i.e., from a detector, such as a camera) and then provides pointing commands in real time as it works to keep the target object in the FOV.

A closed-loop system is much more difficult to create and maintain, but would set NPS apart and ahead in the field of satellite tracking and provide a foundation for future research and experimentation in emerging communications technology. It would also contribute significantly to the educational mission of the NPS SSAG, which in turn would benefit the U.S. armed services that send dozens of their officers to study space systems operations and space systems engineering as postgraduate students.

A CubeSat tracking capability has the potential to improve and reinforce important aspects of the NPS curriculum. A telescope with the ability to perform something as complex as tracking a satellite in LEO could be utilized by the SSAG to demonstrate core concepts of orbital mechanics, including orbit determination—that is, taking a few positional measurements (azimuth and elevation) over a given timeframe and calculating the trajectory of a satellite in orbit and the associated parameters which describe the motion. The real-world application of orbit determination, which is currently only taught in the classroom setting, would reinforce students' understanding of this core concept. Students could utilize a telescope to take measurements required for orbit determination and appreciate the challenge faced by organizations tasked with keeping account of satellites in orbit.

An additional concept taught by the SSAG that could be reinforced through operating a closed-loop optical satellite-tracking telescope is the foundation for satellite communications (SATCOM): accurate pointing. Students would be able to gain hands-on experience with the challenges that accompany accurate pointing required to enable SATCOM. An NPS closed-loop telescope system would demonstrate the same capability that is required by modern communications systems.

Lastly, a core concept that the SSAG teaches that can be reinforced with students is space situational awareness (SSA). SSA is another field in which students would benefit from demonstrating the ability to visually detect or photograph a satellite through use of a telescope. Even amateur astronomers that have the capability of visually finding and tracking a satellite can contribute to overall SSA. SSA is becoming increasingly important as space becomes more congested: commercial companies have plans to launch thousands of small satellites into orbit in the near future (Henry 2019). SSA is also vital for Department of Defense operations, as U.S. adversaries are becoming spacefaring nations and deploying satellites in increasing numbers—making space another domain that is a contested environment. Adversary nations are well on their way to denying U.S. the free and unhindered use of space that it has had in the past. Using a telescope system for a SSA exercise would lead students to appreciate the challenges and importance of maintaining precise SSA.

This thesis provides a roadmap for NPS to build an optical system capable of tracking CubeSats, detailing a plan to bring NPS's capabilities a step further with a closed-loop tracking system, through the purchase and use of mostly COTS products. This system would provide an invaluable practical experience to SSAG students and allow for new research and experiments to be carried out at NPS.

A. RESEARCH QUESTIONS

1. What metrics and factors are necessary in order to successfully acquire and track a satellite, as small as a CubeSat, with a computerized optical telescope?
2. What components should NPS purchase or create in order to achieve this capability?

B. THESIS OVERVIEW

The next chapter, Satellite Tracking Fundamentals, discusses the requirements behind detecting and tracking small satellites in LEO. The chapter includes characteristics of necessary equipment, satellite locational data, and factors that affect the capability to find and track objects with a ground-based, computerized, optical telescope system. Chapter III, Open- and Closed-Loop Satellite Tracking System Requirements, gives details regarding the necessary components of a satellite tracking system. Chapter IV, Demonstration and Results, describes the proof of concept testing toward building this new capability for NPS SSAG. Based on research and proof of concept testing, Chapter V, Conclusion, lists recommended equipment that NPS SSAG needs to purchase and / or build in order to achieve a long-term sustainable closed-loop tracking system that will be capable of detecting and tracking objects in LEO as small as a CubeSat.

II. SATELLITE TRACKING FUNDAMENTALS

Many complex factors must be accounted for in order to detect and track an object in low Earth orbit (LEO), or at a range between 180–2,000 km altitude. The task of tracking satellites in LEO grows more important and more challenging as technology allows for smaller satellites to be placed into orbit in greater numbers. The characteristics of both a target satellite and the telescope system being utilized impact the success of acquiring and tracking on-orbit objects. The visibility of a CubeSat, categorized as a small satellite, depends on its size, materials, and orientation. A computerized telescope system, which can be easily customized due to commercially available options, is typically described by features including its aperture size, focal length, and slew rates. This section explains the characteristics of both CubeSats and telescope systems that contribute toward the capability of acquiring and tracking a satellite, as well as information necessary to understanding how a computerized telescope system is able to find and track an object as small as a CubeSat.

A. CUBESAT CHARACTERISTICS

The mission of a satellite is the driving force behind its design–CubeSats achieve a balance between cost, size, and capability. The small size of a CubeSat keeps production costs low, and makes them more economical to launch into orbit. However, their small size presents a challenge to those wanting to track them. As their name suggests, most CubeSats are cubes or rectangular, composed of six flat panels, with a 1 Unit (1U) CubeSat measuring 10 cm by 10 cm by 11 cm with a mass between 1 and 1.33 kg (NASA, 2017). Another common configuration for a CubeSat is 3 Units (3U), which is simply three 1U CubeSats; these configurations are pictured in Figure 1.

Figure 1. CubeSat Dimensions. Source: NASA (2017).

A CubeSat's size is only the first characteristic that makes it a challenge to view with a ground-based telescope. The materials with which the CubeSat is built impact its ability to reflect sunlight, as does the geometry between the satellite, the sun, and the observer.

A CubeSat's materials are one factor that contributes to how easily visible it is from Earth—its visibility is rated on a scale, referred to as visual magnitude. Visual magnitude is essentially a ranking system based on how much light is transmitted or reflected, allowing it to be detected (by a human eye or a camera). There are two methods for satellite illumination: reflected and transmitted. Reflected illumination relies on sunlight and is considered passive. Passive illumination implies that there is no energy transmitted from the ground or from the satellite. The opposite is transmitted illumination: an active source of energy (such as a laser) is directed from the ground, or the satellite transmits light via an onboard beacon. In his paper for the Smithsonian Astrophysical Observatory, "Optical Tracking of Artificial Satellites," George Veis, a professor at the National Technical University in Athens, Greece, explained visual magnitude at a basic level:

> The apparent magnitude of an artificial satellite, expressed in stellar magnitudes … is a major element in optical tracking. Since almost all satellites are sun-illuminated, the apparent magnitude will depend on many factors, the most important being the size and shape of the satellite, its distance from the observer, and its orientation. (Veis 1963, 253)

This thesis focuses on reflected light because currently, most small satellites are not equipped for transmitted light.

An understanding of the visual magnitude rating system is helpful when determining the likelihood of being able to find and track a CubeSat with a telescope. Visual magnitude is a number that indicates brightness of an object; greater positive values indicate less bright objects, while negative values indicate brighter objects. Most sources of satellite locational data, as well as web-based applications that cater to the amateur astronomer hoping to see a satellite pass overhead, give an expected visual magnitude rating. Satellites' magnitudes, based on the location of the observer, are difficult to predict because the brightness of a satellite is influenced by multiple constantly changing factors. These factors include Earth's atmospheric conditions, the geometry between the observer and the satellite and the sun, and even the age of the satellite. This means that the same CubeSat may be visible during one pass and not visible during the next; each opportunity must be individually estimated. Estimation of the visual magnitude is just that: although an indication that the satellite will not have a favorable visual magnitude, due to the many possible variations, an attempt at detection and tracking is not unwarranted.

The National Oceanic and Atmospheric Administration (NOAA) summarizes on its website the foundation for the visual magnitude system: that the brighter an object appears in the sky, the lower the number assigned to its magnitude (NOAA 2015). Table 1 lists well-known celestial objects and their visual magnitudes, as well as the naked eye limit. The naked eye limit is the highest (i.e., dimmest) visual magnitude the average human eye is capable of seeing without any optical aids.

Table 1. Common Visual Magnitudes. Adapted from NOAA (2015).

Visual Magnitude	Celestial Object
-26.7	Sun
-12.6	Full moon
-4.4	Venus (at brightest)
-3.0	Mars (at brightest)
+6.0	Naked eye limit
+30	Faintest observable by the Hubble Telescope

In his thesis “Optical Tracking and Spectral Characterization of Cubesats for Operational Missions,” author Forrest Gasdia of Embry-Riddle Aeronautical University estimated that a 3U CubeSat in a LEO orbit (450 km) may be magnitude +10.1 or dimmer, depending on materials (2016). In order to see an object of this visual magnitude, this value is important to keep in mind when considering the characteristics of the equipment that will be needed.

Because a CubeSat’s visual magnitude is partially dependent on the reflectivity of its surfaces, it is difficult to generalize their visual magnitude. The wide variety of missions requires a variety of components and sizes—for example, if a CubeSat’s mission is communications-based, it may have antennas, which likely are composed of metal, which would increase its visual magnitude. Solar panels, another common feature on CubeSats, are highly reflective and would contribute to an increase in visual magnitude. If the solar panels deploy outward from the body of the CubeSat, it will significantly increase its apparent size, which would increase its visual magnitude. A smooth finish tends to be more reflective than a rough finish; this is true for spherical and cube-shaped satellites (Gasdia 2016). A highly reflective satellite will be more easily detected by a telescope; a 3U CubeSat with solar panels on the four long sections will be brighter than a 1U CubeSat under the same conditions. Specifically for cube-shaped satellites, the visual magnitude is impacted by the area of the plate of the satellite; Figure 2 shows this relationship between area and visual magnitude. For comparison, a 1U CubeSat has a plate area of 0.01m^2 and a 3U CubeSat has approximately 0.03m^2 of surface area on its largest surface—a worst-case estimate gives a 1U CubeSat a visual magnitude of +12 and a 3U a visible magnitude of +10.5. As expected, a 3U CubeSat will have a better visible magnitude due to its larger surface area.

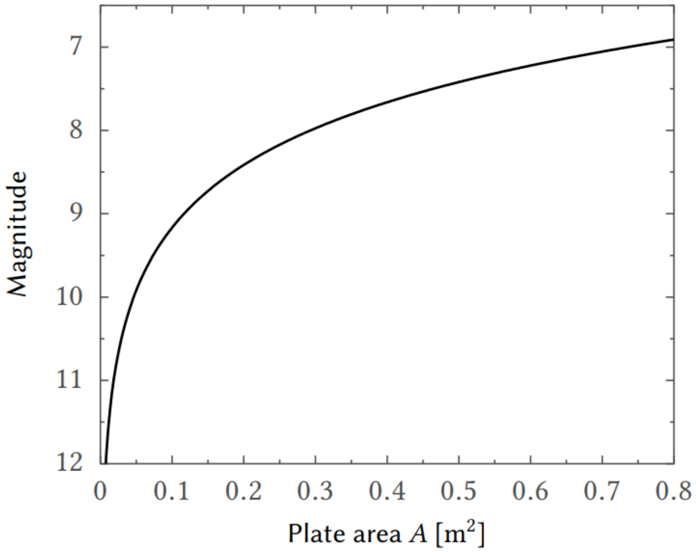


Figure 2. Satellite Magnitude by Plate Area. Source: Gasdia (2016).

A satellite's visual magnitude relates to its distance from the observer on a logarithmic scale. Each increment of 1 on the visual magnitude scale equals an approximate change of 2.512 times in brightness (Gasdia 2016). For example, if a satellite's visual magnitude increases from +11 during one pass to +10.0 during the following pass, it will appear roughly 2.5 times brighter on the second pass than it did the first. Likewise, an object with a +5 visual magnitude will appear 100 times brighter than an object with +10 visual magnitude because it is 5 orders of magnitude brighter ($2.512^5 = 100$). The visual magnitude scale is an important factor when considering the likelihood a telescope, based on its aperture size, will be successful in detecting and tracking the satellite. Telescopes and their limiting magnitude (i.e., the brightest visual magnitude it is able to detect) are discussed in B.1.

Another key aspect of being able to detect a CubeSat with a commercial optical telescope is the orientation and geometry of the satellite. In order to see a small satellite, some basic conditions are ideal: the observer is in darkness, while the satellite is illuminated by sunlight (as illustrated in Figure 3); the weather (terrestrial and atmospheric) between the satellite and the observer is clear and calm; the satellite reflects sunlight toward the observer.

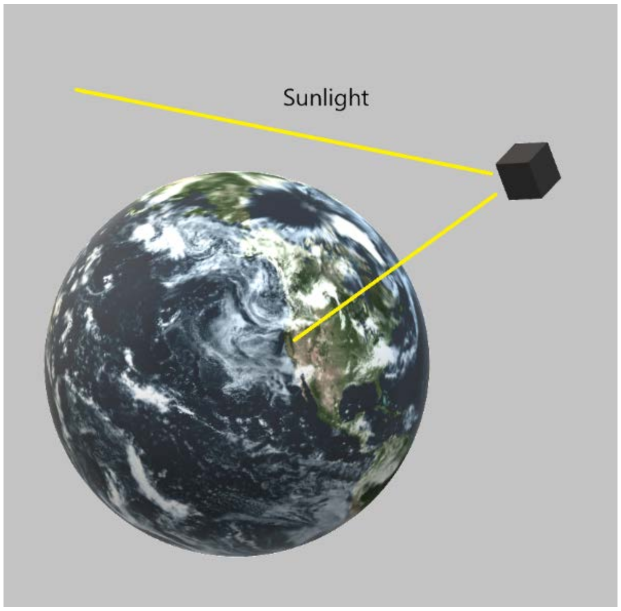


Figure 3. CubeSat Illumination

Because a CubeSat is such a small object to detect with a commercial telescope, it would be difficult (but not impossible) to use COTS equipment to determine the attitude of the satellite—i.e., how the CubeSat is oriented with respect to the Earth and sun. The attitude is important if the satellite requires aiming in order to accomplish its mission. For example, if a CubeSat is equipped with a camera for photographing weather patterns, its attitude needs to be controlled to orient the satellite's camera toward Earth. CubeSat attitudes are difficult to maintain due to size, weight, and power restrictions that prevent them from having precise and sophisticated attitude control systems that much larger satellites are equipped with. However, new CubeSats often are stabilized, ensuring they are oriented a particular way. Knowing the expected orientation of a CubeSat, particularly for calculating the geometry between the sun, satellite, and observer, is helpful when calculating the visual magnitude.

One final factor in estimating the visual magnitude and likelihood of being able to detect a satellite with a telescope is the distance from the observation site on Earth to the satellite. The range of altitudes of satellites in LEO is 180–2,000 km (Riebeek 2009); this thesis focuses on detecting and tracking CubeSats within this range. Other orbits in which CubeSats can be placed in include Medium Earth Orbit (MEO), Highly Elliptical Orbit (HEO), and Geostationary Orbit (GEO). Figure 4 depicts these common orbits, starting with LEO closest to Earth, moving outward to a MEO orbit, followed by the oval-shaped HEO orbit, and finally the GEO orbit is farthest from Earth.

