PHOENIX

University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Conceptual Design Document (CDD)

Project Customers

Brian Sanders Colorado Space Grant Consortium Discovery Learning Center 270 Boulder, CO 80309 Phone: 303-492-5451 Email: brian.sanders@colorado.edu	**JB Young** Lockheed Martin Space Systems Company 12257 S Wadsworth Blvd Littleton, CO 80127 Phone: 303-977-7798 Email: Jessica.B.Young@lmco.com

Team Members

Gabrielle Massone **Co-Project Manager** Gabrielle.Massone@colorado.edu 970-769-3552	**Tanya Hardon** **Co-Project Manager** Tanya.Hardon@colorado.edu 970-683-8725
Jesse Ellison **Systems Engineer** Jesse.Ellison@colorado.edu 970-759-1415	**Jake Broadway** **Mechanical/CAD Lead** Jacob.Broadway@colorado.edu 303-525-9148
Cy Parker **Software Lead** Cy.Parker@colorado.edu 970-764-5037	**Logan Smith** **Electronics Lead** Logan.T.Smith@colorado.edu 805-746-1337
Franklin Hinckley **Test and Safety Lead** Franklin.Hinckley@colorado.edu 307-460-0982	**Jon Stewart** **Optics Lead** Jon.Stewart@colorado.edu 303-524-2192
Brenden Hogan **Thermal Lead** Brenden.Hogan@colorado.edu 303-483-1161	

Table of Contents

1.0 Project Description ... 1
1.1 nBn Mid-Wave Infrared Detector ... 1
1.2 Phoenix Mission Objectives ... 1
1.3 Phoenix Concept of Operations ... 1
1.4 Functional Block Diagram ... 3
2.0 Design Requirements ... 4
2.1 Customer Project Constraints ... 4
2.2 Phoenix Functional Objectives and Design Requirements ... 4
3.0 Trade Study Methodology ... 5
3.1 Methodology ... 5
3.2 Sensitivity Analysis ... 6
4.0 Optics Design Options ... 6
4.1 Cassegrain Reflecting Telescope ... 6
4.2 Newtonian Reflecting Telescope ... 7
4.3 Offset Parabolic Reflector ... 8
4.4 Single Refractive Lens ... 9
4.5 Refracting Multi-Element Telescope ... 9
5.0 Optics System Design Trade Study ... 10
5.1 Major Design Criteria Under Consideration ... 10
5.2 Other Criteria Not Considered ... 11
5.3 Trade Study ... 11
5.4 Sensitivity Analysis ... 11
5.5 Conclusions ... 12
6.0 Thermal Design Options ... 12
6.1 Passive Deployable Radiator Design ... 14
6.2 Active Thermoelectric Cooler with Radiator Design ... 15
6.3 Active Split Stirling Linear Cooler with Radiator Design ... 16
7.0 Thermal System Design Trade Study ... 17
7.1 Major Design Criteria Under Consideration ... 17
7.2 Other Criteria Not Considered ... 18
7.3 Trade Study ... 18
7.4 Sensitivity Analysis ... 19
7.5 Conclusions ... 19
8.0 Electrical Design Options ... 19
8.1 Single Board Computer Design ... 20
8.2 System on Module Design ... 21
8.3 Custom Electronics Design ... 22
9.0 Electronics System Design Trade Study ... 22
9.1 Major Criteria Under Consideration ... 22
9.2 Other Criteria Not Considered ... 23
9.3 Trade Study ... 23
9.4 Sensitivity Analysis ... 24
9.5 Conclusions ... 24
10.0 Selection of Baseline Design ... 24
10.1 Optical System ... 24
10.2 Thermal System ... 24
10.3 Electronics and Software ... 24
11.0 References ... 25
12.0 Appendices ... 26
12.1 Optics Design Calculations ... 26
12.1.1 Telescope Focal Length ... 26
12.1.2 Telescope Diffraction Limit ... 26
12.1.3 Bennu Radiometry ... 27
12.2 Sensitivity Analysis MATLAB Script ... 28

Acronyms

Table 1: Document Acronyms

BGA	Ball Grid Array
CDH	Command and Data Handling
COSGC	Colorado Space Grant Consortium
COTS	Commercial Off-the-Shelf
DSP	Digital Signal Processing
EGSE	Electrical Ground Support Equipment
FOV	Field of View
FPA	Focal Plane Assembly
FPGA	Field Programmable Gate Array
GNC	Guidance, Navigation, and Control
LMCO	Lockheed Martin Corporation
MGSE	Mechanical Ground Support Equipment
MWIR	Mid-Wave Infrared
nBn	n-semiconductor/Barrier/n-semiconductor sensor material
TBD	To Be Determined
TBR	To Be Reviewed
DRM	Design Reference Mission
ConOps	Concept of Operations
FBD	Functional Block Diagram

1.0 Project Description

Landing on an asteroid provides numerous opportunities for science, research, and commercial purposes. Asteroid investigations are especially applicable to preventing Earth/Asteroid collisions, investigating potential interplanetary resources, and answering questions about the origins of the solar system. Infrared imagery is ideally suited for asteroid analysis, as near-earth asteroids tend to have more intense infrared than visible light emissions. In an effort to address this problem, Lockheed Martin is developing a 6U CubeSat bus, which will capture a series of infrared images from an asteroid, determine the angular rate of the body, and subsequently attempt to rendezvous.

The Phoenix team will contribute to this effort by designing and testing a 2U proto-flight flight level camera payload that is capable of imaging simulated asteroid targets in the mid-wave infrared (MWIR) spectrum, processing the imagery, and determining the angular rate and rotational axis of the target with respect to the camera frame. The camera design will include a high-resolution, high-temperature nBn infrared detector provided by Lockheed Martin Santa Barbara Focalplane.

1.1 nBn Mid-Wave Infrared Detector

The nBn MWIR detector was designed by Lockheed Martin Santa Barbara Focalplane, with the goal of creating a high-resolution, high temperature detector that would not have to be cooled cryogenically during operation. The detector is a photodiode-photoresistor hybrid that derives its name from its n-Type/Barrier/n-Type construction. It can achieve a resolution of 1280x1024 or 1.3MP at an operating temperature of 140 K and a temperature resolution of 35 mK. Currently, no spacecraft has utilized the LMCO/Santa Barbara Focalplane nBn detector. Most high-resolution IR sensors must be cooled to cryogenic temperatures (< 80 K). The higher operating temperature of the nBn sensor makes it a much more viable option for compact CubeSat applications.

1.2 Phoenix Mission Objectives

The protoflight camera unit will image a target with similar thermal and surface properties to the Bennu asteroid. A series of images will be captured with a temporal spacing no less than 22.8 seconds. A temporal resolution of 22.8 seconds ensures that the target will have rotated sufficiently far for the difference between images to be detectable. The Images will be analyzed and compared to compute the angular velocity and rotational axis with relation to the camera.

Additionally, certain constraints are necessary to define the functional requirements of the camera payload. The attitude and rendezvous orbit of the LMCO Bus relative to the Bennu asteroid are unknown at this time, resulting in a myriad of potential configurations. Rather than attempt to accommodate all possible relative velocities and orbits, a series of assumptions have been established to constrain the problem and make the proto-flight test unit design more feasible:

1. The range between Phoenix and the target will vary between 10km and 100km.
2. The relative translational velocity between the object and the bus will be zero during observation.
3. The target object is rotating at a known (to the team), constant angular speed. Phoenix will observe and determine this angular rate allowing a comparison to the known value.
4. Phoenix will observe and determine the spin axis allowing a comparison of the measurement to the known axis.
5. The LMCO bus is oriented so that the Phoenix payload is not exposed to direct sunlight.
6. All target properties (size, surface temperature, etc) are assumed to be the properties, or scaled values thereof, of the asteroid 101955-Bennu.

1.3 Phoenix Concept of Operations

The final integrated system test (Level 4 mission success) is to demonstrate the successful rate determination of the test target under conditions representative – to the extent feasible – of the space environment. The Phoenix assembly is the fully integrated payload, with the optics, thermal control, payload structure, electronics, and software. Phoenix will provide the IR images, health and status data, and the measured angular rate to the bus. The test computer will compute the theoretical observed angular rate from the rotation rate of the target and the distance between the test target and Phoenix. Figure 1 shows how the observed angular rate ($\dot{\theta}$) differs from the rotation rate of the object (ω).

