University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Concept Definition Document (CDD)

GHOST - Ground Hardware for Optical Space Tracking

1 Information

1.1 Project Customers

Daniel Pachura Phone: 571-304-7623 Email: daniel.pachura@aero.org	Roger Thompson Phone: 571-304-7558 Email: roger.c.thompson@aero.org	George Pollock Phone: 719-375-6283 Email: george.e.pollock@aero.org

1.2 Team Members

Jack Toland, Project Manager jack.toland@colorado.edu 206-305-3492	
Ginger Beerman, Software Systems Lead ginger.beerman@colorado.edu 303-946-6796	Jake Vendl, Hardware Systems Lead jacob.vendl@colorado.edu 719-246-8726
Connie Childs, Software coch5233@colorado.edu 760-585-6676	Lucas Calvert, Electronics lucas.calvert@colorado.edu 814-762-3761
Connor Ott, Software connor.ott@colorado.edu 720-475-0232	Duncan McGough, Integration and Test duncan.mcgough@colorado.edu 605-484-3043
Rachel Mamich, Optics rachel.mamich@colorado.edu 303-325-1626	Keith Covington, Controls keith.covingtonjr@colorado.edu 817-304-7736
Kira Altman, Astrodynamics iris.altman@colorado.edu 719-321-3709	Seth Hill, Manufacturing seth.a.hill@colorado.edu 970-237-2767

Mission Statement

*GHOST (**G**round **H**ardware for **O**ptical **S**pace **T**racking) will utilize low-cost, commercial-off-the-shelf imaging hardware to perform autonomous orbit determination on a set of cataloged resident space objects as part of a Space Situational Awareness sensor network.*

Contents

List of Figures

Table of Acronyms

Acronym	Definition
Az & El	Azimuth and Elevation
CONOPS	Concepts of Operations
COTS	Commercial Off The Shelf
DR	Derived Requirement
DSLR	Digital Single Lens Reflex
EKF	Extended Kalman Filter
FBD	Functional Block Diagram
FOV	Feild of View
FR	Functional Requirement
GEO	Geosynchronous Earth Obit
GHOST	Ground Hardware for Optical Space Tracking
GPS	Global Positioning System
IOD	Initial Orbit Determination
LEO	Low Earth Orbit
LKF	Linearized Kalman Filter
MEO	Middle Earth Orbit
NORAD	North American Aerospace Defense Command
NTP	Network Time Protocol
OD	Orbit Determination
PPP	Precise Point Positioning
RTK	Real-Time Kinematics
SSA	Space Situational Awareness
STK	Systems Tool Kit
STM	Space Traffic Management
TBD	To Be Determined
TLE	Two-line Element
RA & Dec	Right Ascension and Declination
RSO	Resident Space Object
RTK	Real-Time Kinematic
UTC	Coordinated Universal Time

2 Project Description

2.1 Purpose

As the space industry continues to grow, Space Traffic Management (STM) and Space Situational Awareness (SSA), for the purpose of conjunction avoidance, are becoming areas of increased interest. The US relies heavily on its assets in space for navigation, weather forecasting, national security, and countless other daily needs. If a collision in space were to happen, the result would likely be catastrophic, propagating throughout the many operational orbits in space. In order to mitigate the risk of a space collision as space becomes increasingly essential to daily life, The Aerospace Corporation is currently exploring a variety of SSA sensor options. The overarching goal is to identify technologies and systems that can meet a growing demand for more frequent and more accurate space object orbit tracking. The SSA market currently relies on expensive ground systems that exist in low quantities in several locations around the world. Thus, there is an empty niche for low-cost, high production-volume sensors. STM is ultimately performed to generate actionable intelligence; it assists in answering questions for space object operators such as:

- What is the space object's current orbit?
- Did the space object's orbit change as expected given the recently commanded maneuver?
- What are the potential upcoming collision risks based on the object's current orbit?

The purpose of the Ground Hardware for Optical Space Tracking (GHOST) project is to contribute updated orbital states of space objects to a central catalog for the purpose of more accurate and effective STM. Using the sensor's location and sets of right ascension and declination observations for a space object in GEO, MEO, or LEO, the system shall perform a specific orbit determination (OD) and return an orbit state. The low-cost and reduced complexity of the GHOST system will allow for a greater number of systems to be purchased and placed throughout the world, resulting in the ability to gather large amounts of data. A system built for $5000 will be significantly cheaper than a typical optical SSA system. The system will focus on imaging objects with an apparent magnitude equal to or brighter than 10. While high-cost sensors may achieve observations at an apparent magnitude of 18, the ability to cover the majority of space objects brighter than an apparent magnitude of 10 will allow for improved tasking of high-cost sensors on challenging objects.

2.2 Project Objectives

The Levels of Success table summarizes the overall objectives of the GHOST system. Level 1 objectives define a minimally capable system. Level 2 objectives are inclusive of Level 1 and improve the usability and capability of the system. Level 3 objectives are inclusive of Level 1 and Level 2 and define a fully function system capable of achieving all given objectives. The GHOST system will be designed for the completion of Level 3 objectives. In the case of unforeseen challenges or failures, the project may be scoped back to a Level 2 or Level 1 for a given objective after consultation of both the sponsor and the Project Advisory Board. Included below is a summary of each objective and a table containing the levels of success.

1. **Scheduling Software** - The scheduling software will be able to propagate an orbit given the orbit parameters. The scheduling software will use the propagated orbits of multiple satellites to create an imaging task list based on visibility and prioritization that allows for imaging of each satellite.

   Verification: *Model Comparison* and *End-to-End*. At a subsystem level, the scheduling software will be validated by replicating the global scenario in STK (Systems Tool Kit). A comparison will be made to check for ground-to-satellite visibility for the times at which the system is tasked to image a given satellite. The scheduling software will be validated in an end-to-end system test by performing tasking for a Colorado-based imaging test.

2. **Actuation Hardware** - The Actuation hardware will articulate the imaging system such that it can slew the boresight to target a predicted orbit path of the space object being imaged.

   Verification: *Lab*, *Star Registration*, and *End-to-End*. The tracking hardware will be validated at three stages. First, a lab validation will be performed by commanding the system to point at target positions with known azimuth and elevation locations. Second, a field validation will be performed by commanding the system to image specific right ascension and declination targets, the accuracy of which will be confirmed using a star registration with Astrometry.net. Finally, a validation will be performed as part of an end-to-end system validation in Colorado.

3. **Imaging System** - The imaging system shall image space objects in Earth orbits from the Space-track.org catalog with apparent magnitudes equal to or brighter than 10 under ideal conditions.

    Verification: *Star Registration* and *End-to-End*. The imaging system will be validated using two different methods. Preliminary validation will be completed by capturing an image of any portion of the sky at night. The visible stars will be registered and posted apparent magnitudes will be checked for satisfaction of the requirements. Second, the imaging system will be used as part of the end-to-end system validation in Colorado.

4. **Image Processing** - Captured images will be processed for the right ascension and declination of the boresight and space object.

    Verification: *Solved Data* and *End-to-End*. Preliminary validation will be completed using a set of images that have already been processed for a boresight right ascension and declination. The image processing system will be used on the images and checked for a correct result. Final validation will be completed as part of the end-to-end system validation in Colorado.

5. **Orbit Determination** - Use right ascension and declination observations to perform an orbit determination using a standard advanced filtering method.

    Verification: *Model Comparison* and *End-to-End*. For initial validation, STK will be used to generate a set of right ascension and declination points from a propagated orbit. The result of the orbit determination will be compared to the original propagated orbit. Final validation will be completed as part of an end-to-end system validation in Colorado. Results of the system test will be compared to publicly available cataloged orbits.

Table 1: Levels of Success

	Level 1	**Level 2**	**Level 3**
Scheduling Software	- Provide an imaging task list based on the basic horizon constraint	- Incorporate multiple space objects in a given time-frame	- Apply prioritization to imaging target selection based on human input and last seen time
Tracking Hardware	- Track objects in GEO orbits with automated slew between objects	- Track objects in MEO orbits	- Track objects in LEO orbits
Imaging System	- Capture images of space objects with apparent magnitudes brighter than 6.0 (visible to the naked eye)	- Capture images of space objects with apparent magnitudes brighter than 8.0	- Capture images of of space objects with apparent magnitudes brighter than 10.0 (visible with a binocular)
Image Processing	- Report boresight right ascension and declination for each image with angular accuracy $\pm 3\sigma$ arcseconds	- Report object right ascension and declination with angular accuracy $\pm 3\sigma$ arcseconds	- Report angular rate of tracked object with angular accuracy $\pm 3\sigma$ arcseconds per second
Orbit Determination	- Report object right ascension and declination (No orbit determination)	- Complete an unfiltered orbit determination based on angular observations	- Complete a full orbit determination using advanced filtering (Kalman or Batch)

2.3 Concept of Operations

In general, space object observations can be performed using either radar or optical tracking systems. The GHOST system employs the latter - an optical tracking system that performs space object for the purpose of Space Traffic Management (STM). Below are two Concept of Operations (CONOPS) diagrams, the first for the GHOST system end-to-end functionality and the second for the global Space Situational Awareness (SSA) network functionality.

The GHOST module will be transported to an observation site and unloaded from the transport vehicle. The module will be maneuverable for 1-2 people. An operator will power on the device and walk through the guided setup procedure. After the device is ready, the operator will provide a list of NORAD IDs of objects for which they desire an updated orbital state. The module will now perform automated tasking and begin to image the space objects as they become visible. During a single pass of a space object, multiple images will be captured and an orbit determination will be performed. The final orbit estimates of each object will be provided to the operator.

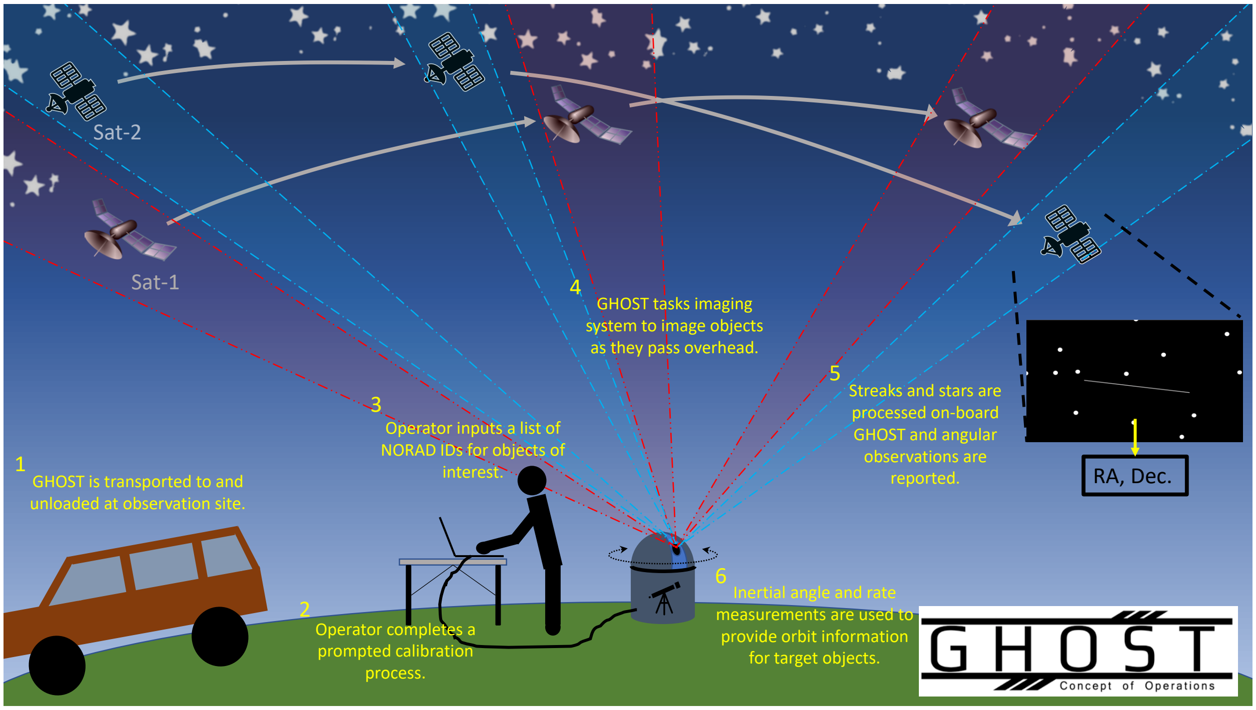

Figure 1: System CONOPS

Although the GHOST senior project will build only one module, the ultimate vision for GHOST is to operate as part of a large, multi-module network. Due to GHOST's low-cost and limited complexity, many units can be purchased and placed around the world. The global concept of operations is shown below. The GHOST network will function in an automated fashion, working through a catalog of space objects and updating them as they become visible. This process will happen repeatedly and continuously. At the same time, a conjunction avoidance screening is performed on all space objects within close orbital proximity. Should the probability of collision exceed a set statistical value, an alert is delivered to an operator. The operator can notify the spacecraft owner and request additional, more frequent observations.