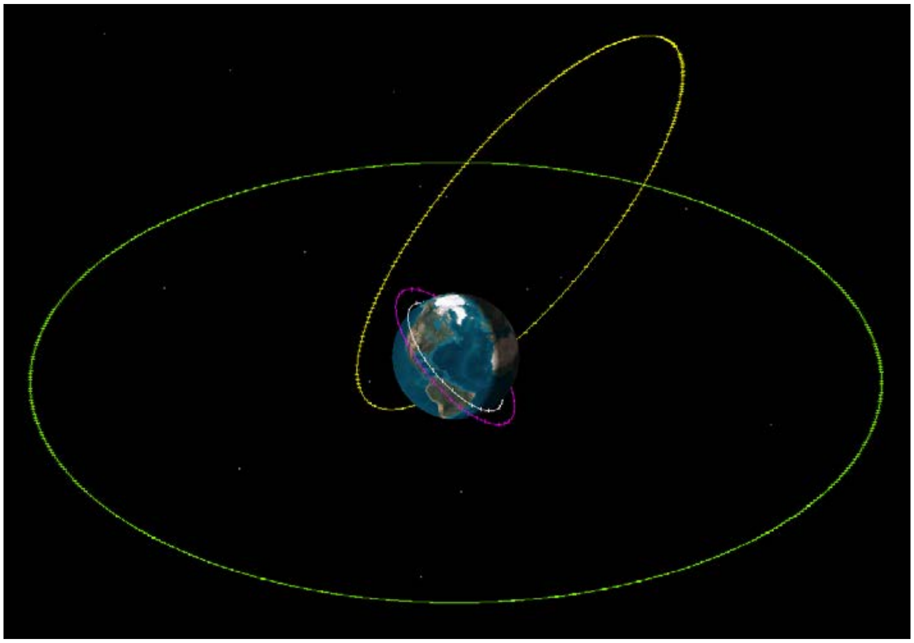


Figure 4. Basic Orbits

The farther a CubeSat is from Earth's surface, and the lower to the horizon it appears to the observer, the more difficult it is to detect and track (all other factors being equal). This is due to the angular distance between the satellite and the observer (Thompson 2012, 21). When the satellite appears to an observer to be low to the horizon, it is farther away than when the satellite is directly overhead (at zenith). This geometric scenario is depicted in Figure 5. The distance marked in red is greater than the distance marked in green.

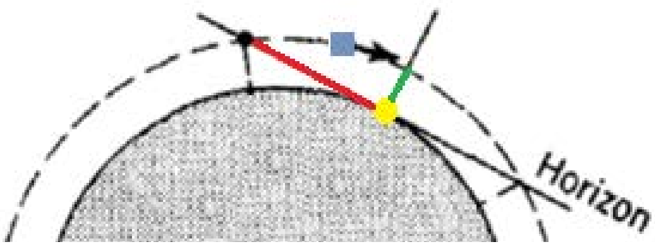


Figure 5. Angular Distance Diagram. Adapted from Thompson (2012, 26).

The distances differ, as do the rates at which the satellite appears to be traveling (from the observer's perspective). Calculating the difference in apparent angular rates for a satellite in LEO can be done in a few steps. First, the apparent angular rate at zenith is calculated using the speed of the satellite, approximately 7.5 km/s in LEO, and an example LEO altitude, 400 km, as shown in Figure 6.

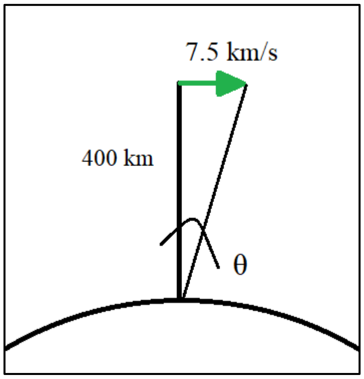


Figure 6. Angular Velocity at Zenith Diagram

With the speed of the satellite as a vector, solving for the angle θ gives the angular rate at zenith: 0.01875 radians per second (1.06 degrees per second), using the following equation:

$$\theta = \sin^{-1}\left(\frac{7.5}{400}\right) \tag{1}$$

In order to calculate the apparent angular rate of a LEO satellite at the horizon for comparison to the velocity at zenith, first the range R (as seen in Figure 7, also leg b of the triangle in Figure 7) from the observer must be known. Leg c of the triangle is the altitude of the satellite (400 km in this example) plus the radius of the Earth, 6378 km, equaling 6778 km.

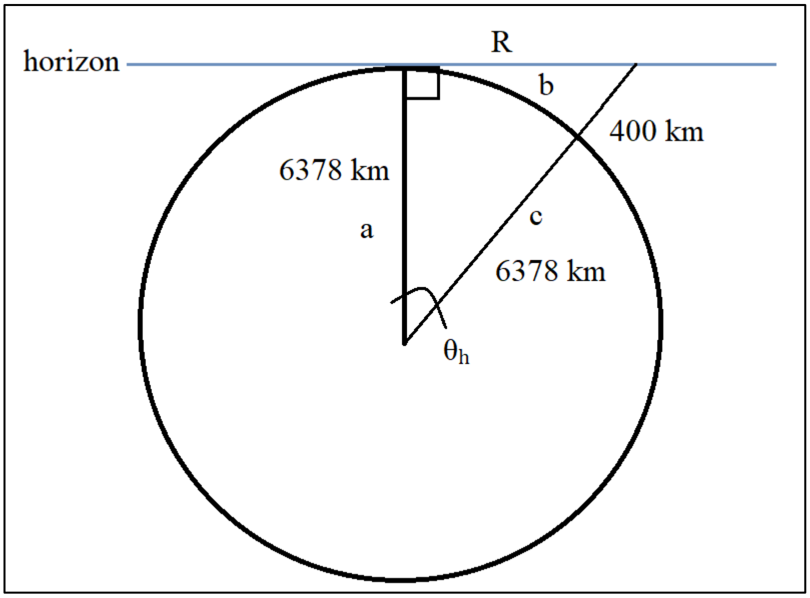


Figure 7. Angular Velocity at Horizon Diagram

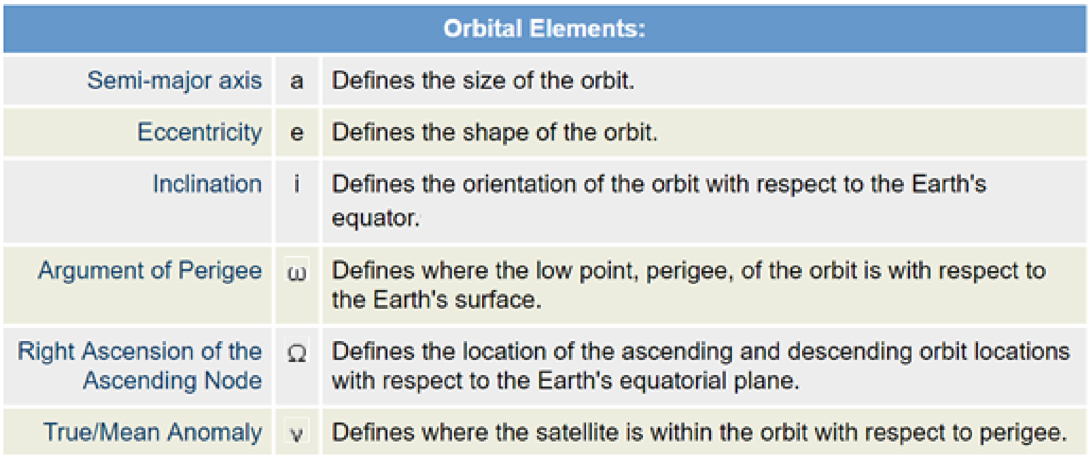
Using geometry to solve for R gives a range of 2294 km. Using the range to the horizon gives a $\theta_{horizon}$ of 0.0033 radians per second, or 0.19 degrees per second. This indicates that at zenith, the satellite angular rate is roughly 5.5 times greater than at the horizon—making the horizon the best possible point to acquire the target satellite.

A satellite's distance from the observer, like its size, relates to its visual magnitude on a logarithmic scale: each increment of 1 on the visual magnitude scale equals an approximate change of 2.5 times in brightness. This is significant because if the target satellite is too dim to detect during an initial pass where the target does not fly directly overhead, there may be another opportunity later with brighter visual magnitude due to better geometry between the satellite and the observer. Additionally, the visual magnitude may vary greatly during a single pass based on the satellite's varying range to the observer and its orientation.

It is important to acknowledge some physical forces influencing a satellite in orbit—the orbital mechanics of a satellite determine its location. In order to track a satellite, the telescope's tracking software needs to perform calculations based on the fundamental physics of orbital mechanics to determine the target satellite's location. First, most satellites in LEO are in circular orbits; this is significant because it simplifies the calculations necessary regarding the prediction of the orbital path across the sky. A satellite in a circular orbit remains at a constant altitude, although its range to the observer varies from horizon to overhead. A computerized telescope system should be able to accurately propagate the path of a known satellite given an accurate description of the orbit. The U.S. government currently tracks satellites in Earth orbit, and makes this information available to interested observers. There are websites and software that are dedicated to updating satellites' trajectories that can be used to give even better accuracy to a telescope. Two of these websites are www.celestrak.com and www.space-track.org. Two commercial software packages capable of orbit propagation are Systems Tool Kit (STK) and TheSkyX. When using a website or software for more precise and updated path information, the data are organized in a specific format called a Two Line Element (TLE).

There are six classical elements that contribute to an object's orbital mechanics, which are included in a satellite's TLE data. These six elements are summarized in Table 2.

Table 2. Orbital Elements Summary. Source: Kelso (2018).



Orbital Elements:		
Semi-major axis	a	Defines the size of the orbit.
Eccentricity	e	Defines the shape of the orbit.
Inclination	i	Defines the orientation of the orbit with respect to the Earth's equator.
Argument of Perigee	ω	Defines where the low point, perigee, of the orbit is with respect to the Earth's surface.
Right Ascension of the Ascending Node	Ω	Defines the location of the ascending and descending orbit locations with respect to the Earth's equatorial plane.
True/Mean Anomaly	v	Defines where the satellite is within the orbit with respect to perigee.

The semi-major axis is essentially the radius of the LEO circular orbit, which has an eccentricity of zero (because it is circular, not elliptical). The inclination, argument of perigee, and the right ascension (longitude) of the ascending node are depicted in Figure 8, which also depicts the relationship between some of these orbital elements. The true anomaly is where the satellite is located from a reference point (perigee) at any given time.

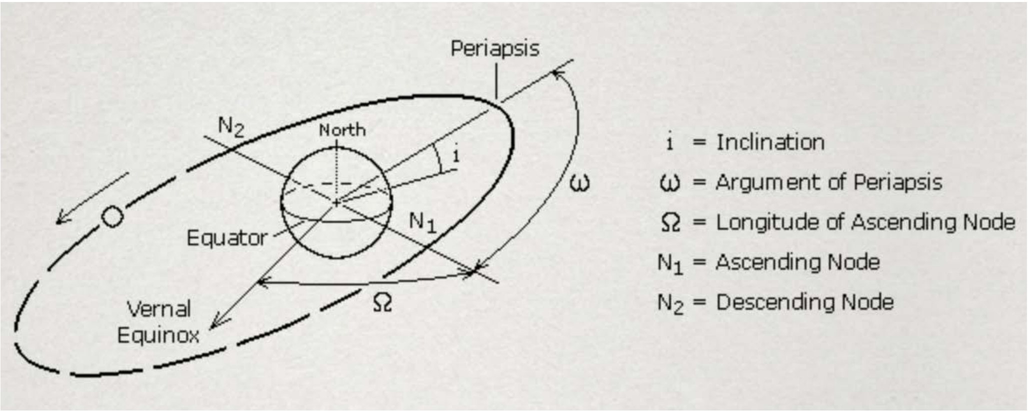


Figure 8. Depiction of Three of the Classical Orbital Elements. Source: Braeunig (2013).

Any miscalculation, by either the TLE source, the computerized telescope mount, or by the telescope software, will likely lead to failure in acquiring and tracking a satellite. Of the several factors that can influence the orbital elements of a satellite, the most well-known is drag.

Drag is a variable factor that influences a satellite’s position and velocity along its predicted trajectory, making it more challenging to successfully acquire and track a satellite with a telescope. Drag varies with atmospheric density, which can vary due to a number of factors, so the effect of drag on a target CubeSat is difficult to determine. In general, calculating atmospheric drag is based on the atmospheric density (which decreases with altitude), the satellite’s cross-sectional area, mass, and velocity. In order to accurately factor in drag, prediction software must also account for a satellite’s mass and velocity.

A satellite in LEO is moving at approximately 7.5 kilometers per second, making it challenging for a telescope, especially with a narrow FOV, to keep up with how quickly the target is moving across the sky. Although the velocity of a small satellite in LEO can be considered constant, small variations due to inaccurate estimates of drag may make a TLE less accurate. The varying factors of velocity and drag increase the difficulty of accurately pointing a telescope with a narrow FOV in order to acquire and track an object as small as a CubeSat.

B. TELESCOPE SYSTEM CHARACTERISTICS

A satellite tracking telescope system must be able to overcome the difficulties of detecting an object in LEO as small as a CubeSat. There are multiple factors that determine a telescope’s performance, to include aperture size, focal length, field of view (FOV), location, and its ability to interface with satellite tracking software. This section discusses common terminology and the general characteristics that must be considered when developing a satellite tracking system with a COTS computerized telescope.

1. Aperture

The first element of a telescope that is key to understanding its ability to detect a satellite is aperture. Aperture is the measurement of the diameter of the circular, main optical surface (a lens or a mirror), and is a common metric by which to judge a telescope's ability to receive light and channel it toward a detector (such as a human eye or a camera). Essentially, the larger the aperture diameter, the more sensitive the telescope is to light. Light sensitivity is arguably the most important factor when it comes to determining if a telescope is capable of detecting an object as small as a CubeSat in LEO. Larger aperture diameter telescopes will also have the benefit of better resolution and increased magnification, as well as brighter images when utilizing an astronomy camera. For a circular aperture (which is a characteristic of all telescopes), the aperture size relates to the brightness of an image by the diameter of the aperture, squared. For example, an increase from an 8 inch aperture to a 12 inch aperture enables collection of 2.25 times more light.

One telescope characteristic related to aperture diameter is limiting magnitude. Limiting magnitude is the brightest visual magnitude possible for a human eye to see through the telescope under average conditions. COTS telescopes will often have a limiting magnitude number associated, given either by a vendor site or by the telescope manufacturer itself. The formula used by some vendors for determining limiting magnitude is 7.5+5log *aperture*, with aperture measured in cm. As aperture increases, the limiting magnitude of the telescope also increases, indicating it is capable of detecting dimmer objects as well as distinguishing between two dim objects located near one another. Figure 9 shows the relationship between aperture and limiting magnitude, with magnification levels labeling the curves.

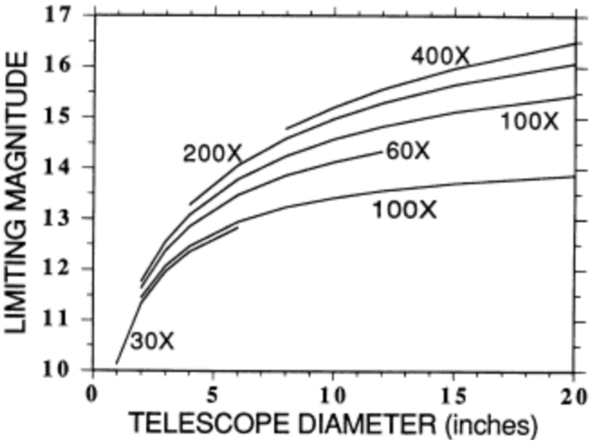


Figure 9. Limiting Magnitude and Aperture. Adapted from Schaefer (1990, 216).

This shows that as aperture increases, generally so does magnification and the limiting magnitude. A telescope will need the right combination of aperture size, magnification, and limiting magnitude in order to be capable of detecting a CubeSat in LEO.