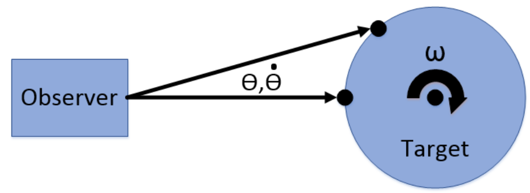


Figure 1: Observation of Target Rate

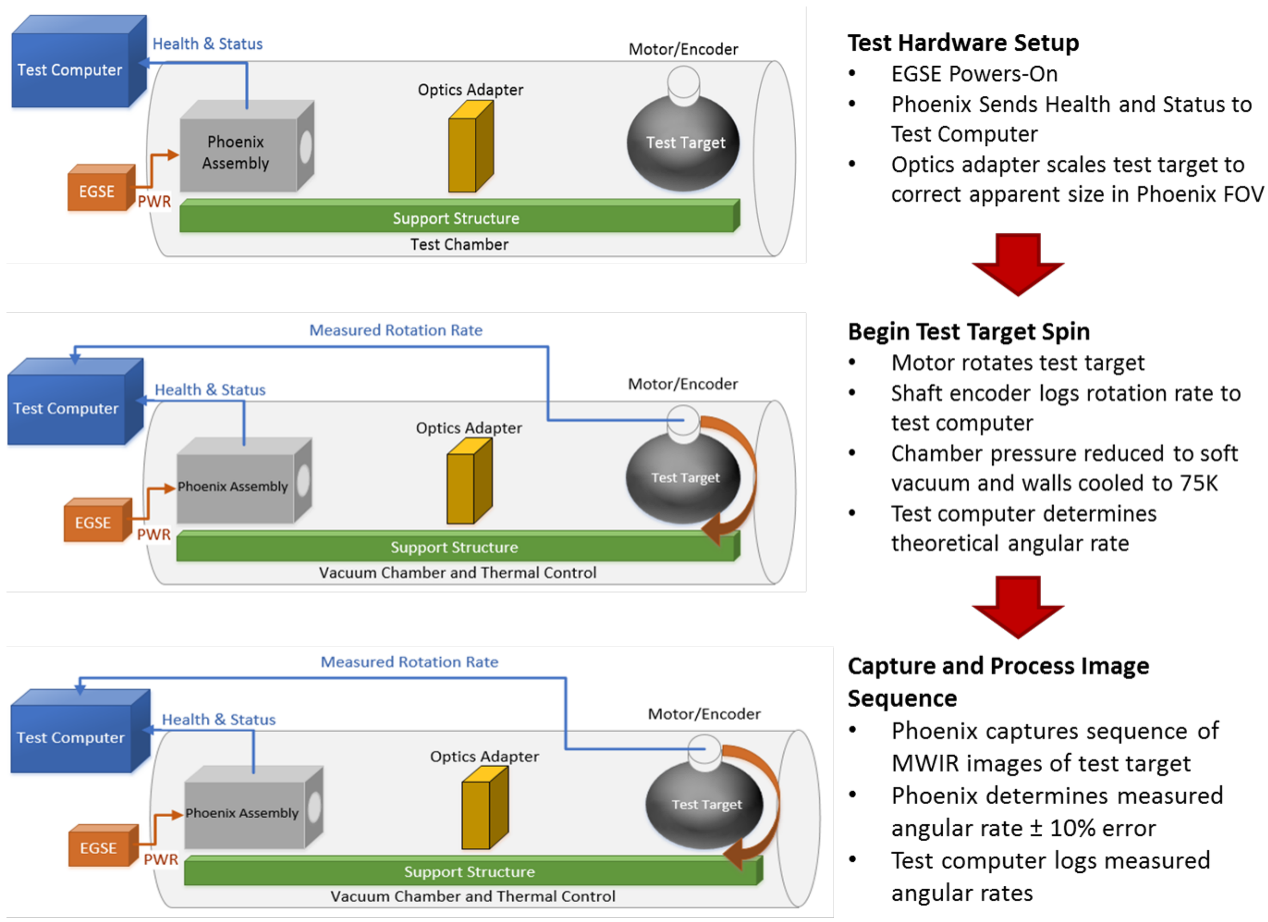


Figure 2: Phoenix Protoflight Testing Concept of Operations

A suitable test target, from a mechanical perspective, would be a ping-pong ball coated in medium sand viewed from eight meters and rotating at 0.43 mrad/sec. Since the radiation from the body due to its temperature is three orders of magnitude greater than the incident radiation from the sun, the thermal gradient of the surface must be sufficient to be resolvable by the image sensor. This can be accomplished in one of two ways: the first is to vary the internal structure of the target so that diffusion across the terminator line is sufficiently variable to show the rotation of the body; the second is to have sufficient surface roughness that the shading of sections of the surface is sufficient to produce resolvable temperature gradients. An example of an object with variable diffusion due to its structure is an I-Beam where the diffusion of heat from the flange is much higher at the web junction than the ends of the flange. While an I-Beam would clearly not be a suitable target it illustrates the ease of achieving variable diffusion due to structure.

As achieving a significant temperature gradient due to shading is most likely not possible on an object the size of a reasonable test target (<30cm diameter) the gradient will likely be achieved by variable diffusion. While the test may not use the discussed target this shows that the required target characteristics are achievable. The optics adapter scales the test target in the field of view of the Phoenix camera so that its effective size is comparable to the size and range of the asteroid, allowing the entire test setup to fit within a soft vacuum chamber. A shaft encoder provides the rotation rate of the target to high accuracy. The environmental conditions for the test are to reduce the density in the test chamber to a soft vacuum and to cool the test chamber. The soft vacuum means that the Phoenix thermal control system is able to primarily reject and absorb heat through radiation, providing a realistic assessment of its performance. At a pressure of 1 Torr, convection accounts for approximately 1% of total heat transfer. The team has ready access to a chamber of sufficient size that can achieve 0.5 Torr. The chilled chamber walls provide a low surroundings temperature closer to that of deep space, which allows more heat to be rejected through radiation, and means that the test target surface temperature can be closer to that of Bennu with a representative temperature difference between the target surface and the background so that the target is distinguishable from the background in thermal imaging.

Table 2: Properties of Reference Object – Bennu[8]

Property	Value
Sidereal Period	4.29746 ± 0.002 hours
Mean Diameter	492 ± 20 meters
Surface Roughness	< 7.5 meters
Surface Temperature (Illuminated Side)	240 – 310 K
Surface Temperature (Dark Side)	180 K

Table 3: Observation Properties of Reference Object - Bennu

Property	Value
Minimum Observed Angular Rate	1.93 μrad/sec
Maximum Observed Angular Rate	21.93 μrad/sec

1.4 Functional Block Diagram

The Phoenix payload, as illustrated in Figure 3, is composed of an image sensor, optics assembly, thermal control mechanism, camera controller, power regulation, and support structure. The nBn image sensor and sensor interface are proprietary and will be provided by the LMCO and COSGC customers respectively. If they are unable to procure those elements within the project time constraints, the Phoenix team will identify a COTS replacement. The LMCO Bus interface will be simulated by EGSE and MGSE fixtures to allow testing of the Phoenix payload independent of the bus development.

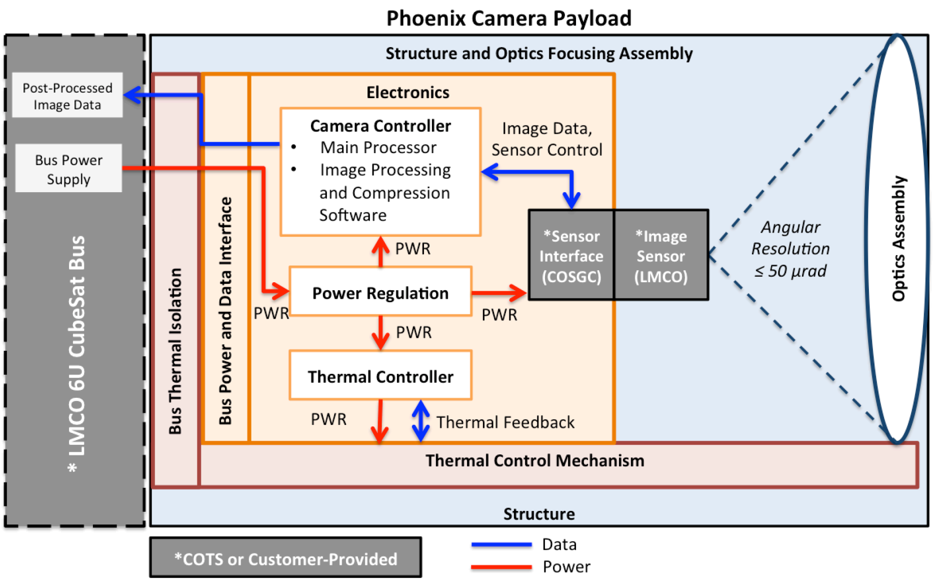


Figure 3: Phoenix Functional Block Diagram

2.0 Design Requirements

2.1 Customer Project Constraints

The Phoenix camera will be designed to integrate with the Lockheed Martin 6U CubeSat bus. Due to the power, mass, volume, and computing limitations of the 6U platform, multiple project constraints are imposed on the camera payload design so that it integrates properly with the bus. These constraints are detailed below:

Table 4: Bus Interface Constraints

Bus Electrical Constraints	
Regulated Voltage Lines	3.3 V - (6.0 A max) 12 V (4.0 A max)
Unregulated Voltage (Battery Line)	6.5 – 8.6 V (6.0 A max)
Total Power	5W nominal 10W for 30 minutes
Command Communication Bus	SPI Slave
High-Speed Communication Bus	Ethernet, Magnetics-less Differential
Backup Communication Bus	I^2C
Bus Structural Constraints	
Total Volume	2U (~ 10 x 10 x 20 cm TBR)
Total Mass	2.66 kg + 0.1 kg/ -0.5 kg

These requirements and more detailed design interfaces will be captured in a LMCO Bus ICD document for future design reference.

2.2 Phoenix Functional Objectives and Design Requirements

The high-level requirements of the Phoenix camera payload are defined as follows:

1.0 The payload shall integrate electrically and structurally into the 2U payload section of the Lockheed Martin 6U CubeSat bus.
  1.1 The Electrical system shall interface with the LMCO 6U CubeSat bus.
  1.2 The Mechanical system shall interface with the LMCO 6U CubeSat bus.
  1.3 The Software system shall interface and communicate with the LMCO 6U CubeSat bus.
2.0 The payload shall capture a sequence of IR images at the 3.5 μm wavelength and determine the angular velocity and axis of rotation of an observed object with characteristics of the reference asteroid 101995-Bennu
  2.1 The electrical system shall capture and store an image from the image sensor.
    2.1.1 The Electrical system shall retrieve an image from the image sensor.
    2.1.2 The Electrical system shall store images received from the image sensor.
  2.2 The optical system shall be able to observe and image the reference target.
    2.2.1 The optical system shall be able to image the reference target Bennu without observable motion blur
    2.2.2 The optics shall be designed to operate at a wavelength band that includes the 3.5 μm wavelength.
    2.2.3 The optics shall be able to resolve a feature that is of angular size 100 μrad.
3.0 The payload shall maintain all components in their operating temperature ranges

3.0 Trade Study Methodology

3.1 Methodology

The following is a general description of the trade study process. Trade studies for each specific design options are shown in subsequent sections . A sample trade study is shown in Table 5 below. The major design options under consideration comprise the table columns, and are separated into raw-score "R" and weighted score "W" columns. The column rows consist of the major criteria for which each design option is being evaluated. A score of 1-10 is given for each option, with 1 being a poor score and 10 being an excellent score.

A score of 10 was given to designs that best satisfy the particular criteria **relative to the other design options.** A score of 10 does not indicate that the design achieves the best theoretical value. Equal scores indicate equal ability of the designs options to satisfy the criteria. The scores breakdown roughly as follows:

10 **Excellent**, design best satisfies the criteria compared to the other design options

8-9 **Good**, satisfies the criteria well

5-7 **Mediocre**, satisfies the criteria with some difficulty or challenge

3-4 **Poor**, difficult to satisfy design criteria, presents technical challenges

1-2 **Very poor,** presents significant challenge to satisfy criteria

Additionally, each design criteria was weighted according to technical challenge or importance in satisfying the mission functional objectives. To determine the weights, 100% was divided by the total number of design options to give a baseline "average" weight. The options were then ranked based on relative importance and the average weighting was adjusted up or down by an appropriate percentage. This process resulted in trade study results like the one shown below:

Table 5: Sample Trade Study

		Design 1		**Design 2**		**Design 3**	
Criteria	**Weight**	**R**	**W**	**R**	**W**	**R**	**W**
Criteria 1	40%	10	4.00	5	2.00	1	0.40
Criteria 2	30%	8	2.40	10	3.00	6	1.80
Criteria 3	20%	4	0.80	8	1.60	10	2.00
Criteria 4	10%	7	0.70	7	0.70	10	1.00
Total	100%		7.90		7.30		5.2

To calculate the weighted score "W" for each design criteria, the criteria weight was multiplied by the design raw score "R". The weighted scores were summed in each design column to obtain the total design score. The highest score is highlighted in green, and is assumed to be the best design option. This assumption was verified through sensitivity analysis to ensure that bias or small errors in scoring did not have a large impact on the results. If design options are particularly close in score, additional analysis will be performed to determine between them.

3.2 Sensitivity Analysis

Due to the somewhat subjective nature of the 1-10 ratings for each criteria, a sensitivity analysis was performed for each trade to ensure that small variations or errors across the trade did not result in a change of results. This is especially important when two or more design options have very similar weighted scores.

After making initial assignments a MATLAB script was created to vary each value by ±1. Every combination of values was simulated and the percentage of cases in which each option had the highest score was computed. As a note, the percentage of wins is not sensitive to the margin of win. For example, the optical trade study sensitivity analysis shows option 5 winning roughly 1700 times more than option 1. However, when looking at the scores for each case both options are only separated by a couple fractions of a point. Nevertheless, the sensitivity analysis is very useful in determining the likelihood of a particular outcome.