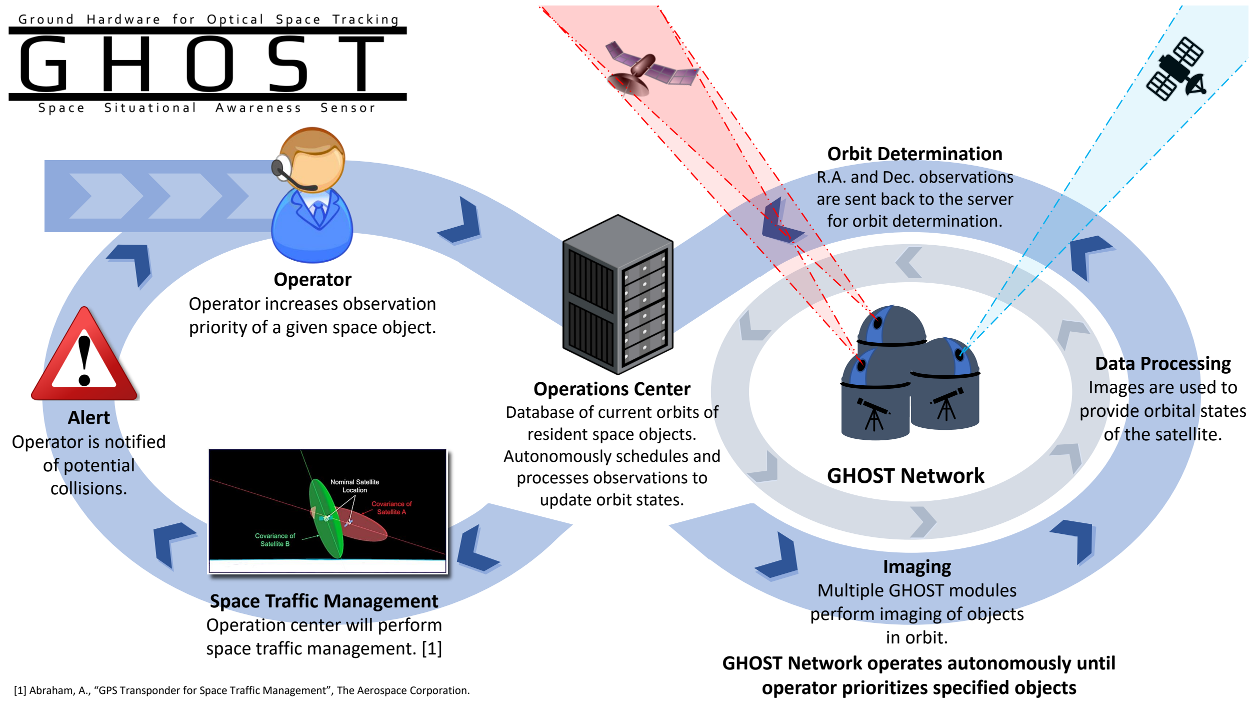

Figure 2: Global SSA Network CONOPS

2.4 Functional Requirements

The GHOST system has five functional requirements derived from the system objectives that completely encapsulate the functionality of a single unit. These functional requirements guide the flow down of design requirements and will additionally guide the trade study process. The functional requirements cover what objects will be imaged, in which orbit the objects will be, and the operator-facing functionality of the system. The design requirements capture the capabilities that must be met to accomplish the functional requirements.

Functional Requirement	Description
FR 1	The system shall be capable of imaging space objects in Earth orbit from the Space-track.org catalog with apparent magnitudes equal to or brighter than 10 under ideal conditions.
FR 2	The system shall be capable of imaging space objects in GEO, MEO, and LEO orbits.
FR 3	The system shall provide an orbit estimate if there are sufficient observations available.
FR 4	The system shall provide a set of orbit estimates when given an operator specified list of NORAD IDs and will do so without intermediary operator input.
FR 5	The system shall use commercial-off-the-shelf (COTS) imaging hardware.
FR 6	The system shall be able to operate with a 120V, 60Hz power source, drawing under 20A.

2.5 Functional Block Diagram

To illustrate the interaction between subsystems in the GHOST system, the following functional block diagram is included. The diagram identifies the information that will be required to flow between various components of the system for complete functionality. The diagram will guide the division of work, subsystem level testing, and transition points between subsystems.

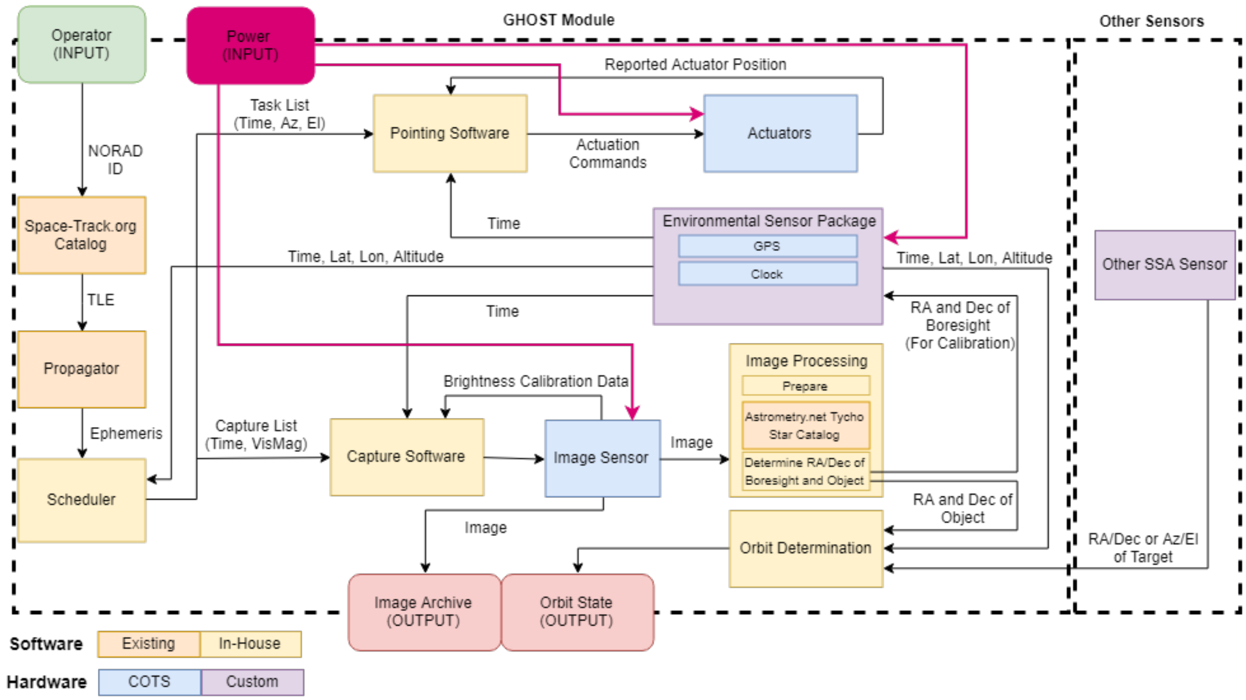

Figure 3: Functional Block Diagram

3 Design Requirements

The following section details the specific design requirements of each functional requirement. Each requirement is justified with a motivation and will be verified via a specified validation process. The requirements are verified by test, analysis, or inspection.

FR 1: The system shall be capable of imaging space objects in Earth orbits with apparent magnitudes equal to or brighter than 10 under ideal conditions. An optical system with a combination of aperture diameter, focal ratio, and CCD pixel size must be chosen such that the space objects can be imaged by the system.

Motivation: An apparent magnitude of 10 is the dimmest light source that can be seen with the eye assisted by binoculars. The ability to see objects at or brighter than an apparent magnitude of 10 will include a wide domain of the potential space objects to track.

Verification: Test - A portion of the night sky will be imaged and the stars will be registered using Astrometry.net. The apparent magnitude of visible stars will be found in a star catalog to confirm satisfaction of the requirement.

FR 2: The system shall be capable of imaging space objects in GEO, MEO, and LEO orbits.

Motivation: In order to perform an orbit determination, the system must be able to take images of a given spacecraft as it passes overhead.

Verification: Test - A field test will be performed with the fully assembled system in which images will be taken. If the system is able to resolve space objects within an image, the requirement passes.

DR 2.1: The mounting subsystem shall be capable of slewing at $\geq 2^\circ$/s.

Motivation: The ISS is one of the fastest moving LEO space objects; it moves across the sky at a resolved speed of up to roughly 1.1°/s. Depending on the imaging method used, the imaging system must be able to slew approximately twice as fast as the space object in order to move ahead of the space object for a stationary, non-tracking image.

Verification: Test - The angular rate will be measured in a laboratory setting by measuring the angular sweep of the system and the time it took the system to complete the sweep, and then solving for the angular rate by using the approximation $d\theta/dt \approx \Delta\theta/\Delta t$.

DR 2.2: The mounting subsystem hardware shall mechanically interface with the imaging subsystem hardware.

Motivation: To properly image objects in any orbit, the actuation subsystem must connect to the optical subsystem in a way that melds them into a fully-functional system.

Verification: Test - This objective will be met if the actuation subsystem can successfully maneuver the optical system to point at a desired angular set.

FR 3: The system shall provide an orbit estimate if there are sufficient observations available.

Motivation: An orbit state estimate is the final output of the GHOST system. A user will task the system with a given object for the purpose of generating an updated orbit state.

Verification: Test - A list of space objects with accurate publicly available orbit states will be given to the GHOST system. The results of GHOST's orbit estimates will be compared with the orbit estimate given in the Space-track.org catalog.

DR 3.1 The system shall provide ≥ 6 angular measurements from a single orbit pass.

Motivation: In order to ensure a fully defined linear algebra problem when performing orbit determination, at least 6 angular measurements should be used. This ensures that any orbit calculation would not involve an under-determined, impossible-to-solve equation.

Verification: If the system is able to capture at least 6 measurements for a given object in a single orbit pass, this requirement is met.

DR 3.2 The system shall provide timing with a precision of ± 5 milliseconds.

Motivation: Precise timing that is synchronized throughout the system ensures that the optical hardware captures an image at the time when a pass of the required satellite occurs. Since the scheduling software relies on internal clock timing rather than an optical feedback loop, the timing method of GHOST dictates the success or failure of the project. 5 milliseconds was chosen as a threshold because this accuracy can be expected of any chosen hardware as well as the fact that any error to a finer degree will not affect the orbit determination to an equal degree due to the law of diminishing returns.

Verification: Analysis - The sinusoidal output of the on-board clock will be plotted against the NIST station time in Boulder, CO to ensure that the seconds correspond to UTC within the allowable threshold over time.

DR 3.3: The system shall be capable of processing an image containing a space object brighter than or equal to an apparent magnitude of 10.

Motivation: Image processing is required to provide observations for a given object and an orbit estimate. In order to meet functional requirements, all listed objects must be processed.

Verification: Test - This will require manufacturing an image of a space object of such that, with respect to the image's SNR, the apparent magnitude equal to 10. This will be overlain on an image of known boresight right ascension and declination at a known location in the image. If the image processing software is able to extract right ascension and declination of the manufactured object, the requirement is met.

DR 3.3.1: The system shall be capable of identifying and rejecting images that cannot be processed for boresight or space object inertial position.

Motivation: An image which cannot be processed for boresight or space object inertial position can break the processing pipeline.

Verification: Test - Two manufactured images will be manually placed in the pipeline - one containing insufficient inertial position information, and one containing insufficient space object positions. If the system flags these images as unfit for orbit determination because the images contain their respective insufficient data, this requirement will be satisfied.

FR 4: The system shall provide a set of orbit estimates when given an operator specified list of NORAD IDs and will do so without intermediary operator input.

Motivation: This is a Level 1 requirement with the customer that must be met for project success. This method is based on how current systems operate to perform orbit determinations.

Verification: Test - The system will be field tested for complete end-to-end operation without intermediary operator input on a list of NORAD IDs. If an orbit estimate is reported for each object with a sufficient number of observations, the requirement will be satisfied.

DR 4.1: The system scheduling software shall be able to schedule imaging tasks given a list of NORAD IDs.

Motivation: NORAD IDs exist for all Earth orbiting satellites. The NORAD ID is the initial input to the system.