A second telescope characteristic related to aperture is resolution, which is the telescope system's ability to distinguish between two objects. Specifically, angular resolution is the minimum angular distance separating two light sources (such as satellites). For example, for a satellite tracking system, the user may desire an angular resolution small enough to discern between two 1U CubeSats in close proximity. The smaller the angular resolution, the better the discernment between two objects close to each other. Associate professor at the U.S. Naval Academy, Carl Mungan, described angular resolution in his article "Approximation for the Rayleigh Resolution of a Circular Aperture." Mungan explains that angular resolution is determined by the Rayleigh criterion, below, which applies to circular apertures (2009):

$$\theta = 1.22\frac{\lambda}{D} \tag{2}$$

For this equation, θ is the angular resolution (in radians), λ is the wavelength of light, and D is the diameter of the telescope aperture (Mungan 2009). The range of visible light is 750–400 nm; given a 16 inch aperture telescope (406.4 mm) and a midrange value for visible light (575 nm) results in resolution of 9.89 x 10^{-5} degrees. By comparison, for a 10 inch aperture telescope, the resolution becomes 15.82 x 10^{-5} degrees. Thus, a telescope with a 16 inch aperture has significantly better angular resolution than one with a 10 inch aperture. Implementing these numbers can give the distance of two CubeSats from one another (in LEO, at a range of 200 km) and still be distinguishable with a 16 inch aperture: 19.78 m apart, given ideal conditions (i.e., clear, dark skies and a bright enough satellite to be detected).

2. Focal Length and Focal Ratio

Focal length is the next important telescope characteristic that will impact its ability to detect an object as small as a CubeSat. The focal length is the distance from the main lens (for refracting telescopes) or mirror (for reflecting telescopes) to the exit aperture or focal plane (where the observer looks through an eyepiece or utilizes a camera). Focal length, usually given in millimeters, is important because it directly impacts magnification and FOV. Figure 10 illustrates that longer focal length gives increased magnification; shorter focal lengths result in lower magnification.

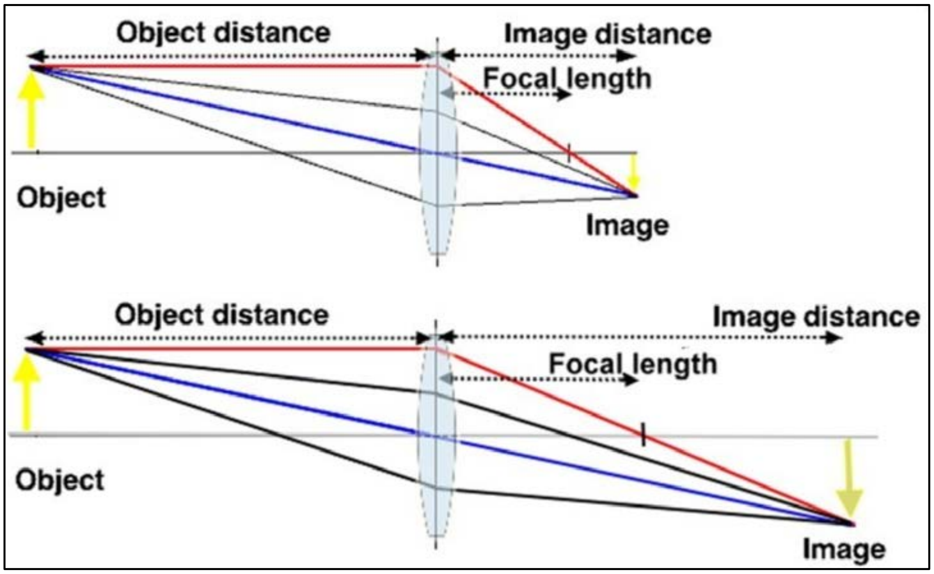


Figure 10. Focal Length and Magnification Diagram. Source: Physics Forums (2014).

Figure 11 shows the difference in FOV with a short focal length compared to a long focal length; the short focal length gives a much larger FOV (labeled as AFOV).

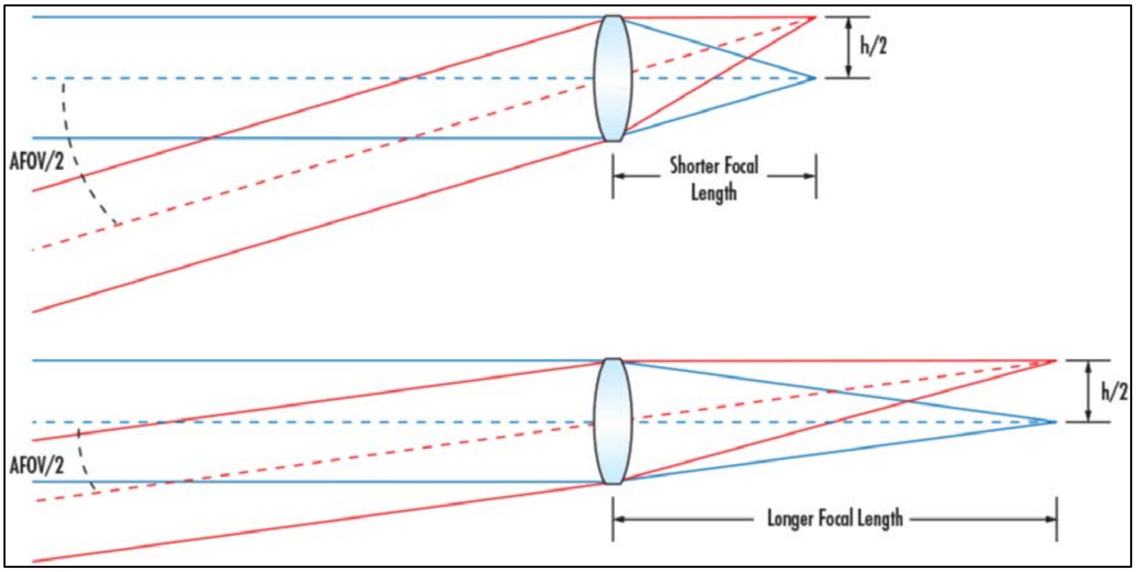


Figure 11. Focal Length and Field of View Diagram. Adapted from Edmund Optics (n.d.).

Focal ratio is a common metric to compare telescopes, and is the focal length (*f*) divided by the diameter of the aperture (*D*), which needs to be in the same units as *f*. It will appear as *f*/# (for example, *f*/8) and indicate whether a telescope has "fast" or "slow" optics. The speed of the optics is a reflection of how quickly photons of light are gathered in the eyepiece or on the detector. Smaller denominators (such as *f*/4 or *f*/5) are considered fast optics, *f*/11 and greater are slow, while the range between *f*/6 and *f*/10 are mid-range. Smaller ratio telescopes give lower magnification and wider FOV, with objects appearing bright through an eyepiece or camera; larger ratio telescopes are better suited for distant objects. A fast or mid-range focal ratio telescope will likely have the necessary magnification and sensitivity to be capable of detecting an object as small as a CubeSat in LEO.

3. Field of View

Field of view (FOV) is another critical factor for a telescope and plays a key role in a telescope's capability of detecting and tracking satellites. The FOV is the angular region seen through the telescope, through either an eyepiece or an attached camera. The relationship between the telescope's focal length and detector size gives the FOV: as the detector size increases, the FOV increases. The equation for calculating FOV with a detector is

$$\theta = 2\arctan\left(\frac{d/2}{f}\right) \tag{3}$$

where θ is FOV in radians, *d* is the width of the detector, and *f* is the focal length (Gasdia 2016). For calculating FOV with an eyepiece, there are two steps. First, calculate the total magnification by dividing the telescope focal length by the eyepiece focal length. Second, calculate the true field of view (TFOV) by dividing the apparent field of view (AFOV) of the eyepiece by the magnification value calculated in the previous step. TFOV is the region viewed through the telescope; the AFOV is the region seen through an eyepiece, independent of the telescope.

Given these equations, the FOV decreases as the focal length increases. This relationship is important because larger focal lengths will give a telescope the magnification needed to detect a CubeSat, but will result in a smaller FOV. Small FOV makes detecting and tracking an object as small as a CubeSat more difficult than with a wide FOV because there is less margin for pointing error—if the telescope is not accurately pointed, or if the satellite is not located precisely where its TLE data projects it to be, then the telescope will be unlikely to acquire the satellite in its FOV.

4. Computerized Mount

Modern COTS telescopes, often with the label "go-to," include a computerized mount: a computer-controlled motor housed in the base of the telescope that controls the telescope orientation. Computerized mounts are often equipped with a Global Positioning System (GPS) receiver for precise alignment, a "handbox" or controller for simple inputs (such as pointing and focusing commands, or accessing a catalog of astronomical objects), and a port for connecting to a separate computer. Ports for connecting to an external computer typically require a USB or a RS-232 cable, and will enable the use of externally hosted guidance software.

Because the computerized mount controls the movements of the telescope, the slew rate is an important feature. The slew rate is the speed that the physical components within the telescope mount can rotate or tilt the telescope, and is measured in degrees per second.

Telescope mounts generally are one of two designs: German equatorial mount (GEM) and altitude-azimuth (alt-az) mount. GEMs only utilize one axis as it tracks, with a counterweight balancing the weight of the telescope. This design offers steady movement when tracking stars, but is not beneficial when tracking a satellite. By moving on only one axis, when a target moves past a midline, the GEM counterweight must reorient in a “flip” maneuver, which requires time. Alt-az mounts, often called fork mounts, move along an altitude axis that tilts the telescope up and down, while the azimuth axis moves the telescope left and right. Alt-az mounts are capable of maintaining pointing smoothly from horizon to horizon.

5. Telescope Software

Computerized telescopes typically have accompanying software, which allows for customization and control of the telescope from a separate computer. Software can be hosted on a laptop computer in the interest of mobility, or a desktop if the telescope system will be permanently located. Telescope software is manufactured and updated by the manufacturer, and there are drivers available that are capable in linking together multiple software programs to control the various types of equipment.

Additional guiding or tracking software is commercially available. The software can include satellite tracking features, which incorporate TLE data and are capable of propagating a satellite’s orbit. Commercial tracking software is maintained by the manufacturer but may have limitations, such as compatibility with accessories produced by other commercial companies. Another option is creating custom tracking software; this can be done through programs such as MATLAB. Using custom software can be beneficial if there is no commercial software available to fit the system's requirements, but it will need dedicated maintenance for updates to maintain compatibility with the commercial products that it must interface with.

6. Coordinate Systems

Telescope software uses one of two coordinate systems to point the telescope. Telescopes receive pointing and tracking commands in steps (incremental points along a propagated trajectory) or rates; the format of these commands is based off of the coordinate system the telescope uses, and affects how the telescope receives pointing and slewing commands. The first of these coordinate systems is azimuth and elevation. Azimuth, measured in degrees, uses cardinal directions (i.e., 0 degrees azimuth is due North). Elevation, also measured in degrees, is the altitude of the object from the horizon. For example, if a satellite is directly overhead (at zenith), it is at 90 degrees elevation. This coordinate system is from the perspective of the observer, as illustrated in Figure 12.

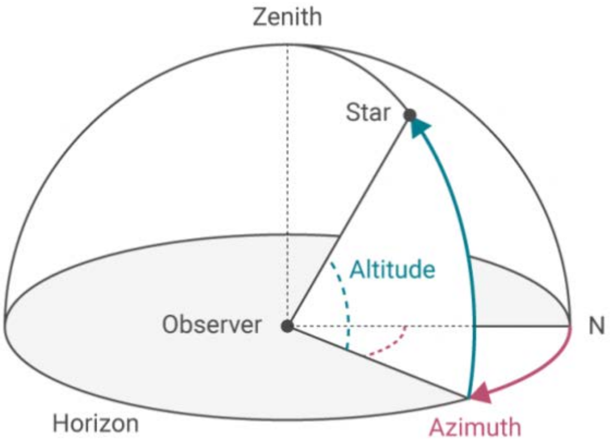


Figure 12. Azimuth and Elevation Coordinate System. Source: Time and Date (n.d.).

The amateur astronomer website SkyandTelescope.com describes the second coordinate system used for pointing a telescope: right ascension and declination. This coordinate system is similar to latitude and longitude, with right ascension being measured from a line called the vernal equinox, which points to the distant star in the Pisces constellation (King 2019). The measurements are in units of hours, minutes, and seconds, with 24 hours equaling 360 degrees. Declination, like latitude, is measured in degrees from the celestial equator. If the target satellite is orbiting at a latitude north of the celestial equator, it will have a positive declination; a satellite will have a negative declination when located south of the celestial equator. If the satellite is at 0 hours right ascension and 0 degrees declination, it lies where the line of the vernal equinox crosses the celestial equator (King 2019). Figure 13 illustrates the right ascension and declination coordinate system, with a star symbol exemplifying a point with positive declination. The benefit of a right ascension and declination coordinate system is that coordinates do not change if the observer's location changes.

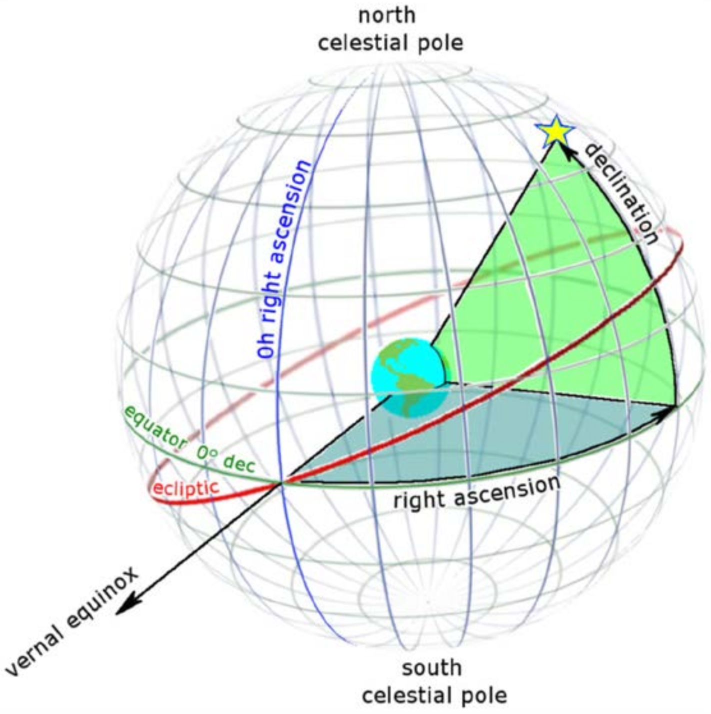


Figure 13. Right Ascension and Declination Coordinate System.
Source: King (2019).

7. Detector Characteristics

Second to the optics of the telescope (aperture and focal length), the detector is the next most significant component of the satellite tracking system. The detector, or camera, is responsible for capturing the reflected light gathered through the aperture of the telescope and displaying it for the observer. There are two common camera types, and both types have two key characteristics that are important for a satellite tracking system: sensor size and pixel pitch.

The first type of astronomy camera is the charge coupled device (CCD). A CCD is made up of rows of capacitors that become charged with light during an exposure, acting as pixels of an image. The final row of capacitors is called the serial register, where the charge is amplified and digitized for display as an image. The second main type of astronomy detector is the complementary metal oxide semiconductor (CMOS). CMOS detectors have a separate location on the chip to amplify and digitize the received charge from photons of light, but have circuitry at each pixel that reduces its area for collecting light in exchange for faster processing of detected light. CCD detectors can have defects that can be removed by software, but are generally more expensive, require more power to operate, and have slower readouts than alternative detectors. However, CCDs are usually more sensitive to light (Gasdia 2016). For a satellite tracking system targeting 1U CubeSats in LEO, sensitivity and fast readout are important because of the low visual magnitude and the speed at which the target is moving.

The first of the key characteristics for a detector is the sensor size. The sensor size has a large impact on the telescope system because it is a factor in the FOV, resolution, and sensitivity (Gasdia 2016). There are two aspects to the size of a detector: the chip size and the pixel size.