4.0 Optics Design Options

Several fundamental specifications of the optics system were determined in order to properly compare design options. In order to properly image Bennu over the ranges of distances that are required, the target object must be fully contained within all images taken. For the target to be fully contained within an image the angular resolution of the system much be such that at a distance of 10km the target is no larger than 1024 pixels (the smallest dimension of the image). The diffraction-limited resolution must also be no larger than the pitch of a single pixel of the focal plane, or 12 micrometers. These two constraints allowed the focal length and minimum aperture of the optical system to be calculated. The resulting constraints are a focal length of 25 cm and a minimum aperture of 8.9 cm for an unobstructed system and a minimum aperture of 9.2 cm for a system with a 2.54 cm obstruction. Detailed derivations and calculations for these constraints can be found in the appendix.

4.1 Cassegrain Reflecting Telescope

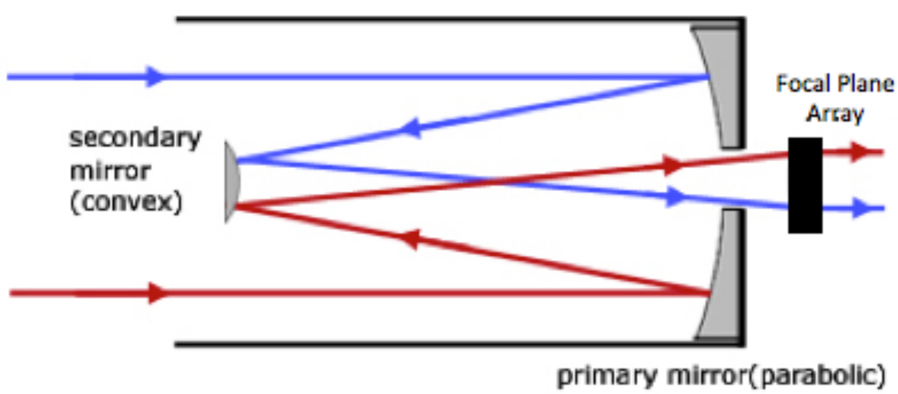


Figure 4: Cassegrain Reflecting Telescope Diagram

A Cassegrain reflector is a two-element reflecting telescope that uses a primary parabolic mirror to begin focusing the incoming light. The light is reflected forward onto a secondary, hyperbolic mirror. This mirror then continues focusing the incoming light through a hole in the primary mirror and onto the focal plane array (FPA). The Cassegrain telescope is a relatively simple telescope that allows for a short mechanical length relative to its effective focal length. However, the secondary mirror obstructs the incoming light into the system, thus requiring a larger aperture diameter to allow the same amount of light to pass through and avoid reaching the diffraction limit.

Table 6: Advantages and Disadvantages of the Cassegrain Reflecting Telescope

Pros	*Cons*
• Short Mechanical Length • Easy access for electrical boards and thermal systems to focal plane array • Simple Optics Design • Easily Focused	• Expensive coatings required for IR mirrors • Large minimum aperture size • Aberrations from obstruction • Spherical aberrations from parabolic mirror

4.2 Newtonian Reflecting Telescope

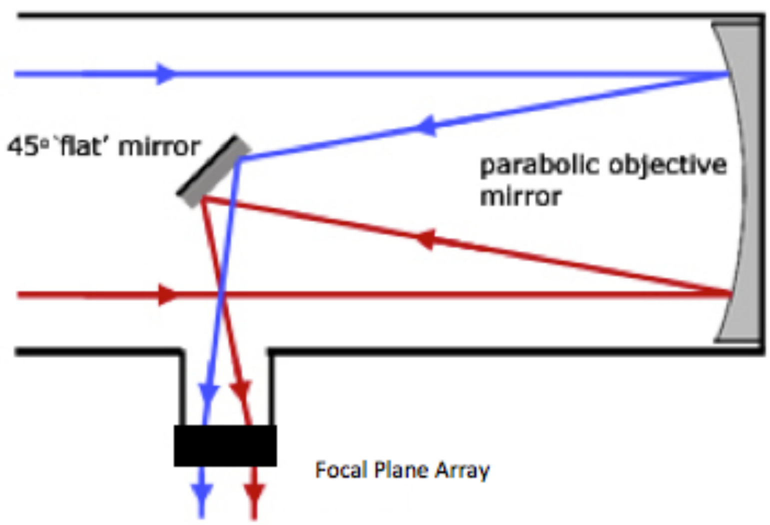


Figure 5: Newtonian Reflecting Telescope Diagram

A Newtonian telescope is similar to a Cassegrain in that the incoming light is reflected off of a parabolic mirror at the back of the telescope. However, instead of then reflecting off a hyperbolic secondary mirror that reflects the light through a hole in the back of the primary mirror, the light is reflected off a secondary flat mirror inclined at a 45-degree angle, where the light is then sent to the focal plane array either at the top or the bottom of the telescope. The Newtonian reflector has many of the same problems as the Cassegrain reflector, as it also has an obstruction in the primary from the secondary mirror at the front of the telescope, which can cause distortions in the final image. It is somewhat simpler than the Cassegrain reflector, as instead of requiring a hyperbolic mirror only a flat mirror is required, and the primary parabolic mirror is a continuous surface and does not require the hole for the focal plane to see through.

Table 7: Advantages and Disadvantages of Newtonian Reflecting Telescope Design

Pros	*Cons*
• Simple optics system • Easy access to radiating surfaces to focal plane • Short mechanical length • Easily Focused	• Expensive coatings required for IR mirrors • Location of focal plane make electronic access difficult • Aberrations from obstruction • Spherical aberrations from parabolic mirror

	• Large minimum aperture size

4.3 Offset Parabolic Reflector

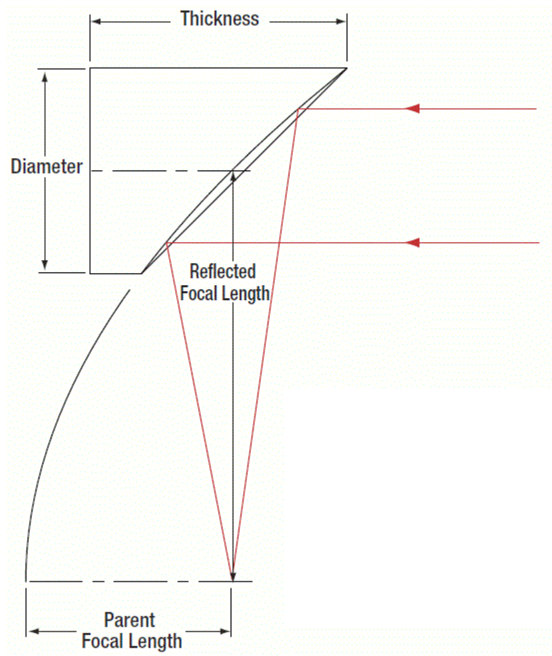


Figure 6: Off-Axis Parabolic Reflector

The off-axis parabolic design consists of a single parabolic reflecting element that focuses the incoming light at an angle off the incoming light. This set up allows for a slightly larger aperture size than the other designs as it enables the focal plane array to look through one of the corners of the CubeSat structure, enabling a size larger than the 10 cm that the other systems are confined to. However, since all of the angles would be off the primary spacecraft body axes, complex mounting mechanisms would be required to constrain the mirror. Additionally, since the system requires only a single element, the mechanical length would be equivalent to the focal length, making the system long compared to the other designs.

Table 8: Advantages and Disadvantages of Offset Parabolic Reflector Design

Pros	***Cons***
• Maximizes aperture size • Only requires single element	• Expensive coatings required for IR reflector • Off-axis light path makes focusing difficult • Single element likely requires deployable • Off-axis parabola requires custom manufactured optics • Off-axis mounting for reflector and focal plane array is difficult to manufacture

4.4 Single Refractive Lens

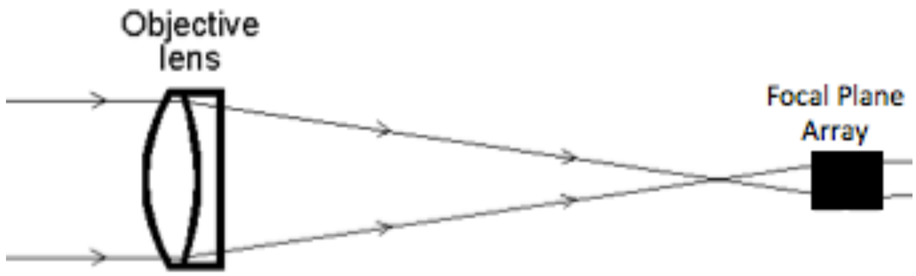


Figure 7: Single Refractive Lens

The single refractive lens design is simple optically, as it consists of a lens that focuses the incoming light directly and axially into the focal plane array. However, due to the presence of only a single element requires that the mechanical length of system is equal to the focal length. Also, because the system behaves axially, unlike the off-axis parabolic reflector, the focal length would be longer than the length of the payload, and thus require a deployable optics assembly, and therefore adding a large degree of complexity to the system.

Table 9: Advantages and Disadvantages of Single Refractive Lens Design

Pros	***Cons***
• Simplest optical system • Only requires one optical element • Easy access to focal plane array for electronics and thermal systems • Small minimum aperture size	• Requires deployable to achieve minimum focal length • Chromatic aberrations • Low degree of accuracy due to deployables

4.5 Refracting Multi-Element Telescope

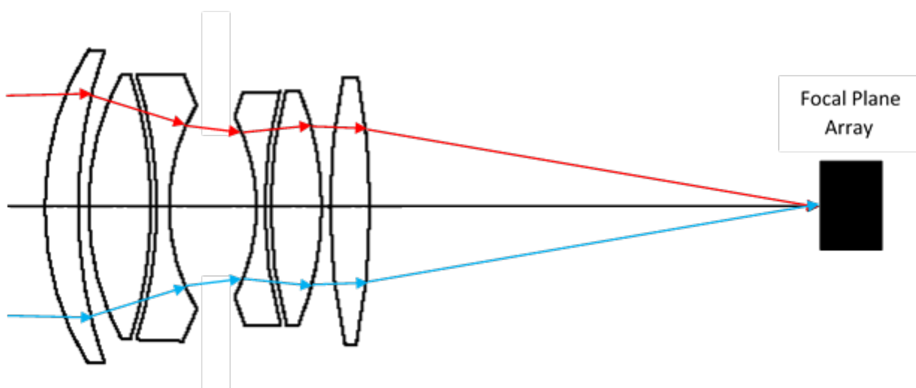


Figure 8: Multi-element Refractive Lens

The refractive optics stack-up would consist of a multi-element system that uses refracting optics to focus the incoming light onto the focal plane array. This system would be similar to the single refractive lens, however the presence of multiple elements would allow for a shorter mechanical length than the effective focal length, and therefore eliminates the need for deployables. However, the presence of multiple separate lenses significantly increases the mass of the system, as well the cost for producing the lenses. Additionally, since the aperture is obstruction free, it allows for a smaller minimum aperture size compared to the reflective telescope designs.