Verification: Analysis - The objects on the list will be simulated in STK. The pointing of the system at various times will be compared to the position of the simulated object. The propagators used for both system and STK will be the same. If the simulated FOV of the system captures the object, the requirement will be satisfied.

DR 4.1.1: T̄he system shall be able to download TLE files from Space-Track.org.

Motivation: TLEs are needed to propagate space objects orbit for scheduling imaging.

Verification: Test - The system will be given a NORAD ID, and if the correct TLE from Space-Track.org is returned, the test will pass.

DR 4.1.2: The system shall have a connection to the internet.

Motivation: An internet connection is required to access TLE data from spacetrack.org.

Verification: Test - The system will pass this requirement if it is able to pull existing data from the internet, verifiable from data inspection.

DR 4.1.3: The system shall propagate a space object's orbit from a TLE.

Motivation: Propagating the object's orbit from a TLE allows future observations to be had along the object's orbital path.

Verification: Test - The propagated orbit will be compared to the same TLE propagated in STK accounting for the same orbital perturbations.

DR 4.2: The GHOST module shall autonomously slew between scheduled pointing angles without operator input.

Motivation: To gather information about multiple space objects, the system must autonomously change its pointing direction to image the currently desired space object.

Verification: Test - This is a time-dependent study where the system will be given the IDs of two space objects passing overhead at notably different times. The test will pass if the system can image both space objects, at two separate times, without user input in between the two objects passing overhead.

DR 4.2.1: The GHOST module shall contain an on-board control algorithm to actuate the optical sensor.

Motivation: A control algorithm is needed to ensure the optical sensor is pointed at the desired rate with minimal overshoot and no hardware damage.

Verification: Test - The optical sensor will be commanded to point at a specific location and if the control system is able to actuate the sensor to point in that direction prior to the space object entering the frame allowing for actuator settling time, this test will pass.

DR 4.3: The GHOST module will perform image processing on-board and without operator input.

Motivation: The image processing software must be able to recognize the space object in the image and calculate right ascension and declination.

Verification: Demonstration - If image processing is autonomous, this requirement will be satisfied.

DR 4.4: The system shall provide timing within $5ms$

Motivation: A timing error of 1 microsecond is equivalent to a distance measurement discrepancy of about 0.75 cm for the case of a LEO space object that travels 7.5 km/s. Any measurement error over the magnitude of 1 cm would critically degrade the accuracy of the orbit determination and the scheduling software would degrade without operator intervention.

Verification: Analysis - Manually compare the drift rate of the on-board clock with the UTC time output by the NIST station in Boulder.

DR 4.5 The system shall know its own geodetic latitude, longitude, and altitude (wrt WGS84 ellipsoid) to an accuracy of 10 meters RMS.

Motivation: The system must know its location to determine where to point the lens to capture space object passes - the skyward location is highly dependent on ground location. GHOST cannot perform an orbit determination without calculating the line-of-sight vector to the space object in question, and this vector relies on the knowledge of ground location.

Verification: Test - Travel to a variety of locations in the Front Range area with known positional characteristics (altitude, latitude, longitude).

FR 5: The system shall use commercial-off-the-shelf (COTS) imaging hardware.

Motivation: It is important to use COTS hardware in order to keep the system low cost, and allow the system to be easily replicated. In the long term, the GHOST module is planned to be used as a unit in a network comprised of many GHOST modules. A system that does not use expensive custom made parts, and instead uses widely available parts, will allow for a network that is easier and cheaper to build and maintain.

Verification: Inspection - This requirement must be kept in mind when selecting the hardware to build the GHOST module. Shopping only with well-known retailers, buying mass produced parts, all the while documenting where the parts are bought from.

DR 5.1: The lens and sensor shall be available within 4 weeks from a US Retailer.

Motivation: The COTS hardware should be easily attainable such that the system can be replicated quickly, if mass production is desired.

Verification: Inspection

FR 6: The system shall be able to operate with a 120V, 60Hz power source, drawing under 20A.

Motivation: The system is designed such that normal usage involves access to wall power. As such, the on-board electronics and hardware shall be designed such that they can be run off of standard 120V, 60Hz.

Verification: Test - The system will be run off of a wall outlet power source and subsystems will be checked for functionality. Of particular interest is the current draw from the outlet.

4 Key Design Options Considered

4.1 Imaging and Tracking Methods

The manner in which images are captured influences how other key elements in the system operate. The three methods considered for imaging are sidereal-stationary capture, space object-stationary capture, and true-stationary capture. The following sections discuss these methods further, including explanations of each method, pros, and cons.

4.1.1 Sidereal-Stationary Capture

The sidereal-stationary capture method involves taking a long exposure image while actuating at a sidereal-stationary rate, allowing the space object to pass through the field of view. Actuation at sidereal rate will keep the background stars from streaking. The image captured will contain a streak from the object passing through the field of view. This streak must then be processed to determine parameters like the mean center of light, start and end locations, and the length of the streak. Streak analysis is not a novel process. Many literary sources exist for extracting observation elements from an image. Sources [1, 4, 21, 28, 32] all provide methods to collect angle observations from a streak in an image. Additionally, the image is used to determine where in the sky the optical system was pointed during the capture. Since the stars are dots, they need no processing. The system can run the image directly through an existing star registration software, such as that provided by Astrometry.net, to get the RA and Dec of the boresight and space object. A weakness of this method is that the apparent brightness of the object will be lower compared to other imaging methods. This is due to the light from the object being spread across the optical sensor, rather than being gathered at a single point. Spreading the object's light across more pixels will make the object more difficult to recognize, and may require a more sensitive optical system.

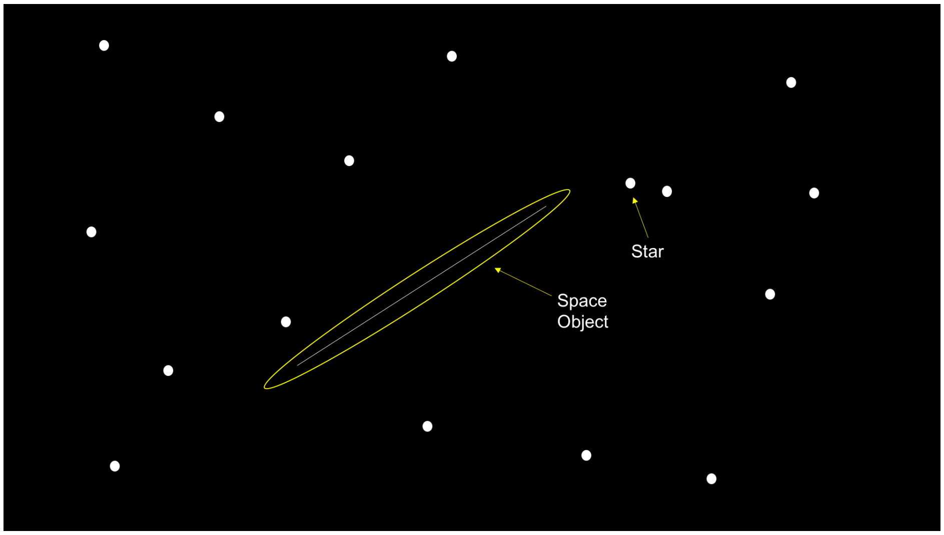

Figure 4: Example of a sidereal-stationary image capture.

4.1.2 Space Object-Stationary Capture

The space object-stationary capture method involves taking a long exposure image while actuating along the space object's predicted trajectory. This method is used most frequently by companies running more expensive existing optical tracking systems. In this technique, the space object of interest is kept centered in the camera's field of view as it traverses across the sky, allowing the system to take many more images per pass compared to other imaging methods. The images produced from this method will ideally contain a space object in the center of the frame as a bright dot, while the background stars will appear as streaks. The length of these streaks depend on both the exposure time of the image and the angular rotating rate of the object compared to the ground location. Processing these images would still require streak analysis, but this time on the stars. In order to perform the desired star registration for determination of boresight right ascension and declination the star streaks will have to be manipulated into points at the streak center. One advantage of this method is that all star streaks will resemble the same form and shape in the image. Before investigating this option, there was some concern about motor jitter creating noise in the images. After some research, along with corroboration from Dr. Holzinger, it was determined that jitter should not manifest itself in the systems observations, as it generally concerns more precise measurements[33, 34, 14].

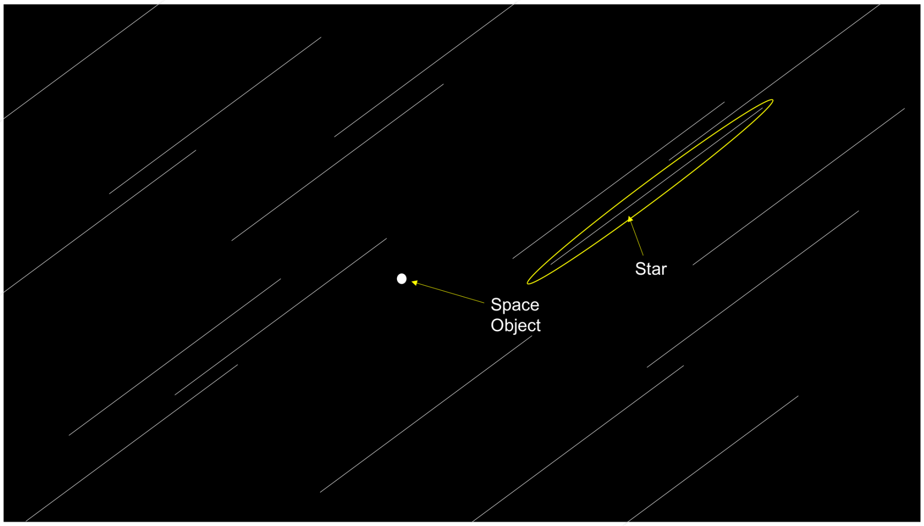

Figure 5: Example of a space object-stationary image capture.

4.1.3 True-Stationary Capture

The true-stationary capture method involves taking a long exposure image while maintaining a fixed local azimuth and elevation of the boresight. This method allows the actuation system to be fixed and stationary. The system would still point towards the predicted region of sky that the space object would be expected to pass through, and would still move ahead of the object's predicted path for another image. A consequence of not tracking either the stars or the space object is that both the space object and background stars will appear as streaks. A benefit to this method over others would be a lighter computational load on the system and the reduction of possible noise in the image due to tracking actuation. However, the image processing system would now have to perform streak analysis on both the space object and background stars in order to retrieve the necessary angular observations.

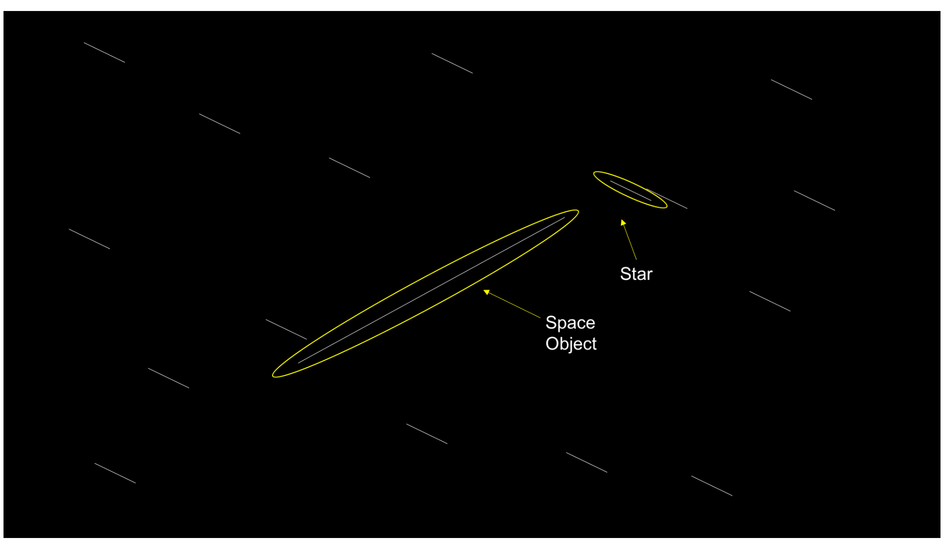

Figure 6: Example of a true-stationary image capture.