The size of the detector chip, usually measured in millimeters, is an important part of the telescope system. Referencing the equation from Section 3, the detector size is a value in the calculation of the FOV. As previously mentioned, the FOV needs to be large enough to forgive pointing error—larger detector chip size results in increased FOV, a significant advantage for a satellite tracking system.

Pixel pitch is the distance from the center of one pixel to the center of the adjacent pixel, and affects resolution and sensitivity. The pixel pitch, usually measured in µm, will impact how much light can be detected. Actual size of the individual pixels also affects its ability to detect low levels of light (Gasdia 2016). Larger pixels allow for better sensitivity to light, whereas smaller pixels can give increased resolution. For detecting and tracking an object as small and dim as a CubeSat in LEO, sensitivity is more important than resolution, making larger pixel sizes and larger detectors preferable.

8. Telescope Configurations

COTS telescopes are generally configured in three basic styles: refracting, reflecting, or a combination of the two. A telescope's general mission is to gather very small amounts of light and magnify them to be visible to the human eye. Refracting and reflecting configurations accomplish this differently. A refracting telescope uses lenses to focus light particles onto a focal plane (such as a telescope eyepiece), while reflecting telescopes use one or more mirrors. A telescope that uses both lenses and mirrors is called catadioptric; one popular configuration is called Schmidt Cassegrain. Catadioptrics are widely used due to difficulty in producing flawless lenses and mirrors. By using a combination of a lens with mirrors, the weight and size of the telescope is lessened, making it both portable and less expensive, while also bypassing the flaws found in using solely lenses or mirrors. Figure 14 illustrates how light travels through the internal components of refracting, reflecting, and catadioptric telescopes.

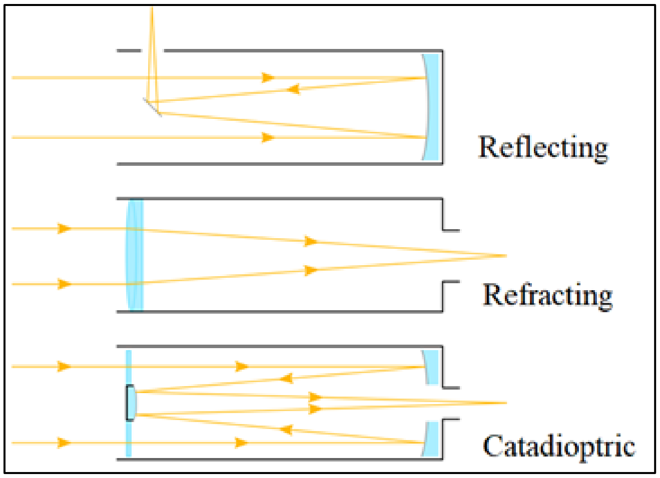


Figure 14. Reflecting, Refracting, and Catadioptric Telescope Configurations. Adapted from Gasdia (2016).

A satellite tracking telescope system may require two telescopes due to the challenge of finding a CubeSat within a limited FOV while having the necessary optical sensitivity in order to detect and track an object of such low visual magnitude. Pairing a short focal length telescope with a wide FOV to a long focal length telescope is not uncommon. (See Figure 10 from Section B.2 regarding FOV comparison of short and long focal length telescopes.) A “spotting” scope refers to the instance that a shorter focal length telescope is attached to a longer focal length main telescope with the purpose of finding the target as quickly as possible and then bringing the target into the FOV of the main telescope. The shorter focal length telescope, likely a refracting telescope, is co-aligned with the longer telescope, as pictured in Figure 15. Co-alignment allows for a target to be found and centered in the wide FOV, which places it also into the narrow FOV of the larger telescope.

Figure 15. Long Focal Length Telescope with Attached Spotting Scope. Source: Meade Instruments (2019).

9. Location of the Telescope System

The location of the telescope system is an important factor because it impacts the number and frequency of sighting opportunities, as well as the duration of the line of sight to a satellite. Knowledge of the telescope's precise location and having accurate timing is key to accurate pointing. A satellite in LEO is moving quickly across the sky, and the telescope and observer are moving with Earth's rotation, causing the geometry between the target satellite and the observer to be constantly changing. Luckily, many computerized telescopes are equipped with GPS receivers, which update it with the telescope's latitude, longitude, elevation, as well as date and time information. A computerized telescope with GPS for initial alignment will have improved pointing accuracy because it has optimal locational data and precise timing.

There are advantages and disadvantages for both a permanently located satellite tracking system as well as a mobile system. If there are any obstructions, a mobile telescope system can be moved to a location that will allow for longer duration line of sight to the target satellite—although this requires accurate alignments at each new location. Permanently located telescopes will not require alignment with each use, but can only benefit from performing one periodically. Mobile systems will require a power source (such as a portable battery) and a computer with up-to-date TLE data. Mobile telescope systems can be placed for ideal conditions to track a satellite, such as an area of clear, dark skies with unobstructed view to the point on the horizon where the satellite will appear. Permanently stationed telescope systems can be remotely operated with dedicated equipment designed for that purpose. Moving a telescope risks damaging it while permanently fixing a telescope to one location may expose it to weather. However, permanently located telescopes can be protected from the elements by placing them in an observatory dome.

Many sophisticated telescope systems are housed in dedicated domes—there are numerous configurations at a wide range of price points. There is the classic slot dome, which has a door that typically slides back enough to have the telescope view an object at zenith. A clamshell dome has one or two doors that slide down, exposing the telescope for 360 degree views to the horizon. Other options include pods, which will open to allow for 180 degrees viewing, and sheds with retractable roofs that slide to give up to 360 degree views when the telescope is mounted to a hydraulic pier. Overall, there are numerous options that can be considered for unique locations and conditions. Domes are compared in Chapter V Section B, as well as in Appendix B.

The most important consideration for placing a telescope is the view to the horizon. Obstructions, such as buildings, vegetation, or terrain, will reduce the tracking capability, especially if there is limited view to the horizon. It is important to have an unobstructed view as close to the horizon as possible in order to take advantage of the slow angular rate that a satellite in LEO is moving when it first crosses the horizon; as the satellite approaches zenith, its angular rate increases, and it becomes more difficult for a telescope with a narrow FOV to acquire the satellite to begin tracking it.

The latitude and longitude, as well as elevation, play a part in which satellites the tracking system is able to detect. Latitude and longitude determine the geometry between the target and the observer. For satellites in LEO, the latitude and longitude of the telescope system's location will be more significant than if the target altitude were one of the other common orbits—satellites at higher altitudes can be visible from a greater range of areas on the Earth. For example, satellites in GEO are nearly stationary in their orbit, making them potentially visible from one third of the Earth's surface at all times. By comparison, lower altitude satellites are in view for much shorter duration and have smaller footprints.

Elevation can have a significant impact regardless of latitude or longitude. Telescopes at higher elevations are less subject to optical interference caused by atmospheric turbulence. Terrestrial weather patterns can also interfere with satellite tracking; a tracking system's ideal location has infrequent cloud coverage, low levels of moisture, no light pollution (such as ambient light from cities), and is at a high elevation to limit the effects of atmospheric turbulence.

C. LOCATING A SATELLITE: TWO LINE ELEMENTS

Two Line Elements (TLEs) contain all of the necessary data for a computerized telescope to calculate necessary pointing positions and slew rates in order to track a satellite. Most modern computerized telescopes are capable of importing TLEs via a connection to a laptop; TLEs are essentially the instructions for the telescope to know where along the horizon to point in anticipation of where the satellite is expected to become visible, but also along the expected path, based on orbital mechanics. Many telescope control interfaces allow for custom TLE data to be selected for importing. Regardless of the software or hardware, the TLE data are formatted the same way. Figure 16 is an example TLE:

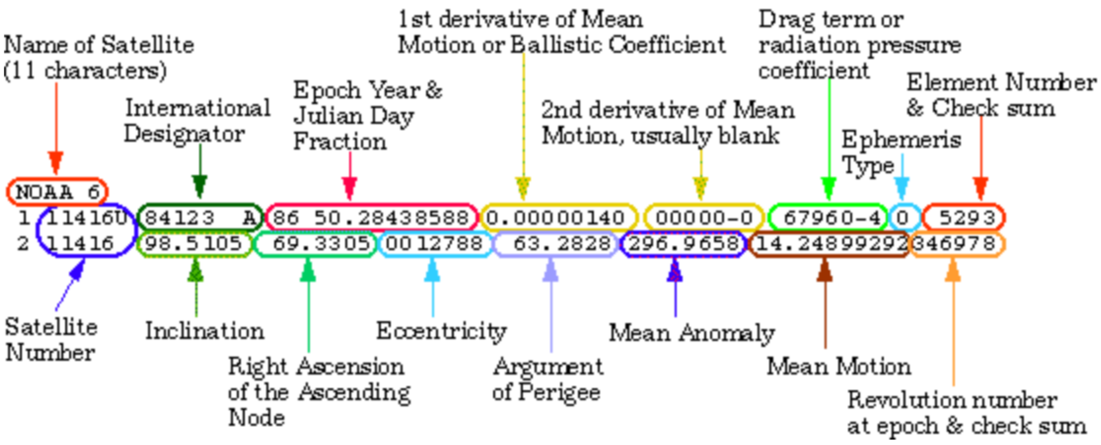
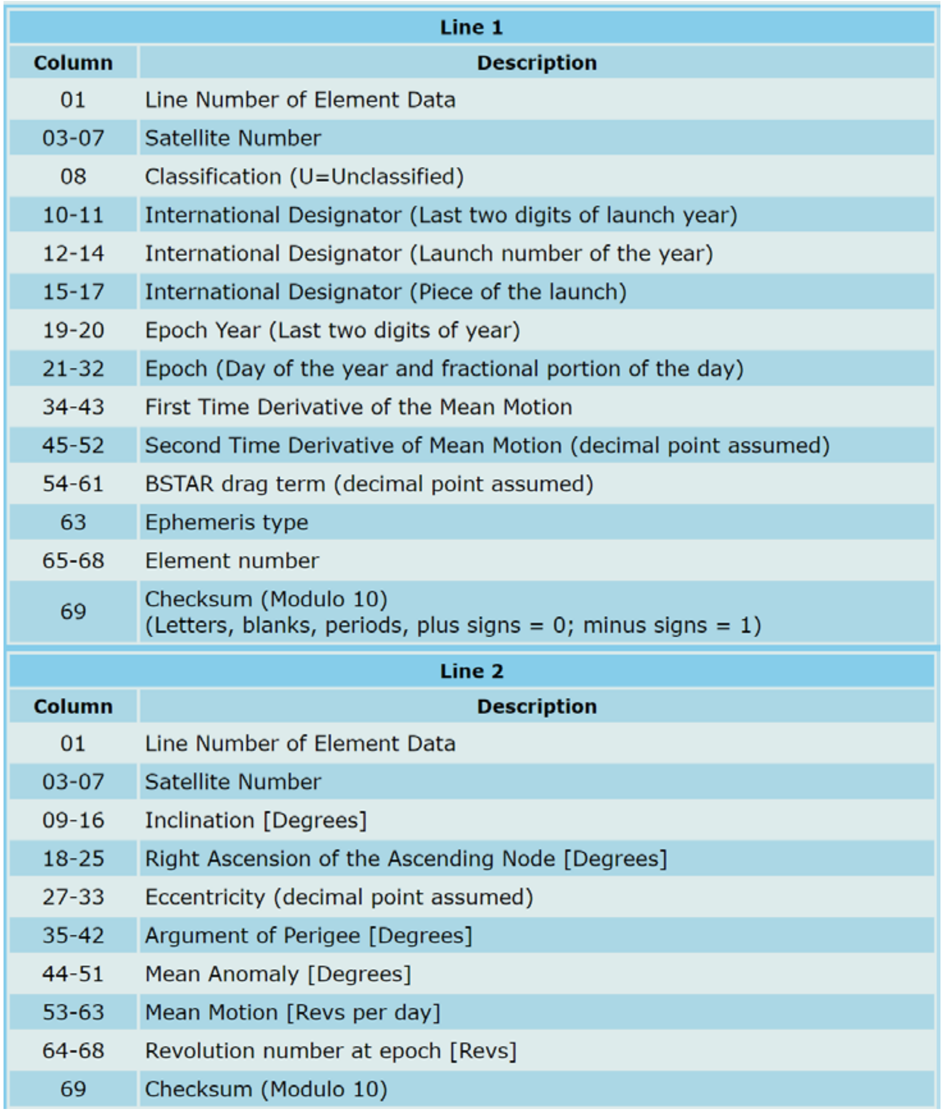


Figure 16. Two Line Element Example. Source: Dismukes (2011).

The first line (Line 0, above "Line 1") contains the satellite name in 24 characters or less, and should match the name of the satellite per the catalog maintained by North American Aerospace Defense Command (NORAD), called the NORAD SATCAT. Lines 1 and 2 follow a formatting used by both NORAD and NASA. Table 3 summarizes and explains the numbers found in the TLE.

Table 3. Two Line Element Content Summary. Source: Kelso (2018).

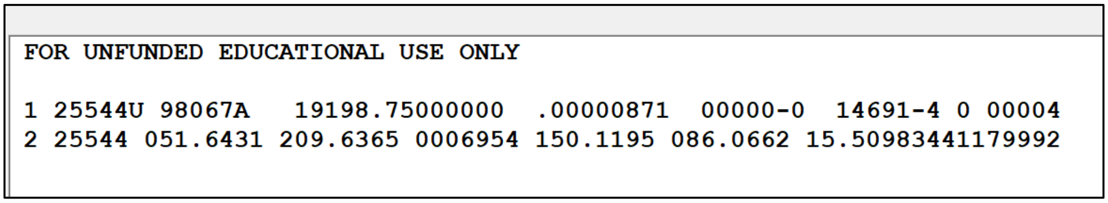


Line 1	
Column	**Description**
01	Line Number of Element Data
03-07	Satellite Number
08	Classification (U=Unclassified)
10-11	International Designator (Last two digits of launch year)
12-14	International Designator (Launch number of the year)
15-17	International Designator (Piece of the launch)
19-20	Epoch Year (Last two digits of year)
21-32	Epoch (Day of the year and fractional portion of the day)
34-43	First Time Derivative of the Mean Motion
45-52	Second Time Derivative of Mean Motion (decimal point assumed)
54-61	BSTAR drag term (decimal point assumed)
63	Ephemeris type
65-68	Element number
69	Checksum (Modulo 10) (Letters, blanks, periods, plus signs = 0; minus signs = 1)

Line 2	
Column	**Description**
01	Line Number of Element Data
03-07	Satellite Number
09-16	Inclination [Degrees]
18-25	Right Ascension of the Ascending Node [Degrees]
27-33	Eccentricity (decimal point assumed)
35-42	Argument of Perigee [Degrees]
44-51	Mean Anomaly [Degrees]
53-63	Mean Motion [Revs per day]
64-68	Revolution number at epoch [Revs]
69	Checksum (Modulo 10)

In order to begin tracking a satellite with a telescope, TLEs need to be accurate. For both open- and closed-loop tracking, the telescope will align itself at the point where the satellite is projected to appear over the horizon. Without an accurate starting point, the telescope (and its user) will likely not be able to acquire the satellite in the FOV and will lose valuable time needed to make small pointing adjustments that are necessary to center the satellite in the FOV. Telescopes with the capability to detect an object as small as a CubeSat will also have a very small FOV; this is one factor that makes tracking a challenge. A small FOV will allow for only a small margin of error. Therefore, ensuring that the telescope is using the most accurate—i.e., most up-to-date–TLE data is vital to successfully finding and tracking a satellite.