Table 10: Advantages and Disadvantages of Refracting Multi-Element Telescope Design

Pros	*Cons*
• Small minimum aperture size • Short mechanical length • Extra lenses can correct for aberrations	• High mass • Large number of optical elements • Possibly difficult to focus

5.0 Optics System Design Trade Study

5.1 Major Design Criteria Under Consideration

Table 11: Optics Trade Study Design Criteria

Design Criteria	*Weight*	*Description and Rationale*
Effective Aperture	19%	The limiting pupil of the optical system determines the diffraction limit of the camera, the highest resolution possible at a certain wavelength. With a fixed focal length determined by observation distance the effective aperture becomes the only remaining factor that determines optical angular resolution. This criterion is weighted the heaviest because it is the only flexible element of the optical design while still driving the volume requirements of the system.
Form Factor	15%	Phoenix is limited to a 2U (10 x 10 x 20 cm) payload volume. Preliminary analysis indicates the minimum effective focal length of the optics system needs to be 25 cm, indicating that the optics will need to be compressed into the available space and also allow room for supporting structure, thermal, and electronic systems.
Chromatic Aberrations	13%	Chromatic aberrations result from the fundamental property that glass has different refractive indexes for different wavelengths and thus are focused in different planes. Chromatic aberrations in a broad band imaging system blur the image and cause distortions. These aberrations are less than desirable because they cannot be easily corrected for in the image processing software.
Manufacturability	11%	Manufacturability is the measure of how difficult the supporting mechanics for the optical system will be. This will include tolerances and the number of mechanical components needed. A well designed optical system makes the mechanical support structure easy to manufacture.
Distortions	11%	Distortions is the field arising out of the other aberrations that can cause the image to be blurred and distorted on the camera. While most aberrations can be corrected for in software, it is extremely processor intensive and not entirely accurate. The best design will have the least amount of aberrations, because these aberrations may produce inaccurate results for the rate determination algorithms.
Mass	10%	A driving requirement of the Phoenix camera is integration into a 2U CubeSat volume, which limits hardware mass to approximately 1 kilogram/unit. Phoenix must have a mass of roughly 2 kilograms or less, of which the optics system is expected to comprise a major portion.
Ease of Focusing	9%	For the protoflight camera, the optical system will need to be focused so that it can be easily tested when imaging the simulated asteroid. Certain designs make this alignment and focusing of the optics easy which significantly reduces the amount of time spent on assembly, integration, and testing of this protoflight camera.

Lead Time	8%	The lead time criteria captures the risk associated with the ordering of custom made optics with different diameters, curvatures, and coatings then COTS optics. Certain designs will require more custom optics, which results in those designs having a higher risk associated with ordering these optics.
Low Cost	4%	The cost is associated with the lead time in that the more custom optics required for the design, the more expensive it will be. However, cost does not play a large role in this trade study because of the budget margin.

5.2 Other Criteria Not Considered

The main optics design criteria that was not considered was the thermal design of the ease of cooling of the optical system. There is currently insufficient information and analysis to determine whether the optical system even needs to be cooled to reduce the background noise of the system. This criterion will be used later to determine which one of the two best designs will be picked.

5.3 Trade Study

Table 12: Optics Design Option Trade Study

		Cassegrain		Newtonian		Offset Parabola		Single Lens		Multi-element Refractive	
Criteria	**Weight**	**R**	**W**	**R**	**W**	**R**	**W**	**R**	**W**	**R**	**W**
Effective Aperture	19%	8	1.52	8	1.52	10	1.90	10	1.90	10	1.9
Form Factor	15%	9	1.35	7	1.05	4	0.60	2	0.30	10	1.5
Chromatic Aberrations	13%	10	1.30	10	1.30	10	1.30	5	0.65	8	1.04
Manufacturability	11%	9	0.99	10	1.10	6	0.66	4	0.44	8	0.88
Distortions	11%	6	0.66	3	0.33	4	0.44	10	1.10	9	0.99
Mass	10%	7	0.70	8	0.80	9	0.90	10	1.00	4	0.40
Ease of Focusing	9%	6	0.54	7	0.63	5	0.45	10	0.90	7	0.63
Lead Time	8%	10	0.80	10	0.80	3	0.24	10	0.80	8	0.64
Low Cost	4%	8	0.32	9	0.36	3	0.12	10	0.40	6	0.24
Total	100%		8.18		7.89		6.61		7.49		8.22

5.4 Sensitivity Analysis

The sensitivity analysis shows that the two design options that receive the highest score the most often are the Cassegrain and the Multi-Element Refractive. The weakness of this method of sensitivity analysis can be seen in this case. The Multi-Element Refractive design wins 83.5% of the time compared to the next highest option, the Cassegrain. This is due to the fact that the analysis does not take into consideration the margin of the final result. Both options score very closely even though the Refractive Lens design usually wins.

Table 13: Optics Trade Study Sensitivity Analysis

Cassegrain	Newtonian	Offset Parabola	Single Lens	Multi-Element Refractive
7.54%	0.0914%	5.53%	3.29%	83.5%

5.5 Conclusions

The results of the trade study demonstrated that two main designs, the Cassegrain and the Multi-Element Refractive, are nearly the same when compared to these design criteria. By interpreting the results and finding that the majority of cases result with a very close score between the two options, it was decided that we would include both in our baseline design. These two optical systems are two of the most commonly used designs in imaging for space-based platforms, from Hubble to GOES-R. More specific designs for the Multi-Element Refractive will be determined so that they can be modeled and compared to the Cassegrain reflector. Thus going forward in the optical design we will do a more in depth analysis on the thermal constraints of the optical design and assess which design will achieve those constraints the easiest. The different optical designs will not change the layouts of the other subsystems, until later in the design process. Therefore both the refractive lens and the Cassegrain reflector will be analyzed going forward.

6.0 Thermal Design Options

Cooling of infrared and optical systems is a problem that many large spacecraft have had to address, including the Hubble Space telescope, Kepler telescope, and James Webb Space Telescope. Many of these spacecraft have addressed their low-temperature needs through the use of cryocoolers or cryostats. There are a variety of options for cryocoolers such as pulse tube coolers, G-M Cryocoolers, and cryostats.

Pulse tube coolers utilize a piston that moves back and forth. This causes the gas within the cooler to move and create pressure fluctuations. Gas from the compressor space moves into the regenerator, and then leaves the regenerator at the cold end. Heat is then transferred into the regenerator material. On the gas' return the heat stored within the regenerator is transferred back into the gas.

The Gifford-McMahon Cryocooler has a cold head that contains a compression and expansion space, a regenerator, and a displacer. The pressure variations are obtained by connecting the high and low-pressure sides of a compressor by a rotating valve. The position is synchronized with the motion of the displacer.

Cryostats come in a variety of configurations but all work in similar ways. A dewar contains liquid helium and attempts to isolate it from the rest of the spacecraft. Instruments that need to be maintained at cool temperatures are connected to the liquid helium using a cold plate. These systems eventually boil away all of their helium but if designed properly can be an effective solution. There are also closed cycle cryostats but these systems tend to have significant power requirements. This style of system was utilized on board the WISE spacecraft as it attempted to image the cosmic microwave background radiation.

The majority of these systems are power, weight, and volume heavy leaving them outside the range of cubesats. A paper was published in 2011 by Air Force Research Labs at the international cryocoolers conference evaluating the current technologies for microsatellites. There were only three laboratory tested technologies at the time of the conference; all pulse tube style coolers. Each weighed 2.8kg, 4.5kg, and 0.86kg respectively putting these options into the edge of the CubeSat domain. However, the power requirements make these technologies infeasible for our bus at 50W, 84W, and 35W.

There is one cryocooler option that is feasible for the Phoenix project; a split Stirling linear cryogenic cooler. The linear Stirling cooler is comprised of a single-piston compressor, a resonant "moving coil" actuator, and pneumatically driven resonant expander. When mechanical energy is put into the actuator a temperature difference is created between compressor reservoir and the expansion reservoir. The advantage of this system is the large range of temperatures that the Stirling cooler can maintain without a significant change in required input power. This allows for a flexible thermal system with a large range of applicable situations. The disadvantages of the Stirling cooler systems are the moving parts that can breakdown in space, as well as the low efficiency ~10% relative to the volume that the Stirling cooler will occupy.

Thermoelectric coolers are two materials that use the Peltier effect to generate a heat flux between them. Heat from one side of the device is transferred to the other and uses electricity to act as a solid-state heat pump. They have the advantage of being highly available and made for many different applications. In addition with no moving parts they have a very long operating ability. The main disadvantage is they are not efficient offering only 10-13% efficiencies in models we looked at.

Passive cooling uses radiators and materials to control heat entering and leaving the system. Many spacecraft rely on this technology as their only form of spacecraft cooling. It has the advantage of not needing any power and while meeting system needs. The disadvantage of this system is that it is not able to respond to a changing environment. Additionally the size of the radiator grows to the fourth power as the temperature requirements are raised. This means that systems that must be very cool require very large radiators. Passive thermal control is an essential part of every spacecraft even if an active thermal system is selected.

To better analyze the technologies that we will consider a simple thermal budget was constructed to understand what the requirements on this system would be.

The input into the satellite from the sun can be modeled as equation 1.

$$Q_{in} = \frac{1376.5}{AU^2}\alpha A \text{ (Watts)} \tag{1}$$

This is where AU is astronomical units from the sun, α is the absorptivity of the surface, and A is area in meters. However, the bus is intending to use deployable panels in order to shield the payload from the sun. The payload is also planning on using a low absorptivity white paint to limit radiation that may come from the backside of these panels. For these reasons the input from the sun into the simple thermal model is assumed to negligible.

Other inputs of heat to the system are the electronics for the image sensor, the image sensor itself, heat reflected from the asteroid onto the optics, and the power to the thermoelectric cooler. It is estimated based on example components that the electronics will use 1-1.2W of power. The sensor has been reported to use 0.3W of power maximum by the manufacturer. The thermoelectric cooler that is being used as the baseline consumes 4W peak power. The optics will also be absorbing energy from the target that it is observing. In this case the absorptivity of Bennu is used to estimate the albedo of the target. Based on equation 2 below and was determined to be 0.219 W:

$$Q_{optics} = Q''\pi R^2\alpha \text{ (Watts)} \tag{2}$$

The heat out can be represented by:

$$Q = \epsilon\sigma T_s^4 A \text{ (Watts)} \tag{3}$$

Where T_s is the temperature of the surface, ϵ is the emissivity, and A is the area. Because the heat in is known, we can solve for the temperature desired as a function of the temperature of the radiator given below:

$$T(A) = \sqrt[4]{\frac{Q}{\epsilon\sigma A}} \text{ (Kelvin)} \tag{4}$$

The plot shown in Figure 9 shows how this relationship varies and the temperatures that can be met. The customer has told us to anticipate a lowest possible operating temperature for the sensor of 140 K. This temperature is expected to have some flexibility, as the manufacturer may be able to provide higher temperature substrates; however, this value will still provide a baseline for the design until that is confirmed.