4.1.4 Imaging Method Summary

Method	Pros	Cons
Sidereal Stationary	• Low actuator activity • Excellent night sky detail due to star-fixed light collection • No star streak processing necessary	• Dim space object streak (increases likelihood of measurement error)
Space Object Stationary	• Bright, recognizable space object dot (simplifies angle measurement extraction and reduces error) • Continuous angle measurement (most measurement data)	• Highest dependence on actuator accuracy. • Dim star streaks (increases likelihood of measurement error)
True Stationary	• No actuator noise during imaging	• Most image processing (star streaks and object streak) • Dim star and object streaks (increases likelihood of measurement error and failed registration)

Table 2: Imaging Methods Summary

4.2 Sensors and Lens

4.2.1 Sensors

The correct combination of optical hardware (sensor + lens) is essential to imaging space objects in LEO, MEO, and GEO Earth orbits. The various parameters important to choosing the right sensor include ISO range, number of pixels in the sensor, size of the pixels, cameras bit depth, and the cost. ISO is a measure of light sensitivity, with low numbers corresponding to low light sensitivity. When imaging space objects, a sensor with relatively high ISO ratings is optimal. The more pixels a sensor has, the higher the resolution the image will have. Possessing a large pixel size is important for astrophotography because the larger the pixel, the more light it can collect. This means the sensor would need to be exposed for a lesser amount of time in comparison with a sensor whose pixels were smaller. The bit depth of a camera is a good indicator of its dynamic range. The number of shades available for each pixel is equal to two raised to the cameras bit depth [29]. The cost of each option is important when considering the system as a whole, as money must be allocated to other subsystems as well.

DSLR and Mirrorless Cameras

The slight difference between DSLR and mirrorless cameras (a DSLR has a reflexing mirror while mirrorless cameras do not) is insignificant in regards to GHOST. The purpose of the mirror in a DSLR is to give the user a look at exactly what the lens is seeing in real time, something that has no place in this project. These cameras exhibit wide ranges in ISO, spanning both the lower and higher ends of the spectrum. A common trade in DSLR cameras is between the number of pixels and pixel size with sensor size and cost. The sensor size is not something of concern to the project, but the cost is. The ideal DSLR or mirrorless camera would have both the most pixels and the largest pixel size while remaining relatively low in cost. A pro for these two sensor options is that there are many specification options, all with variable pixel number and pixel size. These cameras are unnecessarily bulky and heavy for their application within the hardware system. Their size and mass could become significant depending on the mount used and the size of the lens chosen. Additions such as the preview screen, adjust controls and navigation buttons are unnecessary as the camera will be controlled by an API [9, 22].

Industrial Cameras

Industrial cameras are highly integrateable sensors which are designed to perform at professional standards. They have been stripped down in comparison to DSLR and Mirrorless cameras, as they do not include viewing screens, trigger buttons, or dials. They are mainly used in the medical, science, and aerospace fields, where they are designed to withstand extreme conditions (shocks, vibrations, temperatures, etc.). These cameras have variable ISOs and bit depths, a lesser amount of pixels, a smaller pixel size, and cost about the same as DSLR and mirrorless cameras. Some advantages of these sensors is that they are small in size, lightweight, and integrate well with other systems. Unfortunately, the main purpose of these sensors (their durability and robustness) is irrelevant to this project [24, 3].

4.2.2 Sensor Summary

Option	Pros	Cons
DSLR and Mirrorless	• Wide ISO range • Variable number of pixels • Variable pixel size • Documentation easily available	• Large in dimension • Relatively heavy • Expensive for high pixel # and large pixel size
Industrial Cameras	• Small in dimension • Relatively lightweight • Easily integrateable with software	• Small pixel size • Over-designed for GHOST • Expensive

Table 3: Sensor Summary

4.2.3 Lenses

To image space objects of apparent magnitude brighter than 10, the hardware system must include a lens to which an optical sensor will be attached. The astroimaging lens options available to the team include camera lenses and telescopes. The lens parameters important to the success of this project include aperture, focal ratio, field of view, and limiting stellar magnitude. The aperture is the diameter of the lens and indicates the amount of light a lens can capture. The focal ratio is referred to as the speed of a lens and is equal to the focal length divided by the aperture. A smaller focal ratio means that the lens will provide a brighter image, wider field of view, and smaller magnification. A large field of view indicates the lens can capture a large portion of the sky in one image. A limiting stellar magnitude is a term mostly used when characterizing telescopes and refers to the dimmest an object can be such that the lens can still capture it.

Camera Lenses

Camera lenses come in many flavors. There exists telephoto lenses which yield a narrow field of view and a more magnified image, wide-angle lenses with small focal lengths and large fields of view, and standard lenses. The focal lengths of these lenses varies from 8mm on ultra wide angle lenses to 300+mm on super telephoto lenses. This wide range of focal lengths means a variety of focal ratios and fields of view are available for camera lenses. They are also very accessible, with plentiful documentation online thanks to their public popularity, and relatively small and lightweight. Camera lenses vary in price, with high quality lenses costing thousands of dollars and lesser quality lenses costing hundreds of dollars [25, 12].

Telescopes

There exists two types of telescopes - reflectors and refractors. Refractor telescopes are generally very expensive and heavy when compared with a reflector of the same aperture. Telescopes generally have large focal lengths and focal ratios, which makes them very good at magnification and at picking up faint objects (high limiting stellar magnitude). This does make them bulky objects whose weight cannot be considered negligible. When pairing up a telescope with a sensor and a mount, its size and weight must be considered. Telescopes also have a small field of view, which goes hand in hand with their large focal ratio. Depending on the method of imaging and tracking chosen, a small field of view is either a good thing (space object-stationary capture) or a bad thing (true-stationary and sidereal-stationary capture). The price range of telescopes is very similar to that of camera lenses [11].

4.2.4 Lens Summary

text	Pros	Cons
Camera Lenses	• Documentation easily available • Small and lightweight	• Bad at focusing at infinity • Expensive for high quality
Telescopes	• High limiting stellar magnitude • Documentation easily available • Designed to view space objects	• Bulky and heavy • Limited range of focal lengths • Expensive for high quality

Table 4: Lens Summary

4.3 Tracking Mounts

In order to be able to track the desired objects across the sky, the system must have a method of pointing the camera and lens in the right direction [27]. There are several different options available; some options are COTS and some require design and manufacturing.

4.3.1 Consumer Off the Shelf Tracking System

In the astrophotography market, there exists a variety of pre-made motorized imaging system mounts. Such systems are capable of actuation in multiple axes with a relatively high precision and speed. They are often capable of several pre-determined tracking modes that allow the imaging system to be pointed at common celestial bodies and some have calibration/homing procedures built in [18]. These COTS systems are relatively expensive, but provide consistent (and known) performance. An interface between the tracker and the imaging system will be necessary, but these are readily available (for common cameras and telescopes) or even included. Potential downsides are cost and software interfaces. Potential upsides are fine actuation with limited work required from the GHOST team, given that the system comes pre-built to handle fine tracking needs.

Figure 7: Example Image of a COTS tracking System

4.3.2 In-House Tracking System

Another option is for the GHOST team to design and manufacture a tracking mount. This piece of hardware has not yet been designed, but would likely consist of several motors built into a geared, fine-tracking mount. The frame would interface with the chosen image sensor and lens, allowing for the desired motion control. An in-house tracking system would require a significant amount of design and modeling work in order to ensure that the final product would meet the requirements, but this also means that the system could be designed in such a way that the requirements are met exactly. This option could be quite difficult and take a large amount of time to create.

4.3.3 Stationary Fixed-Angle Mount (COTS)

A third option for tracking mounts is a COTS user-adjustable mount where the user specifies both angles for the system to be set at and manually adjusts knobs accordingly. This option relies on an imaging system capable of working on a fixed mount and software able to acknowledge that the camera position is fixed. The software would be initially set up with the right ascension and declination angles and be able to only track space objects which will pass within the field of view.

Figure 8: Example of a fixed-angle mount

4.3.4 Tracking Mount Summary

Option	Pros	Cons
COTS Tracking Mount	• Known and consistent functionality • Customer support potential • Consumer-off-the-shelf • Possible manufacture's warranty	• Potential difficulty in software interfacing • High cost • Limited user specifications in design; pre-determined performance
In-House Tracking Mount	• Can be built to exact project specifications • Relatively inexpensive • Easy to interface	• No guaranteed functionality • Requires manufacturing (not COTS)
Stationary Fixed Mount	• Simple • Robust • Low cost	• Pushes work onto software team • Requires detailed, precise (and possibly complicated) user setup • Limited autonomous functionality

Table 5: Tracking Mount Summary

4.4 Position and Time

Knowledge of the system's position and time is necessary for both space object imaging and orbit determination. The initial latitude, longitude and altitude of the system will be fed to the orbit determination software and scheduling software. Additionally, precise time must be known and constantly updated for orbit determination, scheduling, and imaging. Options for determining the system's position and time are discussed in this section.

4.4.1 Global Positioning System

One of the most common methods of determining position and time is utilizing the global positioning system (GPS). GPS is a satellite-based navigation system that has no associated fees once a GPS receiver is purchased. GPS receivers are small and lightweight so they can easily integrate with other components. The receiver will be able to calculate the system's latitude, longitude and altitude once it is locked on to 4 or more satellites. Additionally, GPS satellites contain atomic clocks and the receivers contain quartz clocks allowing atomic clock accuracy to be output from the GPS receiver. GPS satellites transmit two low-power radio signals that travel based on line of sight. Line of sight will not be an issue in this system since the imaging subsystem will have a higher requirement for line of sight than the GPS. GPS receivers vary in cost based on size, update rate, number of channels, power requirements, and accuracy. The biggest consideration for this system that will drive up cost is accuracy. The number of channels will affect how long it takes the GPS receiver to lock onto the GPS space object.

RTK GPS Receiver

A Real-Time Kinematic (RTK) GPS Receiver provides fast results, though this type of receiver is restricted in remote places and requires proximity to a ground reference station within 70 km. RTK is a type of positioning enhancement that can provide accuracy up to a centimeter with real time corrections. The timing system within this receiver remains stable over time with virtually no noise because of the communication with ground stations providing a clock correction.

PPP GPS Receiver

A Precise Point Positioning (PPP) GPS Receiver increases operational flexibility and can provide positioning solutions autonomously with no need for ground station proximity. This positioning enhancement is less accurate than RTK but is more versatile and less expensive. The positioning data does not correct in real time but the timing and scheduling mechanism has very little clock drift.

Position input at setup/Network Time Protocol

An alternative to GPS is to manually input the position of the system at the time of initial set up. Upon delivery, the GHOST module will be part of a network of imaging systems and will not have to change in location once it is initially installed. The system does not require more than one latitude, longitude and altitude measurement so this solution will suffice for position knowledge. An updated time is required for orbit determination and image scheduling. The time solution would be propagated off of the on-board processor's clock which would be synchronized with a GPS receiver through the free software package Network Time Protocol (NTP). This option is cheap since NTP is open source, but it does require extra initial set up. Using NTP would also eliminate conversions between GPS and UTC time and there would be less margin for error due to the NTP automatically synchronizing.

4.4.2 Position and Time Summary

Option	Pros	Cons
RTK GPS	• High Accuracy for Synchronization • Relatively Low Cost • No manual setup - beneficial to GHOST customers	• Dependence on Ground Station proximity - cannot place system arbitrarily • Noise from timing drift - Could disrupt scheduling software synchronization • Added software component - More difficult scope given the time constraints of this project
PPP GPS	• Highest accuracy - scheduling software will be synchronized with highest confidence • No manual setup - Less margin for setup error • One component - simpler scope for the manufacturers (us).	• Highest cost • Harder to obtain • Harder to synchronize system components
NTP	• No cost • Avoid timing system conversions - simplifies scope for manufacturers • All components synchronized	• More setup required for manufacturers (us) • Loss of timing accuracy - could affect scheduling software • Position accuracy depends on initial set up from GHOST customer

Table 6: Position and Time Summary

4.5 On-Board Computer

An on-board computer is required to perform orbit propagation, scheduling, image processing and control of the tracking and imaging hardware. The on-board computer will take raw images from the image sensor and run an image processing algorithm to output right ascension and declination of the space object. This computer will also need to create the task/instruction list using the scheduler software and control the pointing and imaging hardware. These requirements drive two main capability requirements:

1. The on-board computer's processing power must be sufficient to handle all of the aforementioned tasks simultaneously.
2. The computer selected must be capable of interfacing with tracking and imaging hardware.

This leads to the consideration of the following options for the on-board computer on GHOST.

4.5.1 Microcontroller

COTS Microcontrollers are a low-cost solution that can be programmed to perform computing tasks (possibly image processing) as well as controlling the tracking and imaging hardware. Microcontrollers and microcontroller boards, such as Arduinos, are well known to be effective in interfacing with hardware for simple applications, though are rarely used for sophisticated programs due to lack of processing power and memory. This could pose a problem since the image processing requires significant processing power.

4.5.2 General Purpose Computing Board

A general purpose computing board, such as a Raspberry Pi or Intel NUC kit, provides a cheap, COTS computing source with the generic hardware interfacing capabilities of a laptop. There are a plethora of options for general purpose boards with a large range of computing power. Most have at least a multi-core processor with speeds up to that of a laptop. These boards can generally run an entire operating system (OS), which provides networking capabilities and the ability to run (headless) desktop applications. This would be advantageous if there exists free/open-source desktop applications for OD or image processing.