One accurate and reliable program for generating satellite TLEs for using with a computerized telescope is called Systems Tool Kit (STK). STK maintains a database of common satellites, and generating a TLE is straightforward. Generating a TLE Report, quickly accessed by right-clicking on the target satellite and selecting the Satellite option, then selecting Generate TLE gives output in a standard format, depicted in Figure 17.



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1 25544U 98067A   19198.75000000  .00000871  00000-0  14691-4 0 00004
2 25544 051.6431 209.6365 0006954 150.1195 086.0662 15.50983441179992
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Figure 17. STK TLE Generation Example

STK is a commercial software suite that uses sophisticated algorithms for predicting satellite trajectories, but is only as accurate as the last time the TLE database was updated. Free, reliable, and accurate TLEs can be found at www.celestrak.com and www.space-track.org. Accurate TLE data for a target satellite are absolutely vital to successful acquisition and tracking with an optical telescope.

III. OPEN- AND CLOSED-LOOP SATELLITE TRACKING SYSTEM REQUIREMENTS

As previously mentioned, there are essentially two methods for tracking satellites with COTS computerized telescopes: open-loop tracking, which is based on orbit propagation/prediction, and closed-loop tracking, which adds feedback (from either a human or a detector, such as a camera) in response to a measurement gathered in real time. Based on the characteristics of CubeSats and telescopes described in Chapter II, this chapter will discuss the requirements for the equipment necessary for both open- and closed-loop satellite tracking systems. While the goal may be to achieve a closed-loop tracking system, it is best to begin with developing an open-loop system and build to a closed-loop system: many unforeseen issues may arise that can be more easily overcome in the stages of designing an open-loop tracking system.

Regardless of which type of tracking the system is doing, accurate pointing and precise telescope alignment are necessary. Without knowing exactly where the telescope system is located in relation to the point that a target satellite will become visible, it is unlikely that a telescope system will detect and track the target. Another issue that must be addressed for both open- and closed-loop tracking systems is latency. Latency is a delay between the software issuing commands and the telescope receiving, processing, and executing the command. Latency must be accounted for, either by the human observer commanding the telescope to begin tracking within an appropriate timeframe of the satellite crossing the horizon or by the algorithm of a closed-loop tracking system. Both open- and closed-loop tracking systems must overcome the issues of precise pointing and latency; the following sections discuss the equipment capable of overcoming these factors.

A. REQUIREMENTS FOR OPEN-LOOP TRACKING

There are a few essential components of an open-loop satellite tracking telescope system. First, and most important, are the telescope and computerized mount. Non-computerized telescopes are technically capable of open-loop tracking, but tracking a satellite requires propagation of the satellite’s orbital data (i.e., doing necessary calculations to determine the satellite's trajectory based on TLE data, which gives the orbital elements for one point in time). The orbit propagation then must be formatted and sent to the telescope, or a computer must give pointing commands to the telescope. For this reason, the minimum standard for a satellite tracking system is to utilize a computerized telescope.

1. Telescope and Mount

There are numerous designs and configurations of telescopes to choose from when creating a system with the goal of tracking satellites. The telescope's size, weight, and portability should be carefully considered—with so many options commercially available, it is more cost-effective to purchase from a reputable commercial telescope company than it is to contract a company to create a customized telescope and dome. (In initial research for this thesis, an estimate cost of a contractor-built telescope system began at $40,000.) A computerized telescope benefits from the following features at a minimum:

- GPS alignment capability. An accurate alignment is absolutely vital to finding and tracking a satellite from the ground. GPS capability not only gives excellent locational awareness (latitude, longitude, and altitude) but also accurate timing, which is crucial to predicting and detecting the location of a satellite.

- Guidance software. Most commercial telescopes are paired with software designed to help observers easily find celestial objects from a menu database, which is accessible either by a handset attached to the telescope mount or via telescope controlling software. For example, the NPS SSAG telescope (Meade LX600) includes Meade Autostar II software. Software is often designed to overcome telescope latency issues, which is key to successful satellite tracking.

Slew speed of at least 1 degree per second. Given an object in LEO travels at approximately 7.5 km per second, one example of a directly-overhead pass with an in-view duration of 6 minutes means the satellite will traverse

180 degrees (horizon to horizon) in 360 seconds. This gives an average angular rate of 180 / 360 = 0.5 degrees per second. Due to the angular distance variations over the course of the pass (refer to Chapter II Section A, Figures 6 and 7) the satellite will appear to be traveling fastest when it is directly overhead—at approximately 1 degree per second. Fortunately, most new models of COTS computerized telescopes have a slew speed of at least 1 degree per second.

- Computer interface ports if the computerized mount is not capable of propagating satellite TLE data. At least one interface port is necessary to physically connect a computer to the telescope mount, which allows for commands to be issued from commercial or software using a graphic user interface (GUI) or a command line interface (CLI). Typically, the port is for a RS-232 cable; in addition to an RS-232 cable, most modern computers will require an adapter that converts to USB.

- Options for including a spotting scope. An astronomy spotting scope, which has a wide FOV (between 4-5 degrees), will ideally be installed on the main optical tube assembly. Once co-aligned, a spotting scope is useful for bringing a target object into the FOV of the main telescope. (Co-alignment is done by centering a target in both the spotting scope's FOV and in the main telescope's FOV.) In general, having a spotting telescope greatly increases the likelihood of successful tracking.

An ideal system for tracking small satellites has a refracting telescope with a short focal length paired and aligned with a longer focal length reflecting or catadioptric telescope. The computerized mount needs to be compatible with satellite tracking software as well as the computer running the software in preparation for eventually creating a closed-loop system. The telescope will also need a power source; if the system is designed to be mobile, a portable battery is required.

2. Computer

Next, a satellite tracking system needs a dedicated computer to host the software for command and control of the telescope. At a minimum, the computer must be able to run software to propagate the orbit of a satellite and be compatible with the telescope it will control. For orbit propagation, the computer must be capable of running orbit propagating software (such as STK or a software package from the telescope manufacturer) and have access to the most updated TLE for the target satellite. STK supports multiple operating systems and requires a CPU speed of 2+ GHz, 3+ GB of memory, and 3+ GB of disk space, and lists compatible processors and graphic cards on its website (http://help.agi.com/stk/index.htm#install/sysreq.htm). Internet connectivity is required to ensure access to the most recent TLEs from reliable websites, such as www.celestrak.com or www.space-track.org, whether using STK or another software package. To control the telescope, a computer will need to host the specific telescope software. For example, the NPS SSAG Meade LX600 can be controlled by the Meade Autostar Suite, as well as by free software called Satellite Tracker (from heavenscape.com). It is important to check for compatibility between the telescope, computer operating system, and any desired software, as well as ensuring the computer downloads the necessary software drivers.

3. Software

Software (custom or commercial) is the next essential component of the satellite tracking system. The purpose of satellite tracking software is to give the telescope the pointing and slewing commands necessary for keeping a target satellite in the FOV. Satellite tracking software needs to, at a minimum, be compatible with the telescope. Software developers maintain lists of compatible telescopes on their websites. Essentially, the software must be able to issue commands compatible with the telescope "language" to be correctly interpreted and executed by the telescope. A distinguishing factor between computerized telescopes that impacts their compatibility with tracking software is whether the telescope must be issued commands by rate or by "steps." Computerized telescopes use coordinate systems based on either azimuth and elevation, or right ascension and declination. (These coordinate systems are explained in Chapter II Section A.) The telescope’s coordinate system typically does not affect its operations unless there are problems with software compatibility with the satellite tracking function. Overall, step or rate commands issued by tracking software are sent in rapid succession so the movement of the telescope is smooth. In addition, software compatibility often involves the use of software drivers. Drivers are essential components for satellite tracking systems in that they enable tracking software to communicate properly with the telescope. Without a driver that enables the software to properly communicate with the telescope and detector, a satellite tracking system will not be successful.

Drivers are often provided and maintained by the software creators. However, in the astronomy community, developers worked together to create a driver that promotes compatibility between equipment and software, called ASCOM. ASCOM drivers are designed to work with Windows operating systems at the time of this writing, with mention of Linux and MacOS compatibility as a current project. The website for ASCOM is https://ascom-standards.org/index.htm, and the drivers are free to download. ASCOM drivers can link together a wide variety of COTS telescopes, cameras, and astronomy software.

4. TLEs

For both open- and closed-loop tracking, the telescope system needs the TLE of the target satellite. TLEs can be obtained from a website, such as www.celestrak.com and www.space-track.org, or they can be propagated internally by software such as STK; data contained in and formatting of TLEs are discussed in Chapter II. There are generally two methods of implementing TLE data for satellite tracking. The first method requires the TLE be imported to the telescope software (i.e., the TLE is saved from www.space-track.org and then imported into telescope-specific software, such as Meade Autostar II). STK can generate a TLE data file for multiple satellites, then output a report in a format that can be imported via the telescope command software. The second method is internal to satellite tracking software—some commercial software, such as TheSkyX Pro, will update TLEs within the software or draw updates from the internet. Once the software has updated the TLE, it will utilize that data when commanding the telescope system. Since both methods for using TLEs involve a computer with tracking software, the satellite tracking system requires a connection between the computer and the telescope. This is done either by a RS-232 cable with a USB adaptor, pictured in Figure 18, or wirelessly using a wi-fi adapter for the telescope.

Figure 18. RS-232 Cable with USB Adapter. Source: Amazon (n.d.).

The RS-232 cable connects directly to the telescope mount; Figure 19 shows a Meade LX600 drive base. The drive base panel clearly labels the RS-232 port for ease of use.

Figure 19. Meade LX600 Computerized Mount Interface. Source: Meade Instruments (2019).

5. Open-Loop Operations

After the TLE data have been updated and imported and the satellite is approaching or at the horizon, the software can be used to command the telescope to begin tracking. Ideally, the software will direct the telescope to the point on the horizon that the satellite will first come into view. With accurate timing, the software will command the telescope to move at the appropriate speed as the satellite passes overhead. In open-loop tracking, the observer may use a viewfinder or an astronomy spotting scope in order to manually point the telescope to move the target satellite into the center of the FOV of the main optics. The observer may be required to give minor “nudging” commands to center the target satellite into the FOV, either through the telescope software or the tracking software. Nudging commands are necessary in the event that TLE data are inaccurate or the telescope did not have a precise alignment. Nudging commands are incremental aiming adjustments—as small as 0.1 degree, but may vary among telescope control software. The small increments are useful when the satellite is low on the horizon, moving at a relatively slower speed than the faster rate the target appears to move when it is directly overhead; allowing for adjustments to the increment size is thus a useful feature for tracking software.

For early stages of creating and learning to operate a satellite tracking system for objects in LEO, it will be easier to successfully detect and track an easily visible satellite (such as the ISS) by starting with a shorter focal length telescope with an eyepiece that allows for a wide FOV (3-4 degrees). Cameras will affect the telescope’s FOV differently from an eyepiece, so once tracking is mastered with a short focal length telescope and eyepiece, the eyepiece can be replaced by a camera. After successfully tracking using a camera, the next phase would be to use a larger focal length telescope, which will be capable of detecting smaller satellites with a lower visual magnitude. As discussed in Chapter II, the larger focal length will result in a smaller FOV, but is necessary for detecting and tracking objects as small as a CubeSat in LEO.

Once open-loop tracking is accomplished with a larger focal length telescope, the next phase is to create a closed-loop tracking system.

B. REQUIREMENTS FOR CLOSED-LOOP TRACKING

A closed-loop satellite tracking system builds off of a successful open-loop system. A computerized telescope and mount, a dedicated computer, satellite tracking software, and associated drivers will still be necessary. The key difference between an open- and closed-loop system is that rather than merely pointing to a predicted position, the tracking software will compute the necessary aiming or speed correction based on feedback from a detector (such as a camera) that is measuring the location of the satellite relative to a desired position. This feedback is sensed and processed in real time, and the corrective commands are issued by the software to the telescope in order to keep the satellite in the FOV of the sensor.

Commercially available software programs from reputable vendors claim to include satellite tracking functions, which can be used in creating a closed-loop system. Starry Night Pro and Starry Night Pro Plus, manufactured by Simulation Curriculum (https://starrynight.com/starry-night-8-professional-astronomy-telescope-control-software.html), are for ASCOM-compatible telescopes. Another example is TheSkyX Pro, manufactured by Software Bisque (http://www.bisque.com/sc/pages/TheSkyX-Professional-Edition.aspx). Another option is finding freely available open-loop software, created by volunteer developers and hobbyist astronomers, which can then be paired with a feedback feature to create a closed-loop system. Satellite Tracker, found at www.heavenscape.com, is an example of free software maintained by a hobbyist astronomer. A third option is creating custom software, unique to the individual elements of a specific tracking system. Custom software requires a satellite tracking algorithm, which can be done in programs such as MATLAB; the tracking algorithm will need to calculate pointing changes for the telescope based on orbit propagation as well as updating the pointing of the telescope based on centering the target satellite in the FOV of the detector. The computer for a closed-loop tracking system will need a processor capable of running multiple programs simultaneously.

One option is to combine software from two or more of these sources; this has been done by universities that have achieved closed-loop tracking capability, such as the Air Force Institute of Technology (AFIT) (Salvador 2015, 15). Regardless of the software source, a satellite tracking system must have telescope and software compatibility.

C. SUMMARY

There are some essential components and factors that must be met in order to establish an open- or closed-loop satellite tracking system. The necessary equipment includes the telescope and computerized mount, tracking software, a computer to run the software, a detector (such as a camera), a source for TLEs, and means to connect (via software drivers and physical cables, such as an RS-232) the computer, software, telescope, and detector together. Important factors that must be met include the necessary illumination conditions (described in Chapter II), as well as favorable weather between the target satellite and the telescope system, ideally at a dark location with unobstructed views to the horizon.

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IV. DEMONSTRATION AND RESULTS

In order to determine how completely the NPS SSAG telescope system meets the requirements outlined in Chapter III, the next step was to do proof of concept testing. This chapter will describe the equipment utilized for early testing. The SSAG hopes to be able to track and photograph CubeSats orbiting in LEO, a capability that few organizations have mastered and offers future research opportunities to NPS. As space becomes increasingly congested, the ability to detect CubeSats—and ideally, discern between two CubeSats orbiting in close proximity to each other—will be imperative.

A. THE NPS SSAG TELESCOPE SYSTEM

In the fall of 2018, the Space Systems Academic Group (SSAG) at NPS purchased a new telescope and computerized mount system–a Meade LX600 with a 16 inch aperture. This system includes the main 16 inch aperture telescope and a computerized mount on a tripod. Also included were Meade software packages: Autostar II (for pointing and guiding the telescope) and SkyCapture (for interfacing with Meade astrophotography cameras). These software packages were installed on a new SSAG laptop dedicated for pairing with the telescope system. The Meade telescope system was purchased as the first step toward attaining the capability to view and track satellites. Additionally, the SSAG purchased TheSkyX Pro software, which incorporates a satellite tracking feature, as well as a variety of Meade-manufactured eyepieces and cameras.

The LX600 is a computerized "go-to" telescope with a slew speed capable of tracking an object traveling the speed that CubeSats move at in LEO. Meade is a reputable company that produces numerous sizes of telescopes; a 16 inch aperture is the largest manufactured by Meade and is the largest available amateur telescope. As previously discussed, visually detecting an object as small as a CubeSat requires a telescope capable of seeing small amounts of reflected light, and a large aperture allows for higher sensitivity for detecting light. The telescope's long 3251 mm focal length gives it a narrow FOV: only 0.33 degrees with an 18 mm eyepiece and only 0.13 degrees with the Meade LPI-G camera. The Meade LX600 diagram in Figure 20 shows some of the key features.