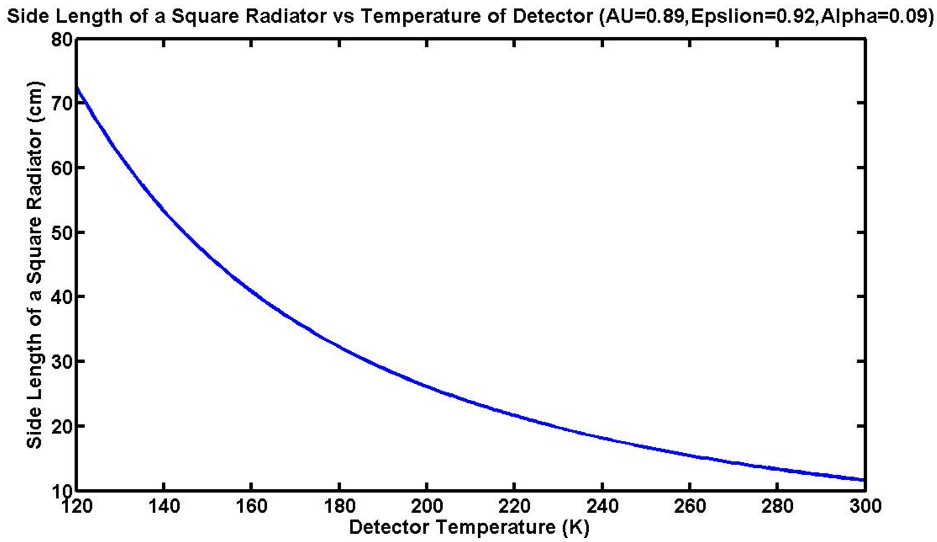


Figure 9: Radiator Length (cm) vs. nBn Detector Temperature (K)

Utilizing a 3061cm^2 radiator, the optical system could be kept at 140K, the known minimum requirement of the image sensor. This is however more area than would be available on the bus 700cm^2. This would require a deployable radiator and a restriction on the ConOps of the bus. As thermal constraints are lifted the size of the radiator rapidly decreases and make the deployable system more feasible.

If all sides but the aperture of the payload were used (700cm^2) as radiators then a temperature of 205 K could be achieved with margin. The active thermal system is able to maintain a temperature difference of 65K and meet the requirements of the system.

Thermoelectric coolers and Stirling coolers are capable of a differing amounts of heat absorptions but can all maintain ~65K temperature difference for these absorptions. If the radiators could be kept at 205K then a minimum initial temperature of ~140 K could be achieved. As time goes on until the system archives steady state the temperature of the system would increase. The goal of additional analysis would be to prove that this steady state temperature would either be below the threshold for useful imagery or take sufficiently long that photos could be captured on a duty cycle. The goal before PDR would be to develop a simple 10-20 node Simulink or excel thermal model in conjunction with a model in thermal desktop so that the models could provide concurrent verification.

6.1 Passive Deployable Radiator Design

The goal of a passive system is to dissipate all heat into the system out a large radiator while maintaining a sensor temperature of 140K. To achieve this goal this system would require more surface area than can be provided by using just the sides of the payload. This 3061cm^2 of area that was derived above would have to be provided by a deployable radiator. Deployables rapidly increase complexity and can put additional risk on the mission. The system has the advantage of being able to maintain the sensor at 140 K at steady state. This would allow for continuous operation of the sensor during operations, not a requirement of the system.

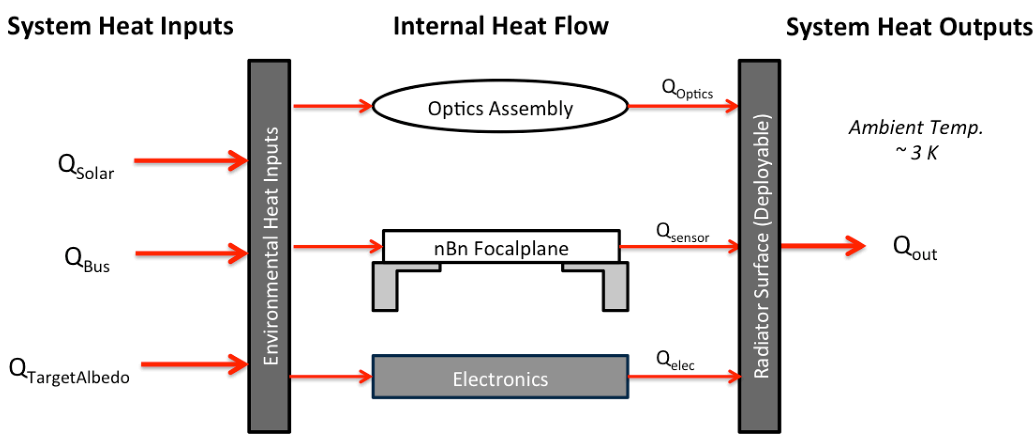


Figure 10: Passive Thermal System Functional Block Diagram

Figure 10 depicts a simple version of the heat path that would come into and out of the system. In this case all heat conducts directly to a radiator and then out into space shown on the right side of the diagram. The heat into the system is expected to come from the sun, target albedo, and the heat of the busses electronics, the left side of the diagram. The internal components of the system also generate heat as well. The optics will be heated by the target's albedo, as they will be facing it. Both the electronics and the nBn sensor also will produce heat as they are powered. In this model all internal heat is transferred to the radiator.

Table 14: Advantages and Disadvantages of the Passive Thermal System

Pros	***Cons***
• No power required for this option • System can operate indefinitely at 140k • Additional heat is not generated by cooling system	• Deployable radiator is required • Electronics will either have to be isolated or heated • Bus concept of operations may change to keep radiator in shade

6.2 Active Thermoelectric Cooler with Radiator Design

The thermoelectric cooler design is very similar in heat path to the passive cooling design. The system gains an advantage in that only the focal plane needs to be kept at 140k. Since the entire system does not need to be cooled a much smaller radiator can be used to cool the rest of the payload. The radiator for this system would be small enough as to only use the panel area of the bus. This would eliminate the need for a deployable on the payload and decrease risk. It however does come at an increase to power over the passive system. This is all possible because of the use of a thermoelectric cooler. This device maintains a temperature difference by transferring heat from the sensor to the radiator. To accomplish this change though work has to be put into the TEC which acts like a solid state heat pump.

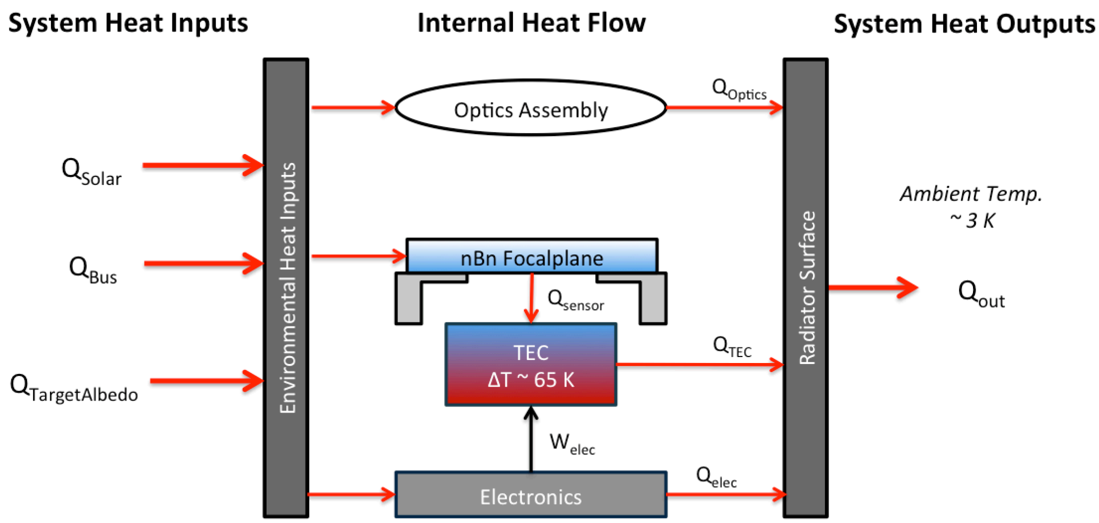


Figure 11: Thermoelectric Cooler Functional Block Diagram

As can be seen in Figure 11 the heat path is very similar but now a TEC pulls heat ways from the sensor and to the radiator. This will allow for the rest of the spacecraft to stay at ~205K while the sensor is maintained at 140K. This does require that work energy is put into the TEC in order to maintain this difference. This work will eventually also have to be dissipated be the radiator as well.

Table 15: Advantages and Disadvantages of TEC Design

Pros	***Cons***
• 140 K can be maintained just at the focal plane instead of cooling the entire system • Radiators can sit on the surface of the payload and no deployables are required. This limits restrictions on the bus's ConOps and reduces risk. • Electronics system will not need to be actively heated	• Power is required to draw heat away from focal plane • Control of the power into the TEC will need to be created for regulation • TEC is only 10% efficient and therefore a large amount of the energy into the system is waste heat.

6.3 Active Split Stirling Linear Cooler with Radiator Design

The split Stirling linear cryogenic cooler design utilizes both an active and a passive thermal system. By utilizing the Stirling cooler the radiator for this system would be small enough to only require the panel area of the bus. This would eliminate the need for a deployable on the payload and decrease risk. However, the Stirling cooler does require power input and generates heat that the radiator will need to dissipate. In order to cool the focal plane of the optical system mechanical energy is put into the actuator of the Stirling cooler causing the expander to move between the compressor reservoir and the expansion reservoir.

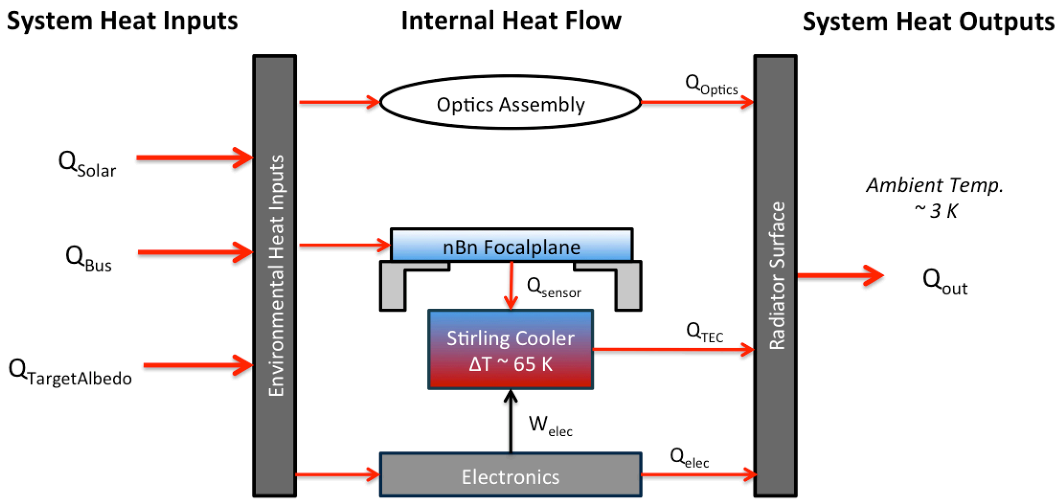


Figure 12: Flow Diagram of Stirling Cooler Design

As can be seen in Figure 12 the heat path is very similar, but the TEC is now replaced by a Stirling cooler that pulls heat ways from the sensor and to the radiator. This will allow for the rest of the spacecraft to stay at ~205K while the sensor is maintained at 140K. This does require that work energy is put into the TEC in order to maintain this difference. This work will eventually also have to be dissipated be the radiator as well.