Figure 9: Intel NUC kit

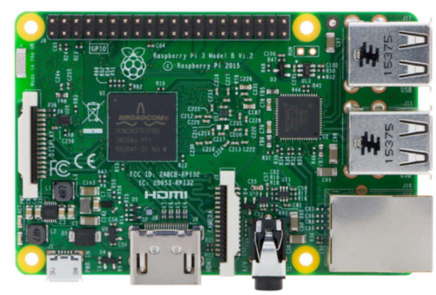

Figure 10: Raspberry Pi

4.5.3 Custom Computer

A custom computer could be built for this system that would leverage pre-built general purpose boards while allowing for a choice of CPU, RAM, etc. While a custom computer would be slightly more complex to manufacture, it would allow for the choice of individual component specifications that are required for the exact computational tasks of this system.

4.5.4 Laptop

A laptop could function as the on-board computer unit for the GHOST system. A laptop likely has the processing power needed and can run an OS, but comes with unnecessary hardware such as a screen, keyboard, trackpad, speakers, camera, etc. A laptop is also bulkier than needed, which reduces portability.

4.5.5 On-board Computer Summary

Option	Pros	Cons
Microcontroller	• Almost no unnecessary hardware • Very cheap	• Little computing power (likely insufficient for image processing) • Can't run an OS • More time required for assembly
General Purpose Computing Board	• Relatively cheap • Little unnecessary hardware • Can run an OS	
Custom Computer	• Customizable specs • Can run an OS	• More time needed to assemble
Laptop	• Can run an OS • Trivial setup	• Generally more expensive • Unnecessary hardware

Table 7: On-board Computer Summary

4.6 Orbit Determination Methods

Orbit determination is an ongoing problem for scientists in industry and academia. The problem stems from the many different well-defined and ill-defined forces acting on spacecraft constantly throughout its orbit. This creates difficulties when attempting to predict where an object will be using a simplistic model. That being said, there are filtering methods designed to reduce this uncertainty in orbit determination/estimation over the course of several different observation periods.

4.6.1 Batch Filter

Batch filtering, also known as least squares regression filtering, refers both linear and non-linear filtering methods. These two methods of filtering are very similar in that they both begin with a physical model that represents the motion of the body in question. The model then is used to create an expected estimate for where the body will be at a given time. Using this estimate and collected data (from imaging and image processing in the case of project GHOST), the residuals for each collected data point are calculated and averaged to find the covariance of the body's location. It should be noted that the covariance calculation includes systematic errors from things like expected distortion due to the camera lens, etc. The time derivatives of the model states are then used to estimate where the body will be at the next data point (the chosen model will be used to back out the orbital parameters based on this estimate). The big difference between the linear and non-linear methods are how the derivatives are handled. The derivatives for the non-linear case are generally taken assuming that the time steps are very small, thus the non-linearity of the model is minimized. Since the chosen model will likely be non-linear in nature, the non-linear batch filtering method would be used.

It should be noted that Batch filtering is a post-processing method which utilizes multiple data points in order to project the next location of the body.

4.6.2 Kalman Filter

Kalman filtering is essentially the industry standard for real time estimation of a spacecraft's position and attitude[?]. It is a filtering technique for computing the best-estimate of the state in a time varying process. One benefit of Kalman filtering is that it carries all past measurements and calculations in the current state and covariance estimates. This means that all that is needed to estimate the next state and covariance is the current estimates and a new measurement.

Linearized Kalman Filter

Linearized Kalman Filters (LKF) are simplified Kalman filters that work off the assumption that the initial estimation of the orbit is nominal and thus relatively unchanging. This assumption makes LKFs very quick to process as the initial guess is never updated. Without updating the initial guess the orbit propagation can continue without having to start over with each new data point. If the orbit drifts over time, the state can be reinitialized which is computationally expensive. LKFs are often used in autonomous navigational systems due to the reduction in computational burden of the filter[31].

Extended Kalman Filters

Extended Kalman Filters (EKF) are the most popular Kalman filter choice in industry. EKFs are more computationally expensive than the formerly mentioned LKFs, but they provide more accurate estimates of state for trajectories with less well defined orbital parameters. EKFs update the reference trajectory of the body with each new observation as well as the error state transition matrix. Updating the "initial" state to the current estimate is the main difference between the LK and EK filters. This updated initial state allows the filter to account for things like drift which would bring the orbit further and further away from the initial guess.

The mathematics behind Kalman filtering are far beyond the scope of this project, and it's unreasonable to expect an undergraduate engineering student to understand them fully. However, the GHOST team has several different resources available for assistance in setting the Kalman gains appropriately. The Kalman gains will depend both on the hardware that the GHOST module will have on board as well as the dynamic state model chosen to propagate the orbit.

4.6.3 OD Methods Summary

Method	Pros	Cons
Batch Filter	• High accuracy • Math within undergraduate scope • Model can be altered on the fly (handle drift, etc.)	• Computationally expensive • Requires multiple images per orbit
Linearized Kalman Filter	• Low computational cost • High accuracy	• Expensive to alter orbit estimation • Replies on accurate initial esitmate and covariance • Mathematically out of scope for undergraduates
Extended Kalman Filter	• High accuracy • Can handle orbital drift	• Computationally expensive • Mathematically out of scope for undergraduates • Requires initial estimate and covariance

Table 8: Orbit Determination Summary

5 Trade Study Process and Results

5.1 Trade #1 - Imaging Method

There are multiple ways to image space objects. The following metrics were developed to measure the overall feasibility of a given imaging method. These are Dim Object Capability, Image Processing Complexity, Actuator Dependency, and Data Available per Pass. These metrics were then weighted based on contribution to overall feasibility. Further explanation is found in Table 9.

Metric	Weight	Driving Requirement(s)	Description and Rationale
Image Processing Complexity	0.35	FR 3	The type of image capture method will determine the amount of processing required to extract measurements from the image. This includes filtering noise, analyzing the night sky for boresight measurements, and analyzing star streaks, object streaks, or both. This metric makes up the bulk of the impact of the imaging method on the overall system, meaning a high weight 35% is needed.
Data Available per Pass	0.3	DR 3.1	This metric is the result of an interest in the speed of data acquisition based on the combination of number of observations available per pass, and number of measurements available per observation. The resulting measurement allows for insight into how certain we can be that some capacity of orbit determination can be performed after a single orbit pass. Optimally, only one orbit pass would be necessary to develop and orbit state. A faster rate of data acquisition frees up the scheduling system to assign observations for other objects. Because this measurement describes the impact on a larger goal of the project, it's been given a weight of 30%.
Dim Object Capability	0.2	FR 1	Measurement of how capable an imaging method is at capturing dim objects. This metric determines the impact of this trade on other subsystems, which should be low to allow for a more diverse set of options in those areas. As such, this method is weighted 20%.
Actuator Dependency	0.15	FR 2, DR 2.1	Similarly to how the imaging method depends on the optical system, the actuation system plays a large role in the imaging method. It should be noted, it is possible for a method to have high dependency on one part of system hardware, and not on the other. The actuator dependency metric is weighted at 15% because of the

Table 9: Metrics, Weighting and justifications.

Each metric was then broken down into ratings from 1 to 5. 1 being extremely undesirable, and 5 being the best case scenario. The scale is broken down with greater description for each metric in Table 10.

Metric	1	2	3	4	5
Image Processing Complexity	Complex beyond reason	Extensive and complex processing required	Some complex techniques required	Simple processing required	Trivial processing required.
Data Available Per Pass	Unable to perform OD after a single object pass	Unlikely able to perform IOD after a single object pass	Likely able to perform IOD after a single object pass	Likely able to perform reliable OD after a single object pass	Consistently able to perform reliable OD after a single object pass.
Dim Object Capability	Unreasonably high requirements and dependence	High amount of optical requirements and dependence	Reasonable dependency and requirements are asked for the optical system	Light amount of optical requirements and dependence	No optical requirements or dependence
Actuation Dependency	Requires highly advanced actuation system out of price range	Requires extremely accurate pointing and slew rate at high angular rates	Requires accurate pointing and slewing at high angular rates	Requires constant and accurate slewing at low angular rates	Requires only that actuators slew to position and hold for image capture.

Table 10: Metric Values

Metric	Weight	Sidereal-Stationary	Space Object-Stationary	True-Stationary
Image Processing Complexity	0.35	4	3	2
Data Available Per Pass	0.3	3	4	3
Dim Object Capability	0.2	4	4	3
Actuator Dependency	0.15	4	2	5
TOTAL	**1.00**	3.7	3.35	2.95

Table 11: Trade Study Results - Image Processing

Each imaging method is scored base on the metric scales in table 10, and granted an overall score based on the weighted sum of individual metric scores, seen in table 11. The justification for each score is detailed in the following paragraphs.

Sidereal-Stationary Imaging:

Image Processing Complexity, 4: High amount of literature in streak analysis for OD, minimum amount of image processing since star are already dots in the image.

Data Available Per Pass, 3: Since an object streak allows for extraction of two measurements (one from each streak endpoint), this method allows for more measurement data per pass, resulting in higher OD fidelity.

Dim Object Capability, 4: The optical system will be fixed relative to the background stars in the image. This allows for greater night sky detail with a lower optical capability.

Actuator System Dependency, 4: Slewing during image exposure is required at low speeds. Many COTS photography systems available purpose-built for sidereal slew rate. Actuator must be able to move faster than object to set up sequential image captures.

Space Object-Stationary Imaging:

Image Processing Complexity, 3: Streak analysis required to find true location of background stars, but motor data can now be used to aide in calculation of angular rate of the space object across the sky, an additional piece of data useful for OD.

Data Available Per Pass, 4: The imaging system will constantly be tracking the space object, eliminating the need for the imaging system to jump ahead of the space object's predicted to prepare for another image. This method allows for continuous repeated observations.

Dim Object Capability, 4: The optical system will be fixed relative to the space object in the image. This allows for space objects with lower brightness to be seen, but reduces the amount of background stars able to be seen.

Actuator System Dependency, 2: Slewing during image exposure is required at high speeds. Both accuracy and low noise are required to keep object stationary in the field of view without streaking.

True-Stationary Imaging:

Image Processing Complexity, 2: Streak analysis required to find true location of background stars, and true location/streak length of the space object. The limitation of this process is that both processes must be performed

Data Available Per Pass, 3: Since an object streak allows for extraction of two measurements (one from each streak endpoint), this method allows for more measurement data per pass, resulting in higher OD fidelity.

Dim Object Capability, 3: The optical system will not be fixed relative to anything in the image. This requires longer exposure times since the light from the imaged stars and object will be spread out over more pixels, such that objects do not lose their apparent brightness when compared to the other methods. lower brightness to be seen, but reduces the amount of background stars able to be seen.

Actuator System Dependency, 5: Slewing only required for preparation of next image capture. No concern about actuator noise during image exposure.

5.2 Trade #2 - Sensor and Lens

The metrics found below were chosen based on the requirements of this project and their pertinence to the sensor and lens subsystem. These are Cost, Ease of Internal Integration, Optical Capability, and Weight. These metrics were weighted based upon their importance to the functionality of the entire GHOST project, as explained in Table 12.

Metric	Weight	Driving Requirement(s)	Description and Rationale
Optical Capability	0.35	FR 2, DR 3.1.1	The camera and lens must be physically capable of capturing images of objects whose apparent stellar magnitude are brighter than 10. Further, aspects like pixel size, sensor size, and field of view must be considered to ensure that the system can accurately capture the positions of space objects.
Ease of Internal Integration	0.30	Scope of the project, DR 5.2	This metric is weighted heavily as the sensor and lens combination must interface with other hardware involved and be controllable by chosen software for a successful project. Thus, minimal strain to incorporate the optical system is desired.
Cost	0.20	Budget	The sensor and lens combination is a large cost factor as these systems can be very expensive.
Weight	0.15	DR 2.1	The optical subsystem must attach to the actuation subsystem such that it can be maneuvered across to pan across the sky. As such, a lightweight system is preferred for ease of maneuvering.

Table 12: Metrics and Weighting

The following table shows each metric broken down into ratings from 1 to 5, with 1 being undesirable and 5 being the best option. Each metric rating is accompanied by a brief description.