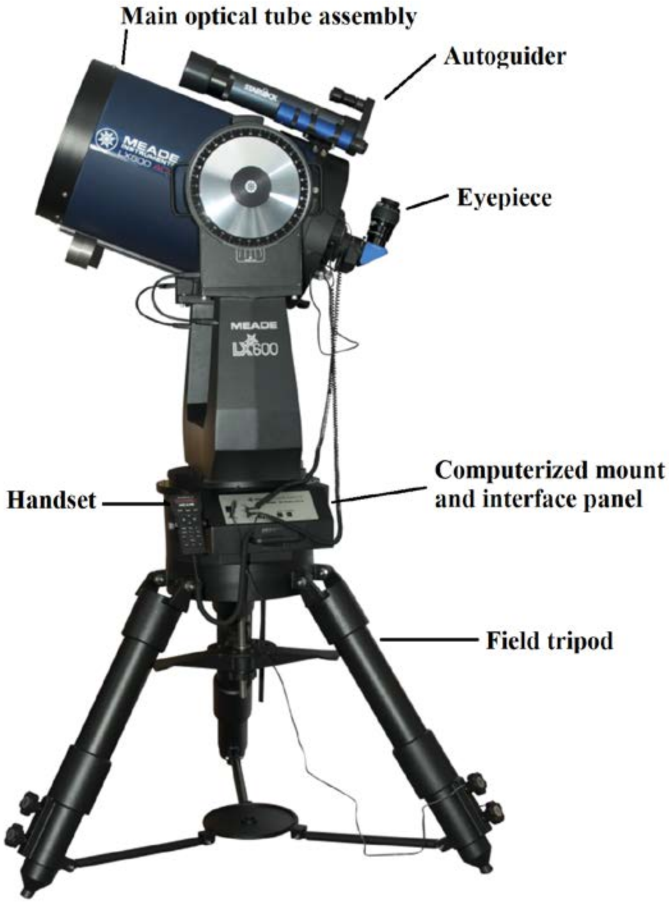


Figure 20. Meade LX600 Telescope. Adapted from Meade Instruments (2019).

Software, such as TheSkyX Pro, has the capability of sending open-loop, satellite tracking commands to compatible telescopes. Through testing, it was discovered that although TheSkyX Pro advertises compatibility with the LX600, the compatibility did not extend to the satellite tracking feature. TheSkyX Pro software was not successful in commanding the LX600 in satellite tracking due to an undetermined incompatibility between the software and the computerized mount. TheSkyX Pro software can be used for guiding the LX600 to point at celestial objects or satellites in GEO, but not for tracking fast-moving satellites in LEO.

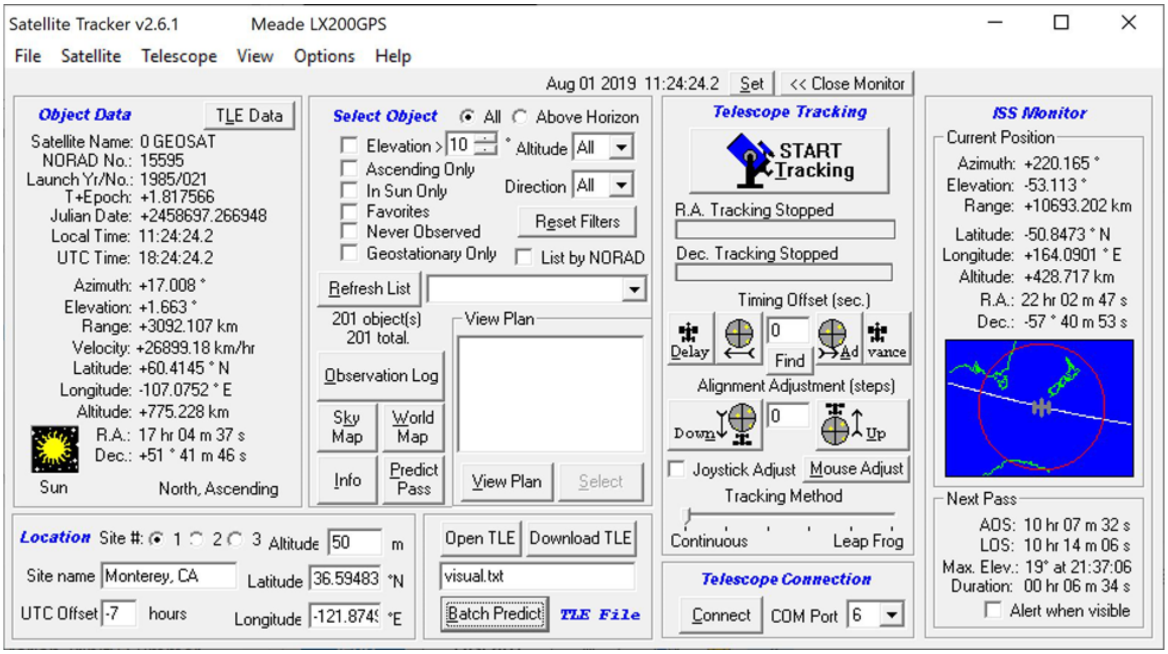
During the course of this research, the only commercial, off-the-shelf (COTS) software compatible with the Meade LX600 system was the publicly available software provided by heavenscape.com, called Satellite Tracker. Utilizing Satellite Tracker was successful and resulted in open-loop tracking of the International Space Station (ISS).

Additionally, the SSAG has customized tracking software for directing ground-based antennas for communicating with three NPS CubeSats in LEO; adapting this software to control the LX600 was unsuccessful. This was largely due to the fact that the LX600 command set is proprietary data, and differs slightly from the publicly available LX200 command set.

B. TRACKING THE ISS

Proof of concept testing was done using a Meade LX200GPS, which is similar to the Meade LX600 but is an older model with a smaller aperture. A key advantage to using the LX200GPS is that the command scripts can be found online; when contacted about commands for the LX600, Meade representatives did not want to share them, citing them as “proprietary data” (Meade customer service representative, personal communication, January 3, 2019). The LX200GPS, with a 203 mm aperture and 2670 mm focal length, was placed on the rooftop of the Spanagel building at NPS, which gives the best unobstructed view to the horizon possible on campus.

After several months of unsuccessfully using third-party and customized software to command the LX600 to track satellites, some headway was made with the LX200GPS. Free software, Satellite Tracker, from heavenscape.com was used to command the LX200GPS to track the ISS. Figure 21 is a screenshot of Satellite Tracker software when connected to the Meade LX200GPS.



Aug 01 2019 11:24:24.2

Satellite Name: 0 GEOSAT
NORAD No.: 15595
Launch Yr/No.: 1985/021
T+Epoch: +1.817566
Julian Date: +2458697.266948
Local Time: 11:24:24.2
UTC Time: 18:24:24.2
Azimuth: +17.008 °
Elevation: +1.663 °
Range: +3092.107 km
Velocity: +26899.18 km/hr
Latitude: +60.4145 ° N
Longitude: -107.0752 ° E
Altitude: +775.228 km
R.A.: 17 hr 04 m 37 s
Dec.: +51 ° 41 m 46 s
Sun
North, Ascending

● All ○ Above Horizon
☐ Elevation > 10 °
Altitude: All
☐ Ascending Only
☐ In Sun Only
Direction: All
☐ Favorites
☐ Never Observed
☐ Geostationary Only
☐ List by NORAD
201 object(s)
201 total.

Site #: ● 1 ○ 2 ○ 3
Altitude 50 m
Site name Monterey, CA
Latitude 36.59483 °N
UTC Offset -7 hours
Longitude -121.874 °E
visual.txt

R.A. Tracking Stopped
Dec. Tracking Stopped
Timing Offset (sec.) 0
Alignment Adjustment (steps) 0
☐ Joystick Adjust
COM Port 6

Current Position
Azimuth: +220.165 °
Elevation: -53.113 °
Range: +10693.202 km
Latitude: -50.8473 ° N
Longitude: +164.0901 ° E
Altitude: +428.717 km
R.A.: 22 hr 02 m 47 s
Dec.: -57 ° 40 m 53 s

Next Pass
AOS: 10 hr 07 m 32 s
LOS: 10 hr 14 m 06 s
Max. Elev.: 19° at 21:37:06
Duration: 00 hr 06 m 34 s
☐ Alert when visible

Figure 21. Satellite Tracker User Interface

Using Satellite Tracker for commanding the LX200GPS for tracking and initial pointing alignment with TheSkyX Pro software finally allowed for successful acquisition and tracking of the ISS during a nighttime pass on the evening of July 17, 2019. The successful tracking was open-loop and with the use of a spotting scope (with a 5 degree FOV) to manually point the telescope to put the ISS into the boresight of the optics. Although several frames of video were captured of the ISS through the telescope, the ISS was not stable within the very small FOV of the camera long enough to allow for focusing. The camera used on the main telescope during the successful test was a 6.3 megapixel Meade Instruments LPI-G Advanced Camera (color) with a 2.4 µm x 2.4 µm pixel size. The limitations of this camera are reviewed in Chapter V, but the FOV with this detector was too small to assess the accuracy of the open-loop capability of the Satellite Tracker software. Of note, the ISS was within the larger FOV of the spotting scope for the entire duration of several passes, confirming that Satellite Tracker and the LX200GPS worked as planned. Figure 22 shows one frame capture of the ISS in the FOV of the main optics of the LX200GPS.

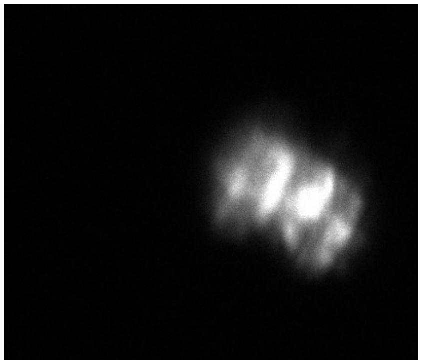


Figure 22. International Space Station Sighting

C. IMPORTANT CONSIDERATIONS WHEN CREATING A SATELLITE TRACKING SYSTEM

Through trial and error, a few key takeaways were obtained regarding considerations when planning to create a satellite tracking system for LEO targets using COTS equipment. First, determining where the system will be placed or stored is an important factor. If the telescope can be permanently located, larger and heavier optical models can be considered. If the telescope needs to be mobile, choosing a reasonable size and weight will depend on the number of personnel that will be routinely moving it, and means with which to move the telescope to avoid damaging any sensitive telescope or mount mechanisms. Placing a telescope on a permanent fixture (i.e., concrete pillar) should also be compared against a tripod. While a tripod gives the option to transport the system, a fixed pillar and less movement means less risk of damage to the telescope and the benefit of better alignment. The main advantages of a permanently located telescope system are that it will not need to conduct a GPS alignment each time it starts, and a larger and heavier telescope will allow for increased sensitivity to light.

Second, observers will be able to detect and track smaller objects with equipment that gives them the most sensitive light detection. However, there is a tradeoff between FOV and focal length that must be carefully considered. A longer focal length will result in a smaller FOV, making accurate pointing an absolute necessity, but gives increased magnification. The challenge behind having a small FOV can be mitigated through use of a spotting scope. Spotting scopes typically have 4-5 degrees FOV, which makes it much easier to find a target (given the target is bright enough to be detected with the spotting scope) than with a telescope of less than a 1 degree FOV. Overall, it is important to consider the difficulty that a narrow FOV brings, and weigh it against getting the best sensitivity to light possible.

Finally, it is important to choose commercial software compatible with the telescope system. Choose software based on the capabilities desired, such as remote access and control of the telescope system. Software is also best when it includes updates; much of the free software online are reliant on volunteers or amateur astronomers contributing their free time to produce updates. Software prices vary, and there are numerous free options available online; always check compatibility of the telescope computerized mount and guiding software when planning to use commercial tracking software as part of the telescope system.

V. CONCLUSION

There are many possible combinations for building an optical telescope system with COTS components capable of detecting and tracking an object in LEO as small and dim as a CubeSat. In order to build a telescope system for satellite tracking, it is important to consider limiting factors of the equipment, compatibility between all components of the system, as well as any environmental limitations (such as location, light pollution, and visual obstructions). This chapter recommends specific equipment that will enable the NPS SSAG to attain a closed-loop optical satellite tracking system.

The closed-loop tracking capability can be built incrementally; NPS SSAG should continue to focus on open-loop tracking initially, and utilize as much of its current equipment as possible. First, it is valuable to review the current SSAG equipment dedicated to satellite tracking that can be utilized in the satellite tracking system.

A. CURRENT EQUIPMENT

The Meade LX600 optical tube assembly offers the largest aperture commercially available (16 inches), and is capable of working with additional components to detect a CubeSat as dim as +12 visual magnitude, which is an estimate for the visual magnitude for a CubeSat in LEO under poor observing conditions. Its focal length of 3251 mm limits its FOV; this challenge can be overcome with the right equipment to compensate. Because it has good quality optics (lenses and mirrors), with a 2 inch exit aperture (where the eyepiece or camera is placed) that makes a variety of COTS accessories compatible, the LX600 is recommended as the main optical tube for the satellite tracking system. It is a Schmidt Cassegrain telescope, which is a catadioptric configuration using both mirrors and lenses; it has powerful enough optics to detect small amounts of light while being compact enough for smaller storage options. The accompanying computerized mount is not recommended because of its incompatibility with the desired satellite tracking software; a recommended replacement is described in Section B. The SSAG also owns a tripod for the telescope optical tube and computerized mount; a new computerized mount (not manufactured by Meade) would need to be modified in order to continue to use the Meade tripod.

SSAG also owns three Meade-manufactured astronomy cameras and multiple eyepieces. Two of the cameras are monochrome (black and white) LPI-G cameras—one standard, one Advanced—and the third camera is a color LPI-G Advanced. The Meade LPI-G Advanced CMOS cameras are 6.3 megapixels (3072 x 2048) with 2.4 µm x 2.4 µm pixel size. These CMOS cameras are not suitable for satellite tracking because when used with the long focal length of the LX600, the combination has a very small FOV. One set of eyepieces ranges between 4.5-25 mm in focal lengths, and have 1.25 in barrels with 60 degree apparent FOV (AFOV). AFOV is the region (in degrees) seen through an eyepiece, separate from a telescope—by comparison, the true FOV (TFOV) is the region (also in degrees) seen through the telescope when combines with the eyepiece. The set of Meade eyepieces would be useful on a smaller focal length telescope, but contribute to the issue of TFOV with the LX600. SSAG also owns a Tele Vue Ethos 21 mm and a Meade 21 mm, both with 100 degree AFOV, which give the best FOV of the currently owned eyepieces. Table 4 uses the FOV equations discussed in Chapter II Section B.3 to show the relationship between longer focal length eyepieces and FOV. These calculations utilize the LX600 focal length of 3251 mm.

Table 4. SSAG Eyepiece and FOV Comparison

Size (mm)	AFOV (degrees)	TFOV (degrees)
4.5	60	0.08
12	60	0.22
18	60	0.33
21	100	0.65
25	60	0.46
32	56	0.55
40	50	0.62

Figure 23 depicts the Moon (0.5 degrees in diameter) in the FOV using an 18 mm Meade eyepiece and an LPI-G Advanced camera—both of which contribute to a small FOV and are not suitable for tracking satellites in LEO. The FOV with the eyepiece is 0.33 degrees, while the FOV of the camera is 0.13 degrees. For comparison, the desired FOV with an eyepiece is 1—2 degrees and at least 0.5 degrees with a camera, based on the proof of concept testing of various combinations of equipment, discussed in Chapter IV. Testing with a 5 degree FOV spotting scope resulted in the successful open-loop tracking of the ISS.