Table 16: Advantages and Disadvantages of Stirling Cooler Design

Pros	***Cons***
• Large range of achievable ΔT • Radiators can sit on the surface of the payload and no deployable is required. This would help limit restrictions on the bus ConOps and reduce risk • Stirling coolers have been used to cool IR optical systems before; there is flight heritage for the option considered	• Power usage becomes very high as the heat that the system needs to dissipate increases • The entire system in approximately 1U in size • Stirling coolers are only 10% efficient and therefore a large amount of the energy becomes waste heat

7.0 Thermal System Design Trade Study

7.1 Major Design Criteria Under Consideration

Table 17: Thermal Trade Study Design Criteria

Design Criteria	***Weight***	***Description and Rationale***
Power	18%	Power is a valuable resource on any satellite but especially a CubeSat. We are currently estimating 10W available from the bus. Since thermal will utilize the majority of this power it is essential to be minimized. For these reasons it was assigned the highest weight in the study.
Form Factor	18%	Our payload was assigned to a 2U payload section of the CubeSat. The optical assembly is estimated to need a majority of the 2U space. The goal of the thermal system should be to accomplish its goal while leaving as much space available as possible. This criteria was rated as equally important as power consumption as both are the two most valuable resources of our payload.

Cooling Factor of Safety	14%	Solutions that are more flexible are preferable over fixed solutions. As the project progresses assumptions that were made now may not be valid. Flexible solutions allow us to be able to adapt to a changing environment both in testing and as we learn more. This criteria was given the second highest rank in the study due to how dynamic the thermal environment and calculations for a satellite may be.
Mass	14%	A driving requirement of the Phoenix camera is integration into a 2U CubeSat volume, which limits hardware mass to approximately 1 kilogram/unit. Phoenix must have a mass of roughly 2 kilograms or less, of which the thermal mechanism is expected to comprise a major portion.
Ease of Operation	10%	Different options that are selected put restrictions on the bus. Time to cool the instrument, if a deployable is required, or if a specific pointing is needed. Additionally controllers were taken into consideration as different design would require different amounts of control. It was given a weight slightly below average.
Efficiency	10%	Unfortunately among active thermal systems all efficiencies for applications of our size are very similar. This criteria does make the passive technologies stand out due to their lack of input power. For this reason this criteria was also given a weight just below average.
Lead Time	10%	Thermal components can vary highly in how easy they are to procure or machine. Some components can be shipped overnight while others require months of lead time. This criteria was given a slightly below average weight to capture this.
Cost	6%	For the thermal technologies under consideration the cost are not overwhelming. Given that the project has been instilled with a large budget to account for the optical and thermal systems it was weighted the lowest of any of the options.

7.2 Other Criteria Not Considered

There were many criteria's that were not considered because they were not as relevant. Temperature difference was not considered as all systems need to be able to maintain the focal plane at 140K. All of the designs were designed and traded according to this constraint. Input voltage and current were not considered as they were summed up in the power criteria. Mission risk was also not considered as it was covered in some capacity in ease of use. All of the technologies considered were not inherently risky to the mission and so this was a huge concern.

7.3 Trade Study

Table 18: Thermal System Design Trade Study

		Thermoelectric Cooler		Passive Thermal		Split Linear Stirling	
Criteria	**Weight**	**R**	**W**	**R**	**W**	**R**	**W**
Power	18%	6	1.08	10	1.80	6	1.08
Form Factor	18%	10	1.80	4	0.72	6	1.08
Mass	14%	10	1.40	4	0.56	8	1.12
Cooling Factor of Safety	14%	5	0.70	9	1.26	10	1.40
Ease of Operation	10%	10	1.00	5	0.50	10	1.00
Efficiency	10%	5	0.50	10	1.00	6	0.60
Lead Time	10%	10	1.00	3	0.30	6	0.60
Cost	6%	10	0.60	4	0.24	7	0.42
Total	100%		8.08		6.3		7.3

7.4 Sensitivity Analysis

The results of the MATLAB sensitivity analysis for the thermal system are as follows:

Table 19: Percentage of Cases in which Each Design has the Highest Score

Thermoelectric Cooler	Passive Thermal	Split Linear Stirling
87.5%	12.5%	0%

These results from the sensitivity analysis for the trade study show that the original best option remains the best option under a variety of scores. The thermoelectric cooler consistently received higher total scores making it a clear choice as a thermal solution.

7.5 Conclusions

After reviewing the trade study the team has decided to move forward with the thermoelectric cooler. In addition to being power conservative, the TEC is a compact design that will fit within the extremely tight 2U volume restrictions.

8.0 Electrical Design Options

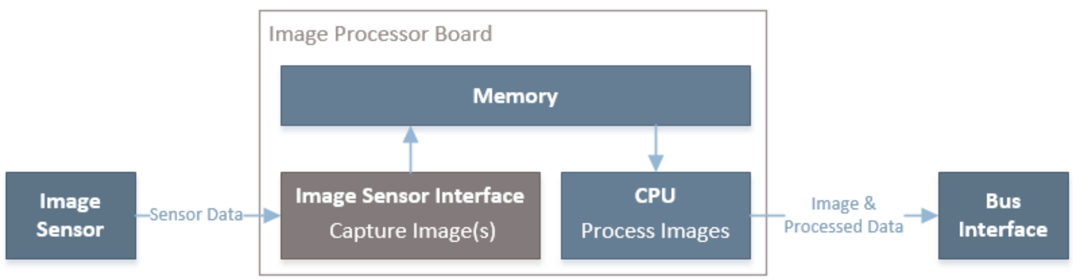
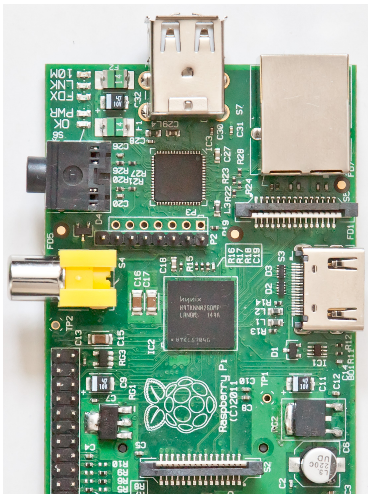


Figure 13: Image Capture and Processing Functional Block Diagram

The electronics subsystem operates in two distinct modes: capture mode, and analysis mode. Capture mode involves using a high-speed interface between the image-sensor and memory to capture a series of images in rapid succession. The thermal conditions of the sensor are checked, and if needed thermal control in actuated. Once the images have been captured and stored, the image sensor and supporting hardware can be shut down while the CPU processes the images and the system returns to thermal equilibrium. Once the images have been processed the result is stored in memory and returned upon request by the supporting satellite bus. The processed images are then compared to previous images in order to determine the rotational rate of the target as well as the axis of rotation.

This architecture can be accomplished in a variety of different hardware configurations as detailed in the following sub-sections.

8.1 Single Board Computer Design



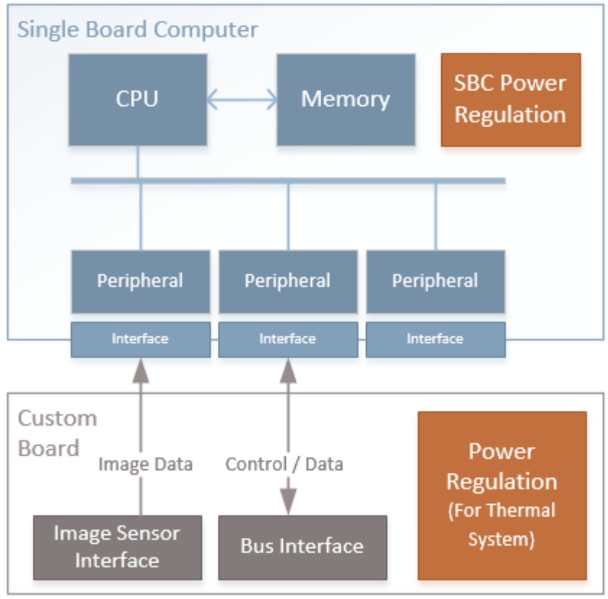


Figure 14: (left) Raspberry Pi SBC. (right) Single Board Computer Functional Block Diagram

A Single Board Computer (SBC) typically includes a CPU, Memory, and a variety of peripherals (such as USB, Ethernet, HDMI, etc.). In recent years there have been a large amount of single board computers put into the market, popular boards include the RaspberryPi and BeagleBone.

It is highly unlikely that a SBC will be able to meet all the needs for the Phoenix project, thus a custom board will need to be created for various interfaces to the bus and power regulation. While most SBCs include on-board regulation, these regulators are likely not sufficient for the needs of the thermal system or image sensor.

Table 20: Single Board Computer Advantages and Disadvantages

Pros	***Cons***
• Simplifies electrical system design • Board design cycle time reduced • Decreased cost of custom boards	• Contains extraneous hardware • Expensive • No control over part reliability • Still requires custom hardware for sensor interface

8.2 System on Module Design

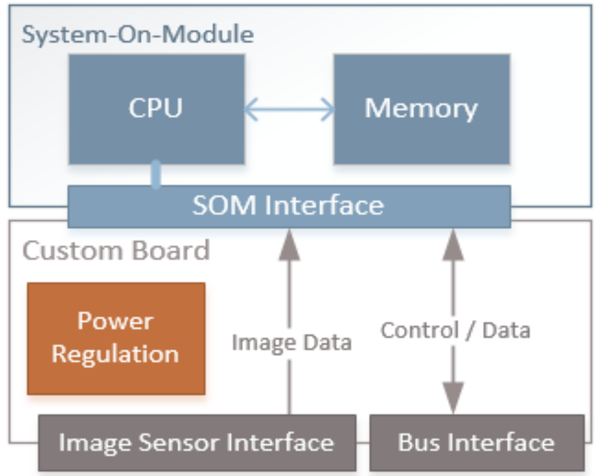


Figure 15: (left) Atmel System on Module. (right) System on Module Functional Block Diagram

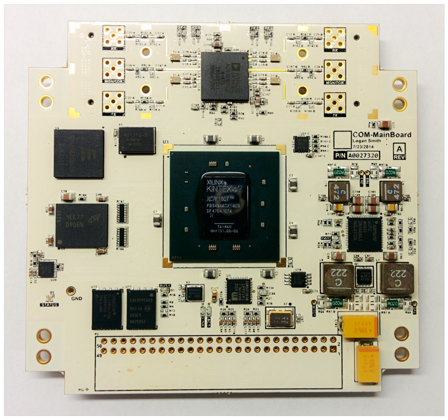
A System-On-Module (SOM) can be thought of as a simplified version of a Single Board Computer (SBC). It typically provides the processor and memory but no power regulation or on-board peripherals. Limiting the functionality to just the bare-minimum needed to boot-up greatly reduces board-size and gives the designer greater flexibility in deciding what peripherals to use in their final system. In addition interfacing the CPU to high-speed memory can often be one of the most complicated parts of a PCB design.

In this design the Phoenix team would need to design an adapter board that supplies power to the SOM and thermal system. In addition this adapter board would need to add any supporting circuitry for the image sensor and bus interfaces.