Metric	1	2	3	4	5
Optical Capability	Small pixel and sensor size, small FOV and aperture	Small pixel and sensor size, small FOV, medium to large aperture	Small pixel and sensor size, large FOV, medium to large aperture	Large pixel and sensor size, large FOV, medium to large aperture	Large pixel and sensor size, variable FOV, large aperture
Ease of Internal Integration	Not Possible	Extra parts necessary and difficult to obtain, difficult to assemble	Extra parts necessary and easy to obtain, difficult to assemble	Extra parts necessary and easy to obtain, easy to assemble	No extra parts necessary, easy to assemble
Cost	>$3,000	$2,700 - $3,000	$2,400 - $2,700	$2,100 - $2,400	<$2,100
Weight	>5kg	3.5kg - 5kg	2kg - 3.5kg	1kg - 2kg	<1kg

Table 13: Metric Values

Metric	Weight	DSLR + Cam. Lens	DSLR + Telescope	Industrial + Cam. Lens	Industrial + Telescope
Optical Capability	0.35	4	2	3	2
Ease of Internal Integration	0.30	5	4	4	4
Cost	0.20	3	4	4	4
Weight	0.15	4	1	5	2
TOTAL	**1.00**	4.1	2.85	3.6	3.0

Table 14: Trade Study Results - Camera and Lens

Each sensor and lens combination is assigned a score for each metric based upon the metric ratings in Table 19. The total score of each combination reflects the weighted sum of that combination, as shown in Table 14. The justification for each score is detailed in the following paragraphs.

DSLR + Camera Lens:

Optical Capability, 4: A DSLR can exhibit pixel sizes larger than 5μm square and sensor sizes larger than 30mm diagonally. A camera lens for astrophotography typically has a FOV >2° and an aperture between 50mm and 100mm.

Ease of Internal Integration, 5: A DSLR and camera lens are easily compatible with each other, requiring no adapter pieces. This system can be secured on various COTS mounts made specifically for camera lenses, and one can interface with a DSLR quite simply.

Cost, 3: An amateur DSLR camera can cost upwards of $1,700 and a camera lens used in astrophotography applications can cost around $750, placing the system at a cost of around $2,450.

Weight, 4: A DSLR typically weighs around 0.8kg without a lens, and a camera lens can weigh around 0.8kg as well. This places the subsystem at a weight around 1.6kg.

DSLR + Telescope:

Optical Capability, 2: While true that a DSLR can exhibit pixel sizes larger than 5μm square and sensor sizes larger than 30mm diagonally, a telescope typically has a FOV <2° with an aperture >100mm.

Ease of Internal Integration, 4: A DSLR and telescope are easily compatible with each other, but require an adapter. This adapter can be readily attained online [6]. This system can be secured on various COTS mounts made specifically for telescopes, and one can interface with a DSLR quite simply.

Cost, 4: An amateur DSLR camera can cost upwards of $1,700 and a telescope necessary for dim object viewing can cost around $650, placing the system at a cost of around $2,350.

Weight, 1: A DSLR typically weighs around 0.8kg without a lens, and a telescope can weigh around 4.5kg. This places the subsystem at a weight around 5.3kg.

Industrial Camera Sensor + Camera Lens:

Optical Capability, 3: An industrial camera in the price range of this project exhibits pixel sizes typically smaller than 5μm square and sensor sizes smaller than 30mm diagonally. A camera lens for astrophotography typically has a FOV $>2^\circ$ and an aperture between 50mm and 100mm.

Ease of Internal Integration, 4: An industrial camera and camera lens are easily compatible with each other, but require an adapter [10]. This adapter can be readily attained online [10]. This system can be secured on various COTS mounts made specifically for camera lenses, and one can easily interface with an industrial camera.

Cost, 4: An industrial camera can cost upwards of $1,600 and a camera lens used in astrophotography applications can cost around $750, placing the system at a cost of around $2,350.

Weight, 5: An industrial camera typically weighs around 0.04kg without a lens, and a camera lens can weigh around 0.8kg. This places the subsystem at a weight less than 1kg.

Industrial Camera Sensor + Telescope:

Optical Capability, 2: An industrial camera in the price range of this project exhibits pixel sizes typically smaller than 5μm square and sensor sizes smaller than 30mm diagonally. A telescope typically has a FOV $<2^\circ$ and an aperture $>$100mm.

Ease of Internal Integration, 4: An industrial camera and telescope are easily compatible with each other, but require an adapter. This adapter can be readily attained online [10]. This system can be secured on various COTS mounts made specifically for telescopes, and one can easily interface with an industrial camera.

Cost, 4: An industrial camera can cost upwards of $1,600 and a telescope necessary for dim object viewing can cost around $650, placing the system at a cost of around $2,250.

Weight, 2: An industrial camera typically weighs around 0.04kg without a lens, and a telescope can weigh around 4.5kg as well. This places the subsystem at a weight around 4.54kg.

5.3 Trade #3 - Actuation Mounts

In order to determine the type of actuation mount that will be used in the GHOST system, a trade study between the three prominent options available (a COTS tracking mount, a tracking mount built by the GHOST team and a fixed COTS mount) was performed. Shown below are the metrics (and rationale) used to help reveal the most optimal choice of actuation mount for the project.

Metric	Weight	Driving Requirement(s)	Description and Rationale
Maneuverability	0.25	DR 2.1, DR 4.2	The project must be able to image orbiting objects - fast and precise tracking may allow for higher quality images.
Design and Manufacturing Complexity	0.20	Scope of the project, FR 2	To remain within the scope of this project, the system selected must be possible to design and manufacture within the given timeline.
Software Difficulty and Complexity	0.15	DR 2.2	The system must be able to be pointed at the desired space objects.
Hardware Complexity	0.15	FR 5	The project must be completed within the given time - additional complexity increases the risk taken on should the system encounter functional problems. A more complex system poses more risk for the team.
Cost	0.10	Budget	The project must fall within the given budget.
Customizability	0.10	DR 2.1, DR 2.2	To properly interface with the optical hardware subsystem and fulfill specific requirements, a degree of customizability is desired.
Support	0.05	FR 5	The project must be completed within the given time - non-functioning COTS hardware may require commercial customer support to rectify.

Table 15: Metrics and Weighting

Metric	1	2	3	4	5
Maneuverability	None (fixed)	Low slew rate, Low accuracy	High slew rate, Low accuracy	Low slew rate, High accuracy	High slew rate, High accuracy
Design and Manufacturing Complexity	Out of Scope	Complex	Simple	COTS: assembly or setup required	COTS: no assembly required
Software Difficulty and Complexity	Impossible	Difficult	Moderate	Simple	Trivial
Hardware Difficulty and Complexity	Impossible	Difficult	Moderate	Simple	Trivial
Cost	>$2000	$1500 - $2000	$1000 - $1500	$500 - $1000	<$500
Customizability	None	Minimal	Intermediate	Large	Full
Support	No documentation or support available	Some documentation but no support available	Documentation and minimal support available	Good documentation and support available	Extensive documentation, tutorials, and complete support available

Table 16: Metric Values

A score in each category was then assigned to all three options. The results are tabulated below in table 17, with justifications following.

Metric	Weight	Full COTS with Actuation	In-House	Stationary COTS
Maneuverability	0.25	5	5	1
Design and Manufacturing	0.20	5	2	4
Software Difficulty / Complexity	0.15	3	4	5
Hardware Difficulty / Complexity	0.15	4	2	5
Cost	0.10	2	4	5
Customizability	0.10	3	5	2
Support	0.05	4	3	3
TOTAL	**1.00**	4.00	3.60	3.40

Table 17: Trade Study Results - Actuation Mounts

Each actuation mounting method is scored base on the metric scales, and granted an overall score based on the weighted sum of individual metric scores. The results are shown in table 17 above and the justifications for each score are detailed below.

Full COTS with Actuation:

Maneuverability: 5, The systems available and within the team's price range show capability of slewing across the sky at the required rate ($\sim 2°$/s)

Design and Manufacturing: 5, No assembly or design of the actuation mount would be required, just a comparison between already available options.

Software Difficulty / Complexity: 3, this option could represent moderate challenges for software interfacing. Depending on the specific system selected, a variety of software interfaces could be present, ranging from built-in APIs to fully in-house code required.

Hardware Difficulty / Complexity: 4, this option will theoretically perform to desired specifications and present minimal strain when it comes to hardware difficulty.

Cost: 2, this option would consume a large portion of the budget based on preliminary research. An actuation mount accurate enough to accomplish the goals of this project (pointing within a few arcseconds) could cost multiple thousands of dollars.

Customizability: 3, this option is only customizable in the sense that the team would get to select among multiple already fully developed systems. It cannot be designed exactly to this project's requirements.

Support: 4, this option scores well on support because it could be purchased from a manufacturer who could provide troubleshooting help.

In-House:

Maneuverability: 5, this option presents an opportunity for maneuverability to be fully satisfied, accomplishing high slew rate and high accuracy.

Design and Manufacturing: 2, Designing and manufacturing a capable actuation mount represents a all-encompassing task on its own. It is not out of scope, but would present quite a challenge for the hardware team

Software Difficulty / Complexity: 4, Interfacing with custom components offers more leeway in terms of physical connections or accepted software packages.

Hardware Difficulty / Complexity: 2, A system capable of ($\sim 2°$/s) slewing *and* fine precision pointing could prove to be complex, possibly requiring time for troubleshooting and error-correcting.

Cost: 4, Using COTS components to be assembled into a bare-bones actuation mount could prove to be less expensive than the fully-developed and functional system.

Customizability: 5, this option presents a plethora of freedom when it comes to design and thus is fully customizable.

Support: 3, this option has documentation available from outside projects and minimal support available from CU faculty who have accomplished similar tasks.

Stationary COTS:

Maneuverability: 1, The stationary mount is incapable of moving an optical subsystem or changing pointing angles without user interference.

Design and Manufacturing: 4, Very little is required here, past potential assembly required.

Software Difficulty / Complexity: 5, There is no software involved in actuation.

Hardware Difficulty / Complexity: 5, The hardware is trivially simple in the scope of this project.

Cost: 5, a capable stationary mount can cost under the $500 mark.

Customizability: 2, There is not much opportunity for customizability in this component.

Support: 3, Documentation is somewhat readily available along with minimal support.

5.4 Trade #4 - Position and Time

Metric	Weight	Driving Requirement(s)	Description and Rationale
Timing Accuracy and Noise	0.25	DR 4.4	The system shall provide timing with a precision of plus or minus five milliseconds - a timing error translates to an in-track range measurement error for all streak image processing. Should the timing error be too large, the distance will be incorrectly calculated and this will degrade the observations performed on the space object.
Position Accuracy	0.20	DR 4.5	The system shall know its own geodetic latitude, longitude, and altitude relative to the WGS84 ellipsoid to an accuracy of ten meters. Position must be known accurately to determine where to point the lens for object capture. GHOST's position will also be used in the calculation of RA/Dec.
Software Complexity	0.20	Scope of Project, DR 4.3	Given a total-system time constraint of one school-year, the timing and positioning system must be within the allowable scope of the project. The software setup cannot drain the full resources of the team.
Cost	0.15	Budget	The project must fall within the given budget.
Manual Setup Risk	0.10	DR 4.3	If the timing component relies on the individual setup from a customer that is not the manufacturer, an added risk is introduced consisting of an error occurring at setup that will be difficult to correct and will affect the autonomy of the system.
Heritage	0.10	FR 4	The system must be constructed within the given time constraint - heritage and supporting documents will significantly decrease the time spent testing this component to better distribute the team's resources. Additionally, if the hardware malfunctions, the error analysis and remedy might come from the customer or commercial support.

Table 18: Metrics and Weighting

Metric	1	2	3	4	5
Timing Accuracy and Noise	Drift rate > 10 seconds over time	Drift rate > 1 second over time	Drift rate > 10ms over time	Drift rate > 5ms over time	Drift rate > 1ms over time
Position Accuracy	Unstable with time	Stable: Error > 100 meters	Stable: Error > 50 meter	Stable: Error < 10 meters	Stable: Error < 1 meters
Software Complexity	Impossible	Difficult	Moderate	Simple	Trivial
Cost	>$1,000	$1,000-$750	$750-$500	$500-$250	<$250
Manual Setup Risk	Critical	Dangerous	Palpable	Noticeable	Trivial
Heritage	None	Unsuccessful previous use	Successful previous use - no documentation	Successful previous use - full documentation	100% success rate with full documentation

Table 19: Metric Values

Metric	Weight	Network Time Protocol	RTK GPS Receiver	PPP GPS Receiver
Timing Accuracy and Noise	0.25	3	3	4
Position Accuracy	0.20	2	4	5
Software Complexity	0.20	3	2	2
Cost	0.15	5	4	3
Manual Setup Risk	0.10	2	4	5
Heritage	0.10	4	3	4
TOTAL	**1.00**	3.1	3.25	3.75

Table 20: Position and Time Trade Study Result: PPP GPS Receiver

Each of the three timing and positioning options is assigned a score for each metric; the justification of which is detailed in the sections below.