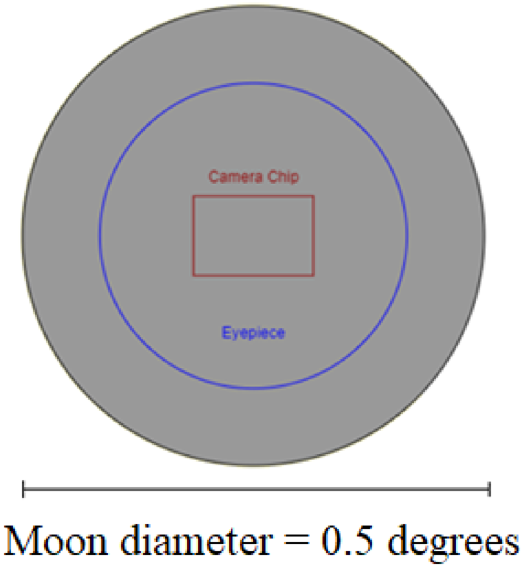


Figure 23. LX600 Field of View of Moon with 18mm Meade Eyepiece and Camera

The commercial satellite tracking software initially used by the SSAG is TheSkyX Pro, created and maintained by Software Bisque. It is designed for controlling "go-to" telescopes, and is compatible with a wide range of commercial telescopes. The software suite includes optional add on packages for controlling cameras and domes, as well as for pointing and tracking analysis. TheSkyX Pro software is easy to use, has excellent customer support, and includes satellite tracking features native to the software. It generates satellite tracking and slewing commands in right ascension and declination rates, which are not compatible with every COTS computerized mount. Although the Meade LX600 is one of the default telescopes in TheSkyX Pro, the satellite tracking capability was discovered to not be compatible with the LX600 mount. The software is also capable of orbit propagation, and of sending updated TLE data to a computerized mount via a RS-232 cable. TheSkyX Pro is compatible with devices that are ASCOM compatible, which increases the options for future equipment that will be compatible. Overall, TheSkyX Pro software is recommended for its ease of use, numerous features, customer support, and compatibility, and will be an asset for creating a closed-loop satellite tracking system.

Other options for satellite tracking software are the use of freely available open-source software or creating customized software; free software was used during proof-of-concept testing for this thesis with software called Satellite Tracker, found on heavenscape.com. While this is an excellent option for low budget satellite tracking systems, there are some disadvantages to relying solely on free software that may affect achieving closed-loop capability. Free software may not include an interface that allows the incorporation of a detector for feedback necessary to implement automatic tracking. Additional software may be required for automated (closed-loop) tracking—which may lead to a custom software solution. One organization that achieved closed-loop tracking capability, the Air Force Institute of Technology (AFIT), used custom scripting in MATLAB (Salvador 2015). The disadvantage to custom software is that the organization must maintain and update it; this was a lesson shared by an AFIT graduate student after mandatory software updates and hardware upgrades caused the satellite tracking system to become inoperable (Salvador 2015). For this reason, commercial software may be preferable.

The laptop for hosting TheSkyX Pro software is a Windows Surface Book 2, with Windows 10 operating system. It has 16 GB of RAM, more than the minimum amount required to run TheSkyX Pro. The processor (8th Generation Intel® Core™) allows for seamlessly running multiple astronomy programs simultaneously, which is important while learning to integrate multiple devices for satellite tracking. The laptop only has 2 USB type A ports, however additional USB type A ports are easily added with a USB hub. The SSAG also used an additional 15 inch display, beneficial for viewing multiple programs during tracking (such as Satellite Tracker and camera software). The screen resolution, 3240 x 2160 pixels, was excellent for viewing images and video from an astronomy camera. There were no issues with battery power during testing since an external portable power supply was used.

The SSAG utilized a quality portable, rechargeable battery to power the telescope system. The Yeti 400 Goal Zero had 400 Watt hours (33 Amp hours) 12-volt battery capacity, with 2 AC power outlets and 2 USB ports. Additional AC power outlets were provided using a surge-protected power strip.

B. RECOMMENDED ADDITIONAL EQUIPMENT

The following recommendations are made with eventual closed-loop capability in mind, and are presented in the advised order of purchase. The recommended order for purchase was decided based on the components that would have the greatest immediate utility to the SSAG in advancing the effort to create a satellite tracking system. Manufacturers were reviewed for reputation and customer service ratings; components were selected based on compatibility with other equipment (especially with TheSkyX Pro software), product reviews, warranties, price, and suitability for a satellite tracking system capable of detecting a 1U CubeSat in LEO. Funding is unknown at the time of writing, but value for cost is carefully considered. Prices are listed in Table 6 in Section C.

1. Astronomy Camera

A new camera with a larger detector than the current Meade cameras would bring immediate and significant improvement to the current capabilities because it would give both a greater FOV to the LX600, as well as increased sensitivity to light. As mentioned in Chapter II Section B.7, the detector size when combined with the telescope focal length establishes the FOV, and the individual pixel dimensions influence sensitivity. CubeSats in LEO, as discussed in Chapter II Section A, may have an approximate visual magnitude on the order of +10 to +12. A large detector size is necessary for a practical FOV and larger pixels for the required sensitivity. As previously stated (Chapter II), astronomy cameras are typically one of two types: CMOS and CCD. Despite being higher priced than CMOS cameras, the recommended camera is a CCD due to decreased noise readouts and better sensitivity. A comparison of the CCD cameras considered for the NPS satellite tracking system is detailed in Appendix A. The astronomy camera, paired with the main OTA, will ultimately be used as the detector for the closed-loop tracking system.

The TRIUS PRO 35 (monochrome), manufactured by Starlight Express, is the recommended CCD camera due to its excellent features. It is a 10.8 megapixels CCD with 9 µm pixel size and a pixel array of 4032 x 2688, as well as a USB (2.0) hub on the main body of the camera. The USB hub, which sets it apart from other CCDs of similar quality and price, allows it to incorporate other equipment (such as filter wheels) in the future and reduces the number of cables required to connect to a computer. Most importantly, the TRIUS PRO 35 gives the LX600 a 0.64 x 0.43 degree FOV, which will allow for much easier detection and tracking of a target satellite than with the Meade LPI-G Advanced cameras. For comparison, Figure 24 shows the FOV of the Moon through the LX600 16 inch aperture optical tube in three ways, with the Moon (0.5 degrees in diameter) for scale: first, the orange outer ring shows the image through an eyepiece with a 0.85 degree FOV; the yellow rectangle shows the FOV with the Starlight Xpress Trius Pro 35 CCD camera; the red rectangle shows the FOV with the Meade LPI-G Advanced camera.

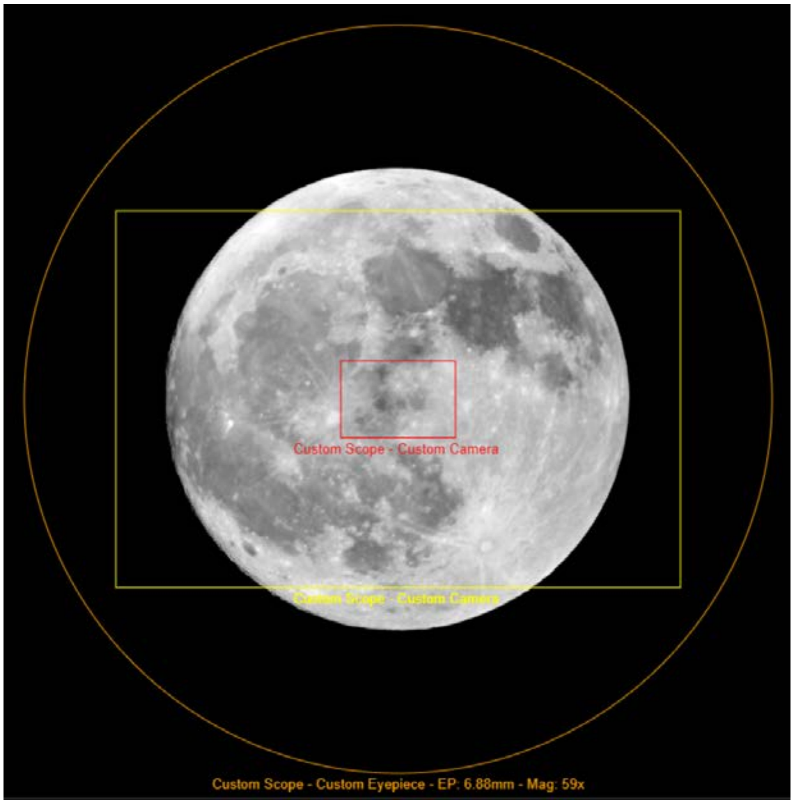


Figure 24. LX600 Field of View Camera and Eyepiece Comparison

2. Spotting Scope

A new spotting telescope—to replace the simple viewfinder currently on the LX600—coupled with a larger FOV camera, would immediately improve the capabilities of the current system and increase the likelihood of successful detecting and tracking by offering a more sensitive telescope for initial acquisition while retaining the larger FOV to accommodate larger errors in initial pointing. Characteristics of a spotting scope for a satellite tracking system are discussed in Chapter II Section B.8 and in Chapter III Section A.1. An ideal spotting scope should have a wide FOV (4-5 degrees) but a large enough aperture to have a limiting magnitude close to the visual magnitude of a CubeSat. The purpose of the spotting scope is to initially detect the target satellite, then aid in centering the satellite into the FOV of the main telescope, which will have better optics for tracking due to its larger aperture, increased sensitivity, and magnification level. While it should not be relied upon to be sensitive enough to detect a 1U CubeSat due to its shorter focal length and smaller aperture, it will aid in the learning process as the system is tested with detecting and tracking brighter satellites.

The recommended spotting scope is a refractor style telescope: the ED80 manufactured by Explore Scientific, pictured in Figure 25. Its price at the time of this writing is approximately $640.00. It has a 480 mm focal length and a *f*/6 focal ratio. Weighing 5.95 pounds, it is light enough to permanently install on the LX600 tube without exceeding weight limits of the Meade mount or the recommended mount. The ED80 is compatible with 1.25 and 2-inch barrel eyepieces and cameras (as is the LX600).

Figure 25. Explore Scientific ED80 Spotting Scope. Source: Explore Scientific (n.d.).

The ED80 spotting scope has a wider FOV than the LX600, making it more suitable for use with the previously purchased Meade eyepieces and cameras. With a 25 mm Meade eyepiece attached, the ED80 has a 3.13 degree FOV and a magnification of 19x. Its advertised limiting magnitude is +12, but that is likely under optimal observing conditions; the spotting scope should not be expected to detect a 1U CubeSat in LEO. The details of the spotting scopes comparison for the NPS satellite tracking system are discussed in Appendix C. Table 5 lists the metrics of the ED80 with some of the currently owned equipment as well as recommended equipment.

Table 5. Metrics of Spotting Scope with Cameras and Eyepieces

Equipment	FOV (degrees)	Magnification
Meade LPI-G camera	0.88 x 0.59	-
TRIUS PRO 35 camera	4.33 x 2.88	-
Meade 25 mm eyepiece	3.13	19.2x
Meade 21 mm eyepiece	4.38	22.86x
Tele Vue 55 mm eyepiece	5.73	8.73x

The addition of a spotting scope will require mounting hardware. Quality, high precision mounting hardware allows for precise alignment between the spotting scope and the main OTA. There are many options; one is a universal dovetail plate for sale through High Point Scientific for approximately $100.00.

3. Observatory Dome

Next, an observatory dome to house the telescope system would provide a dedicated place to store and operate the telescope system. There are multiple configurations of observatory domes, but there is one obvious type that is best for satellite tracking telescope systems: the clamshell configuration. This is best because it opens in a way that clears 360 degrees around the telescope. An important step in acquiring a target satellite into the FOV is for the telescope to aim at the point where the satellite is expected to appear over the horizon, where angular rates are minimum; for details about angular rates, refer to Chapter II Section B.9. Other dome types may obstruct the telescope’s line of sight, either through the nature of the structure or through synchronization challenges (such as a slot dome, which requires the dome opening to rotate with the pointing of the telescope, a difficult task for fast slews).

At NPS, on the roof of the Spanagel building, an old telescope dome sits in an acceptable (but not ideal) location for telescope placement. The location has obstructions that limit approximately 20% of the view to the horizon; a location on the top deck of the roof would be ideal, but is currently unavailable. The existing dome is a slot construction, which is not ideal for satellite tracking because it is unlikely that the dome can move quickly enough during tracking in order to not obscure the line of sight between the telescope and the satellite. Additionally, it would cost significant man hours to repair, automate, and synchronize the dome. The existing dome is pictured in Figure 26.

Figure 26. Existing Telescope Dome at NPS

A new clamshell dome would allow for the best unobstructed views to the horizon around the NPS campus. Due to the size of the LX600 and the necessary equipment required for satellite tracking, a 12 foot COTS clamshell dome is recommended. A high quality option is produced by Aphelion, shown in Figure 27.

Figure 27. Aphelion 12 foot Freestanding Clamshell Observatory.
Source: Aphelion (n.d.).

The Aphelion 12 foot freestanding observatory dome costs approximately $30,750, but with necessary features added (including a door for observers to enter the dome and automation capability), the estimate cost is $38,200.00. Figure 28 shows the dimensions of the dome with an outline of an installed telescope.

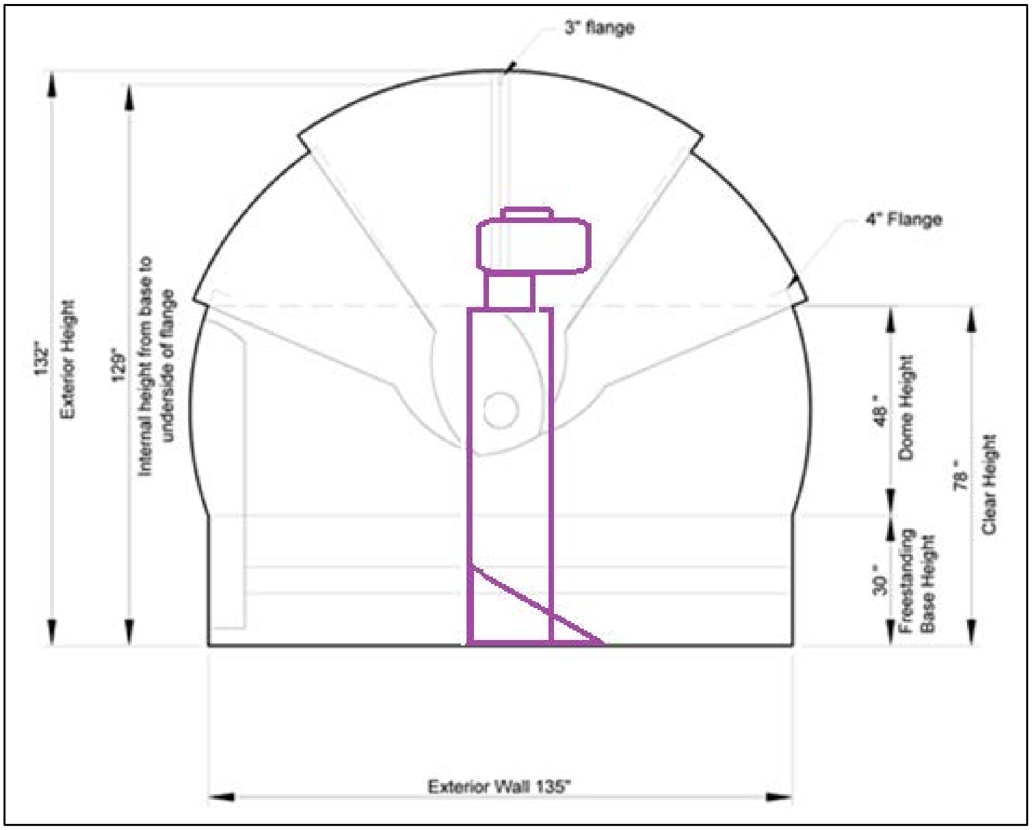


Figure 28. Aphelion 12 foot Dome Diagram with Telescope, Mount, and Pier. Adapted from Aphelion (n.d.).