Table 21: System on Module Advantages and Disadvantages

Pros	***Cons***
• Simplifies critical circuit design • Decreased risk of board revisions • Decreased cost of custom boards	• Less control over form factor • Less control over reliability of electrical components • Still requires custom board for sensor interfaces

8.3 Custom Electronics Design



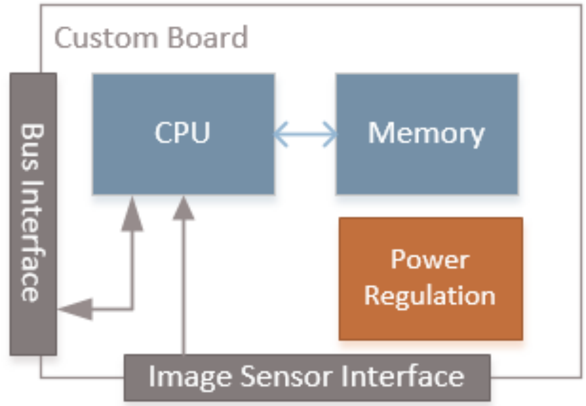


Figure 16: (left) Custom CubeSat Board. (right) Custom Electronics Functional Block Diagram

A custom electronics design would involve placing all necessary hardware on one or more PCBs. This offers the greatest flexibility and integration at the expense of development time and cost. The electrical team members of Phoenix would carry out the component selection and board design work. The hardware assembly of the board would be outsources to an assembly house in order to accelerate the design cycle and maximize quality. Custom electronics will be able to maximize system reliability by allowing complete control over all component selections.

Table 22: Custom Electronics Advantages and Disadvantages

Pros	*Cons*
• Design optimized for our application • Complete control over part selection/reliability • Reduced physical complexity of the system (i.e. integrating multiple PCBs)	• Long design cycle time • Higher risk of board revision • Potentially higher system cost

9.0 Electronics System Design Trade Study

9.1 Major Criteria Under Consideration

Table 23: Electronics System Design Criteria

Design Criteria	*Weight*	*Description and Rationale*
Development Time	23%	In any project with a fast design cycle, the total development time of a system that delays the development of other systems is extremely important. This criteria was weighted the highest as it could have the biggest impact on project success.
Form Factor	22%	Our design requires that we fit within a 2U CubeSat form-factor. With such constraints on volume, a system with higher form factor flexibility or total size will ease design requirements on other aspects of the project. As 2U is a very small volume, this criterion was given a heavy weighting.
Reliability	17%	Due to the fact that our system depends heavily on thermal conditions, we will need to test in a very cold environment. If the electrical system cannot survive the extreme conditions then the entire system cannot be verified. This criterion is weighted high but slightly less than Form Factor, Development Time, and Design

		Flexibility not because of its importance but because it is less of a challenge.
Cost	8%	Cost is a significant concern for every project. However, we have margin in our budget allowing for cost to play a much smaller role in design decisions.
Power Consumption	10%	The thermal control system will consume the majority of the power of the system, meaning that small variations in the power consumption of the electronics will not greatly influence the overall performance. Typically the electronics will amount to roughly 1/10 of the power budget.
Design Flexibility	20%	Due to uncertainties in the project a very flexible design is desired. A flexible design will be able to interface well mechanically even if unusual shapes are required. A flexible design will also allow small component changes if it is discovered that they do not meet reliability or functional requirements. The weighting is high because a highly flexible design will shorten the total development and testing time of the project by reducing time spent during re-designs.
Total	100%	

9.2 Other Criteria Not Considered

At this point the computing element was not considered. There are significant impacts on system design if the computing element is an FPGA, microcontroller, or DSP. These impacts are not important at this time as all three options considered can be executed using any one of the various processors.

Processing power, such as CPU clock speed, was not considered for similar reasons as above. The specifications of the design options are not important as every option has a wide range of specifications. This criterion is a lower level design choice not needing analysis at this level.

Desktop computing systems were also not considered as a very small embedded solution was required. Desktop design software will be leveraged for software development concurrently with hardware development.

Custom COTS options were not considered due to their high cost and the fact that our team has significant electrical design experience. It was determined that a custom design built by our team was a feasible design 6option for the project complexity and time frame.

9.3 Trade Study

		Custom		**System on Module**		**Single Board Computer**	
Criteria	**Weight**	**R**	**W**	**R**	**W**	**R**	**W**
Development Time	23%	3	0.69	6	1.38	10	2.30
Form Factor	22%	10	2.20	8	1.76	4	0.88
Design Flexibility	20%	10	2.00	8	1.60	5	1.00
Reliability	17%	10	1.70	8	1.36	6	1.02
Power	10%	10	1.00	9	0.90	6	0.60
Cost	8%	4	0.32	6	0.48	10	0.80
Total	100%		7.91		7.48		6.60

9.4 Sensitivity Analysis

Sensitivity analysis shows that the Custom Electronics option has the highest score a majority of the time. This margin demonstrates that the results are relatively consistent regardless of bias or small errors in scoring.

Table 24: Percentage of Cases in which Each Design has the Highest Score

Custom Electronics	System on Module	Single Board Computer
61.7%	11.1%	27.2%

9.5 Conclusions

The results of the trade study complement the team's design experience. We will design a custom electrical system in order to easily interface with the thermal and optical systems and to allow hardware optimization to support testing and software development. The design choices of custom electronics and System on Module were close in score. The differences were large enough for the custom decision to be selected for the time being. The SoM design option will be kept as an off-ramp if unforeseen circumstances complicate the custom electronics design. Sensitivity analysis showed that a small error in design option scoring did not significantly influence total scores. While the other options do turn out to be the top score in some cases the fact that the custom option still wins a clear majority of the time and the fact that the sensitivity analysis makes no accounting of how close the scores are means that the decision to go with the custom electronics is logical. Therefore the baseline system design will include custom designed electronics developed by members of the Phoenix team.

10.0 Selection of Baseline Design

10.1 Optical System

The baseline design for the optics system will be either a Cassegrain reflecting telescope or a multi-element refractive design. More information needs to be gathered regarding the price and lead-time estimates for designing the lenses for the refracting telescope. Additionally, further analysis will be conducted regarding the thermal performance of the systems, and how much thermal control will be required for the optical elements as opposed to just the focal plane. Both designs optical elements will be purchased COTS, and the price of these components will also be explored.

10.2 Thermal System

The baseline design for the thermal system was selected from the trade study and sensitivity analysis. The result that stood out as the optimal choice to satisfy our requirements was a thermal electric cooler. They are widely available and reduce the size of the thermal system for this application. A variety of the TEC's are available and space qualified that are able to meet our cooling requirements if the system is designed properly. This system would have the cold side of a TEC in contact with the focal plane assembly. The hot side will then conduct to the radiators. Power will be inputted into the thermoelectric cooler in order to drive this heat transfer. The radiators will comprise the outside of the bus be shaded from the sun or oriented away from it. This system will also require that there is some control over the power into and out of the TEC to regulate the thermal environment.

10.3 Electronics and Software

The baseline electronics system will consist of one or more custom designed PCBs which integrate power regulation, a computing element, memory, thermal actuator control and associated bus and image sensor interfaces. A custom design will allow for a compact form-factor easing optics design and survivability. Designing custom PCBs can be a difficult task and the team hopes to address this risk by performing several internal reviews and allocating at least

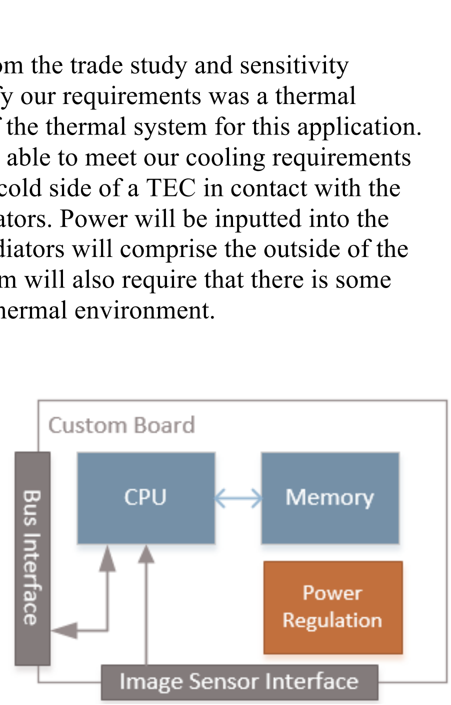


Figure 17: Custom Electronics Diagram

one board revision in the schedule. The electrical team has experience in this area and feels confident about the decision.

The current software flow is shown in Figure 18. The interest point detection will allow for certain "points" to be detected in a sequence of two or more pictures; these are then compared and the location of interest points can be used to calculate the observed angular rate of the target object. The image filtering allows for some image noise reduction to be performed in software. This potentially provides more leeway in the thermal system requirements and also increases the accuracy of our interest point detection algorithm. The rate solution is then sent to the bus along with any requested image data. Each image will be compressed and stored in the Phoenix camera memory until requested by the LMCO bus.

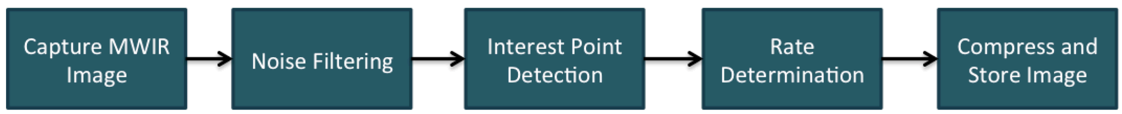


Figure 18: High-Level Software Flow Diagram

11.0 References

[1] Adams, Arn. "ADVANCES IN DETECTORS: HOT IR Sensors Improve IR Camera Size, Weight, and Power." *Laser Focus World*. PennWell Corporation, 17 Jan. 2014. Web. 13 Sept. 2014.

[2] "An Introduction to the NBn Photodetector." *UR Research*. University of Rochester, 2011. Web. 12 Sept. 2014.

[3] "ARCTIC: A CubeSat Thermal Infrared Camera." *TU Delft*. Delft University of Technology, 2013. Web. 13 Sept. 2014.

[4] Cantella, Michael J. "Space Surveillance with Infrared Sensors." *The Lincoln Laboratory Journal* 1.1 (1989): n. pag.*Lincoln Laboratory*. MIT, June 2010. Web. 9 Sept. 2014.

[5] Cleve, Jeffrey V., and Doug Caldwel. "Kepler: A Search for Extraterrestrial Planets." *Kepler Instrument Handbook* (2009): n. pag. 15 July 2009. Web. 12 Sept. 2014.

[6] "James Webb Space Telescope - Integrated Science Instrument Module."*ISIM*. Space Telescope Science Institute, n.d. Web. 13 Sept. 2014.

[7] "NBn Technology." *IR Cameras*. IRC LLC, n.d. Web. 13 Sept. 2014.

[8] Nolan, M.C. et al, "Shape model and surface properties of the OSIRIS-Rex target Asteroid (101955) Bennu from radar and lightcurve observations," *Icarus*, Vol. 226, Issue 1, 2013, pp. 663-670.

[9] Otake, Hisashi, Tatsuaki Okada, Ryu Funase, Hiroki Hihara, Ryoiki Kashikawa, Isamu Higashino, and Tetsuya Masuda. "Thermal-IR Imaging of a Near-Earth Asteroid." *SPIE: International Society of Optics and Photonics*. SPIE, 2014. Web. 13 Sept. 2014.

[10] "Spitzer Space Telescope Handbook." *Spitzer Space Telescope Handbook* 2.1 (2013): n. pag. Spitzer Space Center, 8 Mar. 2013. Web. 8 Sept. 2014.

[11] Vanbebber, Craig. "Lockheed Martin Licenses New Breakthrough Infrared Technology." Lockheed Martin Corporation, 7 Dec. 2010. Web. 9 Sept. 2014.

12.0 Appendices

12.1 Optics Design Calculations

12.1.1 Telescope Focal Length

The focal length of the system can be easily calculated using a geometrical analysis depicted in Figure 19 below.