Network Time Protocol:

Timing Accuracy and Noise: 3. NTP provides timing accuracy to 10 milliseconds. Since the software focuses on synchronization, the noise factor is within the allowable limit.

Position Accuracy: 2. If NTP is used, the position information would have to be input manually, which depends entirely on a localized latitude and longitude receiver most likely from a cellular device. The accuracy of a user-input position cannot be assumed to be stable to within 10 meters.

Software Complexity: 3. NTP is a software package that would require study for synchronization implementation, but such a method is not outside the scope of this project.

Cost: 5. NTP is a free, open-source software that would not put any strain on the budget.

Operator-Imposed Risk: 2. The manual input of location from the customer introduces a large factor outside the manufacturer's control. Should an error be made upon setup, the ramifications would cause the entire system to fail in its requirements.

Heritage: 4. NTP provides thorough documentation through open resources and has been tested extensively.

RTK GPS Receiver:

Timing Accuracy and Noise: 3. RTK GPS Receivers provide timing accuracy within 10 milliseconds. They produce more noise than a PPP receiver because of the communication required with a nearby ground station.

Position Accuracy: 4. An RTK receiver generally produces a location accurate to within 10 meters. This location remains constant for the entire lifetime of the system.

Software Complexity: 2. The software for a GPS receiver requires synchronization and timing conversion/processing from the manufacturers. This software would be complicated but not too difficult for the scope of this project.

Cost: 4. An RTK receiver is within the allowable budget for this project, but it is not free.

Operator-Imposed Risk: 4. An RTK GPS receiver operates autonomously, so the only risk from initial setup would be that the system is placed in a remote location that is too far away from a tracking station.

Heritage: 3. Thorough documentation exists for the use of RTK receivers, and while their dependence is lower than a PPP receiver, there is still a high rate of success in previous uses.

PPP GPS Receiver:

Timing Accuracy and Noise: 4. PPP GPS Receivers can provide timing information to within 5 milliseconds with very little noise.

Position Accuracy: 5. PPP GPS Receivers provide highly precise position calculations to within one meter with no change over time.

Software Complexity: 2. The software for a GPS receiver requires synchronization and timing conversion/processing from the manufacturers. This software would be complicated but not too difficult for the scope of this project.

Cost: 3. A PPP GPS Receiver is the most expensive option out of all choices, but it is still within the allowable budget for the position and timing system.

Operator-Imposed Risk: 5. A PPP GPS receiver is entirely autonomous and poses no risk from an operator setup.

Heritage: 4. Thorough documentation exists for PPP GPS Receiver use, and this type of receiver has the highest success rate.

5.5 Trade #5 - On-Board Computer

Metric	Weight	Driving Requirement(s)	Description and Rationale
Cost	0.35	Budget	The cost of the computing hardware should be minimized.
Computing Ability (CPU speed & RAM)	0.35	DR 4.1.3, DR 4.2.1, DR 4.3	The processor must be able to perform image processing in tandem with controlling the pointing actuation.
Data Storage	0.20	DR 4.1.1, DR 4.1.3	The system must store the list of tasks from the scheduler, the measurements & metadata, and the OD results.
Assembly Complexity	0.10	DR 4.1.2, DR 4.2.1	The project must be completed within given time constraints. Additionally, the computing hardware must interface with the actuation system and be able to access Space-Track.org via an Ethernet connection.

Table 21: Metrics and Weighting - On-Board Computer

Metric	1	2	3	4	5
Cost	>$500	$200 - $500	$100 - $200	$50 - $100	<$50
Computing Ability (CPU speed & RAM)	<100 MHz <1 MB	100 - 500 MHz 1 - 100 MB	0.5 - 1 GHz 100 MB - 1 GB	1 - 3 GHz 1 GB - 2 GB	>3 GHz >2 GB
Data Storage	No option for storage	<100 MB	200 - 500 MB	500 MB - 1GB	>1 GB
Difficulty to Assemble	Impossible	Difficult	Moderate	Simple	Trivial

Table 22: Metric Values - On-Board Computer

Metric	Weight	Microcontroller	General Purpose Computing Board	Custom Computer	Laptop
Cost	0.35	5	4	3	1
Computing Ability (CPU speed & RAM)	0.35	1	4	5	5
Data Storage	0.20	5	5	5	5
Difficulty to Assemble	0.10	2	5	3	5
TOTAL	**1.00**	3.3	4.3	4.0	3.6

Table 23: Trade Study Results - On-Board Computer

Each computing option being traded here has a range of possible specs that can be traded up or down depending on the price paid. The following rankings for each option is an approximated categorization depending on common or likely-to-be-used hardware.

Microcontroller:

Cost: 5, Microcontrollers are known for being affordable since they are much simpler than microprocessors. An Arduino, a very common microcontroller-based board, normally costs around $20 to $40 [7].

Computing Ability (CPU Speed & RAM): 1, Most microcontrollers have very little computing power. The most sophisticated Arduino boards typically have <100 MHz CPU clock and <1 MB RAM.

Data Storage: 1, Microcontorollers are not known for their data storage capabilities. Sophisticated Arduinos typically have flash memory on the order of KB. This being said, Arduinos can be mated with an SD card shield which can extend the storage to 16+ GB.

Difficulty to Assemble: 2, Although microcontrollers are almost exclusively used to interface with hardware, they require a decent amount of knowledge and time to assemble with shields and integrate with COTS hardware due to lack of standard communication ports like USB.

General Purpose Computing Boards:

Cost: 4, General purpose computing boards can be very cost-effective depending on their technical specifications. Boards such as Rasberry Pis, ODROIDs, and BeagleBones, generally range in cost from $40 to $100 [2, 8, 23].

Computing Ability (CPU Speed & RAM): 4, CPU clock speeds and RAM on general purpose computing board can range from 1.4 GHz and 1 GB (for a Raspberry Pi 3 B+ [2]) to 2 GHz and 2 GB (for an ODROID XU4 [23]).

Data Storage: 4, Most general purpose computing boards have SD card slots or other slots for flash memory. The SD and microSD cards that are sufficient for this project (8 - 16 GB can be found for a trivial price ($5 - $15 [26]).

Difficulty to Assemble: 5, General purpose computing boards will require a trivial amount of assembly since all the components will be usable out of the box.

Custom Computer:

Cost: 3, The individual components of a custom computer with sufficient capabilities, when parted together, are estimated to cost around $200 - $300.

Computing Ability (CPU Speed & RAM): 5, On a custom computer, the CPU and RAM would be selectable.

Data Storage: 5, On a custom computer, non-volatile flash memory (storage space) would be selectable.

Difficulty to Assemble: 3, A Custom computer would require parting together the major components of a computer, such as RAM, CPU, non-volatile flash memory, etc. While this is not terrible difficult, the time it would take to find cheap, compatible, and sufficiently capable parts would be considerable.

Laptop:

Cost: 1, Laptops are very expensive. Laptops generally cost >$500.

Computing Ability (CPU Speed & RAM): 5, Laptops can generally be found with CPU clocks speeds of 3 - 4 GHz and 4 - 16 GB of RAM.

Data Storage: 5, Laptops can generally be found with 128 GB - 1 TB of data storage.

Difficulty to Assemble: 5, Laptops require no assembly and have standard communication ports. They are meant to be used straight out of the box with no knowledge from the user.

5.6 Trade #6 - Orbit Determination Methods

The following metrics were developed to measure the overall feasibility and value added of a given orbit determination method. These are Mathematical Complexity, Accuracy of Model, Complexity of Implementation, Robustness, and Resource Availability. These metrics were then weighted based on contribution to overall feasibility. Further explanation is found in Table 24.

Metric	Weight	Driving Requirement(s)	Description and Rationale
Robustness	0.30	FR 3	The filter must be able to handle inaccuracy in orbital estimations to be useful.
Accuracy of Model	0.30	FR 3	The filter must produce accurate enough estimations to be useful.
Complexity of Implementation	0.20	Time Constraint	The project must be completed within the given time constraints. The more difficult the filter is to implement, the more time it will take to implement and debug.
Mathematical Complexity	0.10	Time Constraint	The project must be completed within the given time constraints. The more complex the mathematics behind the filter, the more time it will take to understand and tune.
Resource Availability	0.10	Time Constraint	The project must be completed within the given time constraints. The more resources available, the better chance the project has of succeeding in time.

Table 24: Metrics and Weighting

Metric	1	2	3	4	5
Robustness	Can't handle deviations	Can handle small deviations	Can handle deviations and drift	Can deviations, some irregularities, and drift	Can handle deviations, irregularities, and drift
Accuracy of Model	Not at all accurate	Moderately accurate	Nearly accurate	Accurate	Highly accurate
Complexity of Implementation	Our of Scope	Complex	Hard	Moderate	Simple
Mathematical Complexity	Out of Scope	Complex	Hard	Moderate	Simple
Resource Availability	No documentation/too difficult to understand	Some documentation/difficult to understand	Documentation/m difficult to understand	Good documentation/reasonable to understand	Extensive documentation and tutorials that are easy to understand

Table 25: Metric Values

Metric	Weight	Non-Linear Batch	LKF	EKF
Robustness	0.30	5	3	5
Accuracy of Model	0.30	5	4	5
Complexity of Implementation	0.20	3	3	2
Mathematical Complexity	0.10	3	2	1
Resource Availability	0.10	5	3	3
TOTAL	**1.00**	4.4	3.2	3.8

Table 26: Trade Study Results - Non-Linear Batch

Each orbit determination method is scored base on the metric scales, and granted an overall score based on the weighted sum of individual metric scores. The justification for each score is detailed in the following paragraphs.

Non-Linear Batch:

Robustness, 5: Non-linear batch is a post processing algorithm based on Gaussian distributions. This means that it will be able to handle statistical outliars properly in order to estimate the orbit state.

Accuracy of Model, 5: Since non-linear batch filters account for non-linearity, they are more well suited to accurately estimate the orbital state of RSOs orbiting the Earth.

Complexity of Implementation, 3: Once the proper orbit estimation model is found. It will be difficult to find the proper derivatives in order to properly estimate the change in orbit over time. This will likely be the most difficult portion of implementation.

Mathematical Complexity, 3: As mentioned in section 4.6, the non-linear batch method very closely resembles linear batch filtering. Linear batch filtering is a method simple enough to introduce to sophomore aerospace students in ASEN 2012. That being said, the bulk of the theory behind non-linear batch filtering is fairly straight forward. The complexity of the algorithm comes in with the non-linear partial derivatives. Between the varying gravitational field of the Earth, atmospheric drag effects, and solar pressure, the state model that the algorithm processes will be highly non-linear. This is what drives the mathematical complexity up to a 3.

Resource Availability, 5: There are extensive resources available to understand non-linear batch filtering methods. Since the method is so similar to linear batch filtering, many of the documentation is written to a lower level of assumed knowledge than the other methods analyzed.

Linearized Kalman Filter:

Robustness, 3: The LKF functions based on the assumption that the initial guess is accurate. If the actual state varies from the initial guess too far (an outliar in a Gaussian distribution) the LKF would become inaccurate and may begin to return false state estimates.

Accuracy of Model, 4: The simplifying linearizing assumptions made in the LKF make the model more unreliable for highly non-linear state models.

Complexity of Implementation, 3: The TLEs given to the system by the operator will not include covariance estimations for the state variables. That being said, prior to running the LKF another more simplistic estimation algorithm would need to be used in order to have an initial guess for the covariance. This algorithm could also assume linearity, making the LKF easier to implement than the EKF. Once this step has been completed, an off the shelf LKF could be applied.

Mathematical Complexity, 2: The bulk of the mathematical complexity in the LKF comes from the "under the covers" assumptions that the Kalman filtering algorithm makes to make the algorithm as elegant as it is. Understanding the "under the covers" assumptions is far beyond the scope of an undergraduate to fully understand. That being said, the LKF is one of the more simplified Kalman filters. The assumption of linearity makes the underling mathematics more simplified than other Kalman filters, but still more complex than a non-linear batch.

Resource Availability, 3: Many of the resources out there for Kalman filtering assume a strong statistical background above the current capabilities of an undergraduate.

Extended Kalman Filter:

Robustness, 5: EKFs are meant to handle highly non-linear estimations based on Gaussian distributions. This means that it will be able to handle statistical outliars properly in order to estimate the orbit state.

Accuracy of Model, 5: Since EKFs account for non-linearity, they are more well suited to accurately estimate the orbital state of RSOs orbiting the Earth.