Additionally, a pier is required for the LX600, on a Paramount Taurus 400 mount, to clear the edge of the clamshell dome. The recommended pier needs to be 51 inches tall to allow for the telescope to see to the horizon; one produced by Software Bisque for compatibility with the recommended computerized mount costs approximately $800.00.

4. Computerized Telescope Mount

A new computerized mount that is compatible with TheSkyX Pro software is recommended. Because the Meade computerized mount is not recommended for a satellite tracking system due to its incompatibility with the recommended tracking software, the recommended computerized mount is the Paramount Taurus, a fork mount manufactured by Software Bisque. Choosing the same manufacturer for the tracking software and the computerized mount ensures compatibility. The Taurus 400 is the smallest model fork mount offered by Software Bisque—information about mount types is discussed in Chapter

II Section B.4. The Taurus 400, pictured in Figure 29, is capable of supporting the weight of the LX600 optical tube assembly (125 pounds), the spotting scope (5.95 pounds) and mounting hardware (0.42 pounds), as well as the TRIUS PRO 35 CCD camera (2.5 pounds).

Figure 29. Paramount Taurus Model 400. Source: Software Bisque (n.d.).

This mount is compatible with TheSkyX Pro tracking software, already purchased by SSAG. It has two USB ports, a hand controller, and features built-in wireless mount operation capability, an option available through TheSkyX Pro that would simplify the telescope system setup. Its maximum slew rate is 3.5 degrees per second (both axes); however, based on the payload weight (131.37 pounds) the maximum slew rate is 2.8 degrees per second. This slew rate is more than adequate for tracking satellites in LEO.

5. Wide FOV Eyepiece

Finally, a new eyepiece would be beneficial to the telescope system but is not necessarily required. A Tele Vue 55 mm plossl would give a 0.85 degree FOV with the LX600 and a 5.73 degree FOV with the ED80 spotting scope. This eyepiece would allow for improved probability of successfully visually tracking satellites in LEO because it gives such a wide FOV to the main telescope optics, which will improve satellite acquisition in the presence of initial pointing errors, and is included as part of the cost of the NPS satellite tracking system.

C. SYSTEM SUMMARY

A telescope capable of detecting and tracking a CubeSat must find the correct combination of factors between aperture size, focal length, and FOV. These foundational characteristics need to be paired with a detector (camera) size that will not limit the FOV and will be sensitive enough to detect the CubeSat's low visual magnitude. The telescope computerized mount needs a slew speed of at least 1 degree per second, and a satellite tracking system would benefit greatly from pairing with a spotting scope. The telescope, computerized mount, spotting scope, and camera should be compatible with the satellite tracking software. The system ideally will be configured in a way that allows for smooth tracking, and located where there is an unobstructed view to the horizon. Table 6 lists all the necessary components and their cost. The top portion of the table describes equipment already owned by the SSAG at NPS and their associated cost, while the bottom portion lists recommended items and their associated cost. The final row of the table gives the estimated funds still needed to achieve a permanently located closed-loop satellite tracking system.

Table 6. System Equipment and Cost

Component	Type	Brand / Model	Cost
Main telescope	SCT	Meade / LX600 16 inch aperture	$7,499.00
Tracking software	Astronomy	Software Bisque / The SkyX Pro	$980.00
Eyepiece Set	Variety	Meade / 4000 and 5000	$750.00
Computer	Laptop	Windows / Surface Book 2	$2,400.00
Power Source	Portable battery	Goal Zero / Yeti 400	$450.00
Owned Equipment Value			$12,079.00
Astronomy Camera	CCD	Starlight Express / TRIUS Pro 35	$5,133.00
Spotting telescope	Refracting	Explore Scientific / ED80	$640.00
Spotting scope mounting hardware	Permanent	ADM / Universal dovetail plate	$100.00
Dome	Clamshell	Aphelion / 12 foot freestanding observatory	$38,200.00
Pier	Permanent	Software Bisque / 51 inches	$800.00
Computerized telescope mount	Fork mount	Software Bisque Paramount / Taurus 400	$16,045.00
Eyepiece	Plossl	Tele Vue / 55 mm (50 deg AFOV)	$245.00
New Equipment Total Cost			**$61,163.00**

The estimated totals do not include taxes, shipping and handling, delivery fees, or installation costs. The total system cost is estimated at $73,242.00. Investing in high quality equipment is necessary to eventually achieve a closed-loop satellite tracking system capable of detecting a 1U CubeSat in LEO.

D. FUTURE WORK

Until a new computerized mount is purchased, further testing is required for the LX600 and The SkyX Pro software. Custom scripting within The SkyX Pro may enable it to send compatible slewing commands to the Meade computerized mount, especially if TheSkyX Pro can be modified to change from tracking at a sidereal rate to the fast rate for a target in LEO. While creating custom software does not keep with the intent of this thesis to use primarily COTS components, custom software is an option worth pursuit until a new computerized mount (compatible with The SkyX Pro software) is purchased.

Testing with a new astronomy camera would likely lead to impressive progress in satellite tracking, given that a new camera would allow for a significantly wider FOV than the Meade LPI-G cameras used during initial proof-of-concept testing. With a wider FOV and increased sensitivity, it will be easier to detect a satellite and keep it within the FOV of the telescope system. Once satellite tracking has been reliably demonstrated, additional work can test use of the telescope system for orbit determination, to include verifying TLE accuracy of known objects or satellites.

Additionally, future work can be done with regards to retroreflector technology and laser communications. Retroreflector technology uses directed energy from the ground to the satellite, which then reflects energy back to the ground; this method is used for orbit determination and precision locational data for satellites. Laser communication technology has been improving, and multiple organizations have on-orbit laser communication satellites (Willstatter et. al. 2017, 1). With a reliable satellite tracking system, NPS can partner with other organizations in tracking and testing laser communications satellites using COTS components.

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APPENDIX A. ASTRONOMY CAMERA COMPARISON

Multiple cameras were considered in this research with the aim of finding an appropriately sensitive COTS astronomy camera that would complement the focal length of the Meade LX600 optical tube (3251 mm). Characteristics evaluated include camera AFOV, the resulting true FOV (TFOV) of the telescope system, detector (chip) size, and pixel size. An overview of camera characteristics and types can be found in Chapter II Section B.7.

Table 7 compares the CCD cameras considered for the NPS telescope tracking system. The array size is shown with X Pixels and Y Pixels. FOVs for the main telescope and the spotting scope are given in degrees by the width of the FOV. Of note, the last camera listed requires liquid cooling and is included for perspective of the options considered.

Table 7. CCD Camera Comparison

Camera	Mega Pixels	Pixel Size (µm)	X Pixels	Y Pixels	FOV LX600 (degrees)	FOV ED80 (degrees)	Cost
SBIG STX-16803	16.8	9x9	4096	4096	0.65	4.39	$10,000.00
ATIK 11000	10.7	9x9	4007	2671	0.42	4.30	$5,500.00
ATIK 16200	16.2	6x6	4499	3599	0.38	3.22	$3,780.00
Starlight Express TRIUS PRO 35	10.8	9x9	4032	2688	0.43	4.33	$5,133.00
Starlight Express TRIUS SX-56	16.8	9x9	4096	4096	0.65	4.39	$9,140.00
QHY 45GX	4.3	24x24	2084	2085	0.88	5.96	$16,500.00

The recommended camera is highlighted: the TRIUS PRO 35, manufactured by Starlight Express. It has a large chip and pixel size, which are necessary for detecting and tracking a 1U CubeSat in LEO, but may be too large for brighter and larger objects. Learning to use and testing of the telescope system will require tracking brighter and larger satellites; the TRIUS PRO 35 settings can be adjusted for optimal viewing through a process called binning. Binning is a process that affects pixel size readout by grouping pixels together (Photometrics n.d.). Most cameras have default binning settings of 1x1, meaning each pixel has a readout. A 2x2 binning setting causes a four-pixel region to give simultaneous readout; this setting is applied to the entire detector array. Other binning settings are 3x3 and 4x4. A comparison of 1x1 and 2x2 binning is pictured in Figure 30.

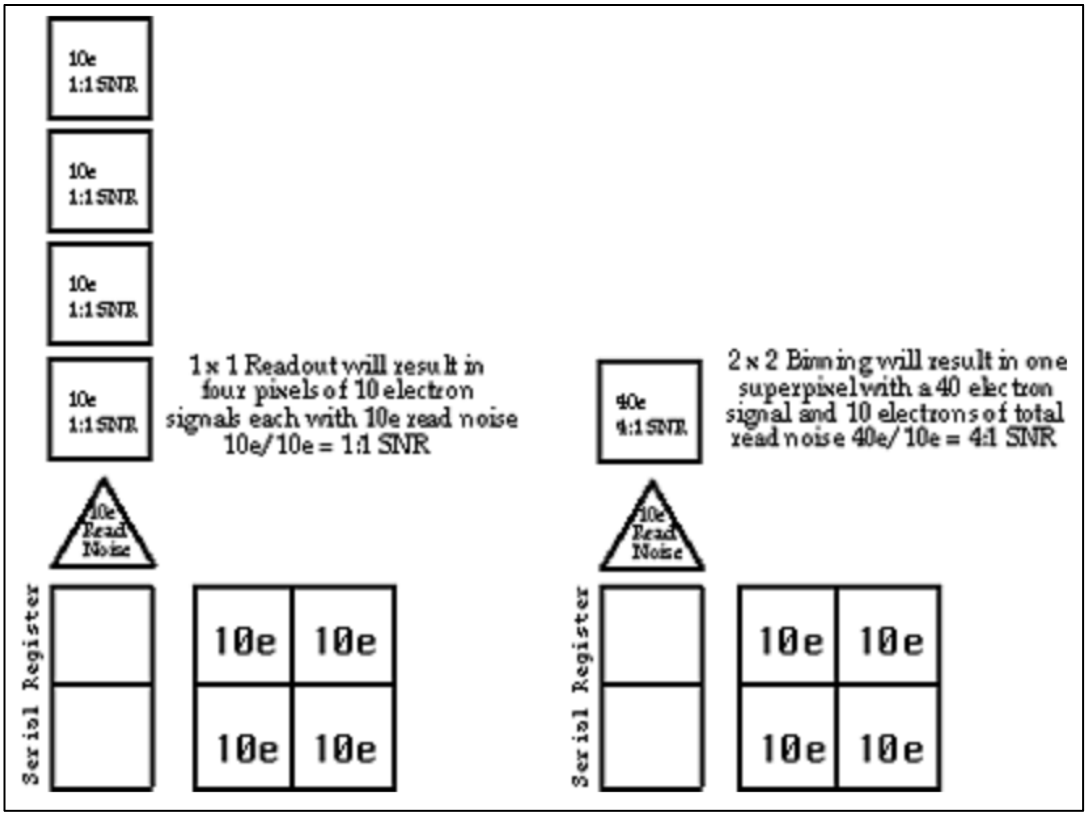

Figure 30. 1x1 and 2x2 Binning Illustration. Source: Photometrics (n.d.).

Advantages of binning are reduced noise and, for astronomy imaging, less oversampling of bright objects. For attempts to view and track large, bright objects with the TRIUS PRO 35 (or any CCD camera with a large detector and pixel size) in combination with the LX600’s long focal length and large aperture, the 2x2 or 3x3 binning setting is recommended.

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APPENDIX B. OBSERVATORY DOME COMPARISON

Multiple COTS dome types were considered for the NPS SSAG satellite tracking system during the course of this research. Dome types are discussed in Chaper II Section B Part 9, as well as Chapter V Section B, with an explanation of why a clamshell-style dome is preferred for LEO satellite tracking. Because a clamshell-style dome is recommended (to prevent the design of the dome from obstructing the view to the horizon), there were essentially only two reputable manufacturers considered in this research: Aphelion Domes and Astro Haven. A 12 foot dome is the recommended size in order to ensure that there is adequate space for the telescope, computerized mount, all of the necessary equipment, and multiple observers to fit inside. Table 8 is the comparison chart for the domes. The Aphelion 12 foot dome is recommended.

Table 8. Observatory Dome Characteristics Comparison

12 Foot Clamshell	Aphelion	Astro Haven
Height (feet)	11	8.5
Automated	Yes	Yes
Remote capable	Yes	Yes
Weatherproof	Yes	Yes
Customizable	Yes	Yes
Includes door	Yes	No
Weight (lbs)	750	880
Estimated Cost	$38,200.00	$42,700.00

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APPENDIX C. TELESCOPE COMPARISON

There are abundant COTS computerized telescope options to choose from for satellite tracking purposes, but the NPS SSAG already owns an excellent optical tube—the Meade LX600 16 inch aperture. Because this optical tube is adequate for detecting an object as small and dim as a 1U CubeSat, there is no need at this time to explore alternatives.

Having a spotting scope that could potentially detect and assist in tracking a 1U CubeSat would be immensely beneficial because the main telescope will have a small field of view, making initial acquisition of the target satellite challenging. An initial estimate narrowed the search for a telescope with an aperture around 100 mm and a focal length between 500-700 mm. With an unknown budget, telescopes with a wide range of prices were considered.

The characteristics of the ideal spotting scope for a satellite tracking system contribute to a wide FOV (i.e., short focal length), compatible with the desired astronomy camera and the satellite tracking software, while also having the ability to detect an object with a (worst-case) visual magnitude of +12. Table 9 displays the important characteristics of several spotting telescopes that were considered. These telescopes were selected based on falling within the desired parameters for aperture and focal length (giving a desired wide FOV), the manufacturer’s reputation for quality, customer reviews, and price. The FOV and Magnification are calculated using a 21 mm 100 degree AFOV in order to evaluate the maximum potential (true) FOV with a currently owned eyepiece. The highlighted option is recommended, as discussed in Chapter V. Overall, the ED80 had the best features and customer reviews for its weight and cost—but most importantly, it gave a wide FOV.

Table 9. Telescope Comparison Summary

Telescope	Ap (mm)	FL (mm)	FOV (deg)	Lim Mag	Mag	Weight (lb)	Cost
Orion EON 85	85	561	3.74	+12.3	26.71x	9.2	$1,800.00
Orion EON 115	115	805	2.61	+13	38.33x	15.2	$1,500.00
Astro-Tech 80	80	480	4.38	+12.2	22.86x	5.5	$800.00
Astro-Tech 102	102	714	2.94	+12.7	34x	8.0	$600.00
Explore Scientific ED80	80	480	4.38	+12.2	22.86x	5.95	$640.00
Explore Scientific ED102	102	714	2.94	+12.7	34x	9.6	$1,000.00
Stellarvue 80	80	560	3.75	+12.2	26.67x	7.0	$1,600.00

Table Abbreviations:

Ap = Aperture

FL = Focal Length

FOV = Field of View

Lim Mag = Limiting Magnitude

Mag = Magnification

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