Complexity of Implementation, 2: The TLEs given to the system by the operator will not include covariance estimations for the state variables. That being said, prior to running the EKF another more simplistic estimation algorithm would need to be used in order to have an initial guess for the covariance. This algorithm could not assume linearity since the EKF assumes non-linearity. This added element of complexity from a non-linear initial estimate drive the complexity of an EKF up. Once this step has been completed, an off the shelf EKF could be applied.

Mathematical Complexity, 1: The bulk of the mathematical complexity in the LKF comes from the "under the covers" assumptions that the Kalman filtering algorithm makes to make the algorithm as elegant as it is. Understanding the "under the covers" assumptions is far beyond the scope of an undergraduate to fully understand. The EKF fully utilizes the underlying assumptions inherent in Kalman filtering, making it more mathematically complex than the LKF.

Resource Availability, 3: Many of the resources out there for Kalman filtering assume a strong statistical background above the current capabilities of an undergraduate.

6 Selection of Baseline Design

To select a baseline design for each of the six key design options, the results of the trade studies were assessed numerically based on the raw resultant scores, but also qualitatively based on a feeling for the validity of the numerical result. When conducting these studies, it is easy to make the mistake of selecting trade options and assigning weights based on a pre-conceived notion of what the result should be. This section aims to mitigate any inherent biases by making the team select a final conceptual design.

6.1 Trade Study Results and Justification

6.1.1 Trade 1 Results: Imaging Method

The imaging method trade study determined that the optimal method for imaging space objects is a sidereal-stationary method. The main draw to this method is the minimal amounts of processing required before boresight measurements can be collected, which neither the true-stationary nor satellite-stationary methods offer. This allows the system to cut out much of the image processing and begin extracting angular measurements of the space object immediately. This also limits the error that may stem from processing star streaks, since the stars will not streak. The system relies very little on the actuation system's capabilities, limiting the error which may arise from inaccurate pointing or slewing. The streak made by the object may hold back the streak detection and extraction somewhat simply because it will be substantially dimmer than many other night-sky objects. However, since streak extraction makes up the majority of the image processing, the software team will have the time and resources to fine-tune the streak recognition capabilities.

6.1.2 Trade 2 Results: Sensor and Lens

The results of the sensor and lens trade study show a clear winner among all options: a DSLR camera sensor with a camera lens attached. This option is most attractive because of its optical capability and high availability. The best sensor for this application was a DSLR due to its large pixel and sensor size relative to those of industrial cameras. A large sensor and pixel size will provide high resolution while not requiring long exposure times. The large pixel size will help to capture large amounts of light in small amounts of time. The best lens for this application was a camera lens which provides a relatively large FOV at medium apertures. A large FOV means that satellite streaks will be easily visible when using the sidereal-stationary tracking method. A camera lens with mid apertures will allow enough light in to keep exposure times to a minimum. This sensor and lens combination integrates well with each other, as camera lenses are explicitly designed to interact with camera hardware. Additionally, most commercially available DSLR cameras have APIs available for remote control.

6.1.3 Trade 3 Results: Actuation Mounts

The trade study for actuation mounts shows two leading contenders: the fully COTS mounting hardware and the ”in-house” design. However, after conducting the trade study and receiving outside opinions, mainly from Professor Holzinger, the team has decided to proceed with the fully COTS option. The main problem in pursuing an ”in-house” fully designed and manufactured option, as elucidated during conversations with Professor Holzinger, is the risk incurred should the design not be fully functional next semester. Also, while it is not a requirement that the tracking mount of the GHOST system must be COTS (FR5 only specifies that the image sensor and lens shall be COTS), including more COTS parts in the system is highly desirable, as it makes the final product more easily reproduced. A fully COTS system offers numerous benefits, the main one being that the full specifications of the system can be known prior to selection and subsequent purchase. This is also theoretically true for an in-house system because it could be designed to specifications, however there is no guarantee that an in-house system would actually function as designed. A COTS system, in contrast, will have manufacturer documentation and potential support available. Essentially, the team will know exactly what it is expected with a COTS actuation system, which is extremely important when it comes to precision-pointing within one arcsecond.

6.1.4 Trade 4 Results: Position and Timing

The Position and Timing Trade study compared PPP GPS receivers, RTK GPS receivers, and manual input paired with NTP for a timing solution. Initially, the idea of using an automatic synchronization software that does not cut into the budget seemed enticing, but the trade study results dictated that the operator-induced risk associated with manual setup proved to be too high. The RTK receiver was a strong contender, but its success depends on the system not being placed in a remote location. Additionally, the RTK receiver's accuracy did not compare to the PPP receiver. The PPP GPS Receiver was chosen due to its high accuracy and low associated error. The results from the trade study proved that the only setback to using a PPP receiver is the high cost, but such a receiver can still be found within the allowable budget. The only other issue with using a GPS receiver over NTP is the added software component involving time conversions from GPS time to UTC time and synchronization across the whole system, but these issues are still within the scope of the team's capabilities. Thus, the results of the Position and Timing trade study led to a Precise Point Positioning GPS Receiver as a clear winner for determining position and time.

6.1.5 Trade 5 Results: On-Board Computer

A general purpose computing board is cost effective, capable, and can be found with technical specifications necessary for this system. Examples of general purpose computing boards that may be suitable for this project include a

Raspberry Pi, an ODROID, or a BeagleBone development board. These boards all have about the same hardware interfacing capabilities of a laptop but are much cheaper and forego unnecessary hardware. While all of the options vary in computing power as a function of cost, some general purpose computing boards have the required specs for this project and are much cheaper than the other options. The boards are also capable of running an operating system, which will allow for the use of general free/open-sourced computer applications for on-board image processing and orbit determination. Finally, since these boards are COTS, there will be less assembly time and risk, allowing the team to focus on integrating the board into the whole system.

6.1.6 Trade 6 Results: Orbit Determination Methods

Much of the value of the GHOST system is derived from how well the orbital state can be estimated. Based on the results of the trade study, a non-linear batch filter will be used in order to estimate the orbit of an imaged space object. The overall complexity of the non-linear batch filter is fairly low compared to the high accuracy of the filter, thus making it an attractive option. The Kalman filter options have a great deal of complexity while only offering, at best, an equal amount of accuracy. Using the non-linear batch over a Kalman filter will help to cut down the complexity of the GHOST system. This will allow the GHOST team to accomplish a high accuracy orbit estimation without over complicating the problem.

6.2 Overall Baseline Design

1. The imaging system will be using the sidereal-stationary capture method.
2. A DSLR + camera lens combination will be the imaging hardware of choice.
3. A Consumer Off the Shelf (COTS) tracking mount will be used as the actuation system.
4. A PPP GPS Receiver will be used to compute position and to synchronize timing within the system
5. A general purpose computing board will be used as the on-board computer.
6. A non-linear batch filter is the preferred OD method.

References

[1] Ackermann, Mark R., Peter C. Zimmer, M. Suzanne Taylor, Jeffrey R. Pier, and Maj. Brian Smith. ”Angles and Range: Initial Orbital Determination with the Air Force Space Surveillance Telescope (AFSST)”. US Naval Observatory, Flagstaff,10391 West Naval Observatory Road, Flagstaff, AZ, 86001-8521. Sep 2008.

[2] Adafruit Industries, “Raspberry Pi 3 - Model B - 1.4GHz Cortex-A53 with 1GB RAM,” adafruit industries blog RSS Available: https://www.adafruit.com/product/3775.

[3] ”Aerospace Cameras”. Imperx Inc. 2018.

[4] Ali, Haider, Christoph H. Lampert. and Thomas M. Breuel. Satellite Tracks Removal in Astronomical Images. ”Satellite Tracks Removal in Astronomical Images”. Image Understanding and Pattern Recognition (IUPR) Research Group. 2005.

[5] Alkan R., Ozulu, and Ilci. ”Precise-Point Positioning Technique versus Network-RTK GNSS”. Hitit University, Corum, Turkey. FIG Working Week, New Zealand, May 2016.

[6] ”All Canon Adapters”. Available: https://www.telescopeadapters.com. 2018.

[7] “Arduino Due,” Arduino Uno Rev3 Available: https://store.arduino.cc/usa/arduino-due.

[8] “BeagleBone®,” Beagle Board - beagleboard.org Available: https://beagleboard.org/bone.

[9] ”Canon EOS 6D”. Canon U.S.A., Inc. 2018.

[10] ”’C’ Mount to ’T’ Mount Adapter”. Available: https://www.telescopeadapters.com. 2018.

[11] ”C6-A-XLT (CG-5) Optical Tube Assembly”. Celestron. 2018.

[12] ”EF 200mm f/2.8L II USM”. Canon U.S.A., Inc. 2018.

[13] Feng, Y. Wang, J. ”Exploring GNSS RTK Performance Benefits with GPS and Virtual Galileo Measurements.” School of Surveying and Spatial Information Systems, University of New South Wales, Australia. January 2001.

[14] Holzinger, M. (2018). *Interview with Dr. Holzinger*.

[15] ”iOptron iEQ45 Pro GoTo Mount”. Available: https://www.adorama.com/

[16] Kim R., Nagayama T., Jo H., Spencer B. F. ”Preliminary Study of Low-Cost GPS Receivers for Time Synchronization of Wireless Sensor Networks.” University of Illinois Urbana Champaign, Urbana IL.

[17] Li, H. Feng, X. ”A High Accuracy Clock Synchronization Method in Distributed Real-Time System.” Communications in Computer and Information Science.

[18] ”LX200-ACF 8” f/10 (No Tripod)”. Meade Instruments Corp. 2018.

[19] Mamich, H. (2018). *Interview with Mr. Mamich*.

[20] Mills, D. Network Time Protocol Version 4: Protocol and Algorithms Specification. IETF RFC5905 (June 2010).

[21] Nikolaev, Sergei, Don Phillion, Lance Simms, Alex Pertica, Scot S. Olivier, and Rita Cognion. ”Analysis of Galaxy 15 Satellite Images from a Small-Aperture Telescope”. Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, 94559. Sep 2011.

[22] ”Nikon D750”. Nikon Corp. 2018.

[23] “ODROID-XU4,” ameriDroid Available: https://ameridroid.com/products/odroid-xu4.

[24] ”PixeLink PL-D725”. Available: http://files.pixelink.com/datasheets/PL-D700/Datasheet_PL-D725.pdf. 2018.

[25] ”Rokinon 35mm f/1.4”. Available: https://www.bhphotovideo.com. 2018.

[26] “SanDisk - Ultra PLUS 16GB microSDHC UHS-I Memory Card,” Product Detail - Compare Page - Best Buy Available: https://www.bestbuy.com/site/sandisk-ultra-plus-16gb-microsdhc-uhs-i-memory-card/3142599.p?skuId=3142599.

[27] Schmitz, Tanja. ”How to Find, Photograph, and Process an ISS Pass”. Photographing Space. 25 Feb 2016.

[28] Schneider, Michael D. and William A. Dawson. ”Synthesis of disparate optical imaging data for space domain awareness”. Lawrence Livermore National Laboratory, P.O. Box 808 L-211, Livermore, CA 94551-0808, USA. 22 Sep 2016.

[29] ”Scientific Imaging - What is the Bit Depth of a Camera?”. Lumenera Corp. Available: https://azooptics.com. 2018.

[30] “The Extended Kalman Filter: An Interactive Tutorial” Available: https://home.wlu.edu/ levys/kalman$_{t}utorial/$.

[31] Vallado, D. A., and McClain, W. D., Fundamentals of Astrodynamics and Applications, Hawthorne, CA: Microcosm Press, 2013.

[32] Virtanen, Jenni, Jonne Poikonen, Tero Santti, Tuomo Komulainen, Johanna Torppa, Mikael Granvik, Karri Muinonen, Hanna Pentikainen,Julia Martikainen, Jyri Naranen, Jussi Lehti, and Tim Flohrer. ”Streak detection and analysis pipeline for space-debris optical images”. Finnish Geospatial Research Institute, Geodeetinrinne 2, FI-02430 Masala, Finland. 25 Sep 2015.

[33] Wang, Mi., Chengcheng Fan, Jun Pan, Shuying Jin, and Xueli Chang. ”Image jitter detection and compensation using a high-frequency angular displacement method for Yaogan-26 remote sensing satellite”. ISPRS Journal of Photogrammetry and Remote Sensing. Wuhan University, 129 Luoyu Road, Wuham, Hubei 430079, China. 29 May 2017.

[34] Zhu, Ying. Shuying Jin, Yuan Tian, and Mi Wang. ”ROI-Oriented Sensor Correction Based on Virtual Steady Reimaging Model for Wide Swath High Resolution Optical Satellite Imagery”. LIESMARS, Wuhan University, No.129 Luo Yu Road, Wuhan, China. 22 Sep 2017.