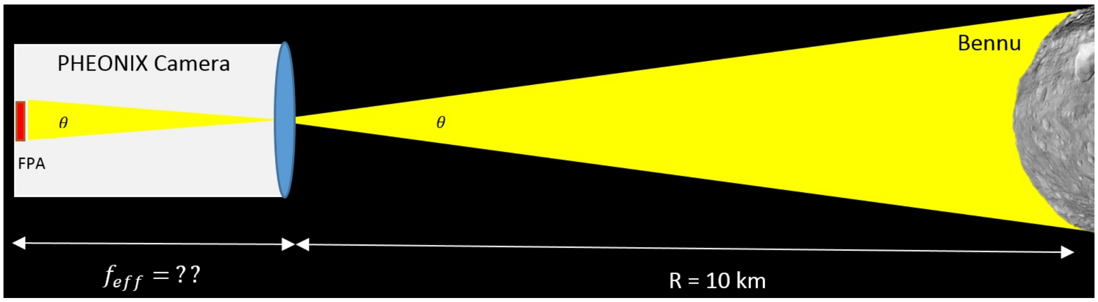


Figure 19: Effective Focal Length Diagram

From simple geometry the following relation can be established between the focal plane array (FPA) size, the effective focal length, the range to Bennu, and the asteroid diameter.

$$\frac{FPA_{size}}{f_{eff}} = \frac{D_{Bennu}}{range} \tag{5}$$

With a full field of view of Bennu at 10 km, the effective focal length of the camera system needs to be 25 cm long.

12.1.2 Telescope Diffraction Limit

The diffraction limit of a circular optical system is the minimum distance between two airy discs for them to be individually resolved. Figure 20-21 below first depict airy discs a resolvable distance from each other and an unresolvable distance from each other.

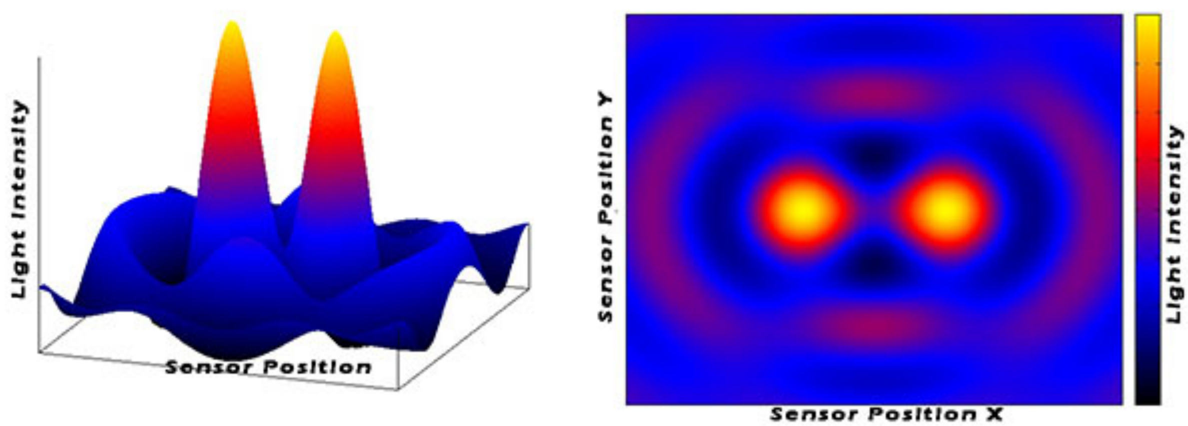


Figure 20: Resolvable Airy Discs

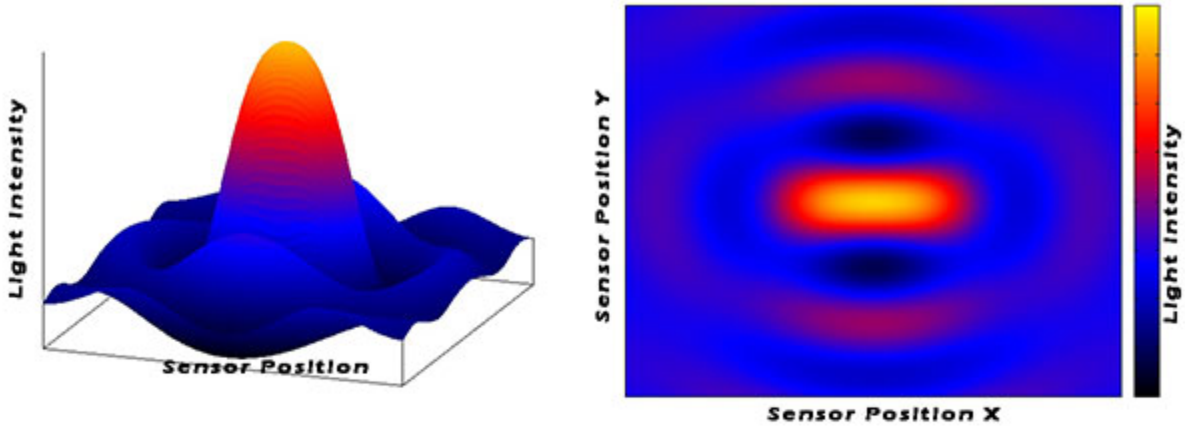


Figure 21: Unresolvable Airy Discs

The minimum resolvable distance between airy discs is the radius of the main peak of the airy disc. The airy disc radius is as follows.

$$R = 1.22\frac{\lambda f_{eff}}{D} \tag{6}$$

Where R is the radius of the airy disc, λ is the maximum wavelength of the optical system, f_{eff} is the effective focal length of the system, and D is the diameter of the limiting pupil of the optical system. For a system to be diffraction limited the pixel size needs to be less than or equal to the diffraction limit, R, of the optical system. To achieve the maximum field of view at the highest possible resolution the pixel size should equal the diffraction limit. Thus we desire to make the diffraction limit at the highest wavelength equal to 12 µm. Thus for a refractive optical system at this diffraction limit with a 9.5 cm aperture diameter and a 25 cm effective focal length, the highest wavelength this system can image is 3.74 µm. The diffraction limit of a reflective system is slightly different because of the central obstruction. The corrected diffraction limit for a reflective system is as follows.

$$R = 1.22\frac{\lambda f_{eff}}{D}\sqrt{\frac{1}{1-\left(\frac{D_o}{D}\right)^2}} \tag{7}$$

Where D_o is the diameter of the central obstruction. Using an obscuration diameter of 2.5 cm, a 12 µm diffraction limit, a 9.5 cm aperture diameter, and a 25 cm effective focal length, the highest wavelength of a reflective system can image is 3.61 µm.

12.1.3 Bennu Radiometry

The next calculation to be made will determine whether thermal radiation from Bennu or reflected sunlight will dominate the spectrum that the Phoenix camera will image around 3.5 µm. On previous Earth surveillance systems, the amount of light radiated by the Earth, a 290 K blackbody, comprised 80 percent of the spectral band over 3.5 µm. This observation will be verified as to whether it will apply to the asteroid Bennu.

12.2 Sensitivity Analysis MATLAB Script

```
%%%%%%%%%%
%Trade study sensitivity analysis
%%%%%%%%%%%%%%%
clear all
close all
clc

%% Electronics
disp('Electronics')
%Weighting vector
wVec=[.23 .22 .2 .17 .1 .08];

%Nominal configuration scoring
sVec1=[3 10 10 10 10 4];
sVec2=[6 8 8 8 9 6];
sVec3=[10 4 5 6 6 10];

%Modified scoring vectors
sVec1p=sVec1+1;
sVec1m=sVec1-1;

sVec2p=sVec2+1;
sVec2m=sVec2-1;

sVec3p=sVec3+1;
sVec3m=sVec3-1;

%Scoring matrices
sMat1=[sVec1p;sVec1;sVec1m];
sMat2=[sVec2p;sVec2;sVec2m];
sMat3=[sVec3p;sVec3;sVec3m];

%Check all combinations
s1=zeros(size(wVec));
s2=zeros(size(wVec));
s3=zeros(size(wVec));
numWins1=0;
numWins2=0;
numWins3=0;
for i=1:length(wVec)
  for j=1:3
    for k=1:3
      for l=1:3
        %Compute modified vectors
        s1(i)=sMat1(j,i);
        s2(i)=sMat2(k,i);
        s3(i)=sMat3(l,i);
        %Compute scores
        s1t=sum(s1.*wVec);
        s2t=sum(s2.*wVec);
        s3t=sum(s3.*wVec);
        %Determine winner
        [~,win]=max([s1t s2t s3t]);
        if win==1
          numWins1=numWins1+1;
        elseif win==2
          numWins2=numWins2+1;
        elseif win==3
          numWins3=numWins3+1;
        end
      end
    end
  end
end

%Determine percentages
tot=numWins1+numWins2+numWins3;
p1=(numWins1/tot)*100;
p2=(numWins2/tot)*100;
p3=(numWins3/tot)*100;

%Print results
disp('Sensitivity Results')
fprintf('Option 1: %4.3g%% (%3.3g
wins)',p1,numWins1)
fprintf('\n')
fprintf('Option 2: %4.3g%% (%3.3g
wins)',p2,numWins2)
fprintf('\n')
fprintf('Option 3: %4.3g%% (%3.3g
wins)',p3,numWins3)
fprintf('\n')
fprintf('\n')

%Nominal results
disp('Nominal')
s1t=sum(sMat1(2,:).*wVec);
s2t=sum(sMat2(2,:).*wVec);
s3t=sum(sMat3(2,:).*wVec);
fprintf('Score 1: %4.3g',s1t)
fprintf('\n')
fprintf('Score 2: %4.3g',s2t)
fprintf('\n')
fprintf('Score 3: %4.3g',s3t)
fprintf('\n')

[~,win]=max([s1t s2t s3t]);
fprintf('Winner: %4.3g',win)
fprintf('\n')
fprintf('\n')

%% Thermal
disp('Thermal')
%Weighting vector
wVec=[.18 .18 .14 .14 .10 .10 .10 .06];

%Nominal configuration scoring
sVec1=[6 10 10 5 10 5 10 10];
sVec2=[10 4 4 9 5 10 3 4];
sVec3=[6 6 8 10 10 6 6 7];

%Modified scoring vectors
sVec1p=sVec1+1;
sVec1m=sVec1-1;

sVec2p=sVec2+1;
sVec2m=sVec2-1;

sVec3p=sVec3+1;
sVec3m=sVec3-1;

%Scoring matrices
sMat1=[sVec1p;sVec1;sVec1m];
sMat2=[sVec2p;sVec2;sVec2m];
sMat3=[sVec3p;sVec3;sVec3m];

%Check all combinations
s1=zeros(size(wVec));
```

```
s2=zeros(size(wVec));
s3=zeros(size(wVec));
numWins1=0;
numWins2=0;
numWins3=0;
for i=1:length(wVec)
  for j=1:3
    for k=1:3
      for l=1:3
        %Compute modified vectors
        s1(i)=sMat1(j,i);
        s2(i)=sMat2(k,i);
        s3(i)=sMat3(l,i);
        %Compute scores
        s1t=sum(s1.*wVec);
        s2t=sum(s2.*wVec);
        s3t=sum(s3.*wVec);
        %Determine winner
        [~,win]=max([s1t s2t s3t]);
        if win==1
          numWins1=numWins1+1;
        elseif win==2
          numWins2=numWins2+1;
        elseif win==3
          numWins3=numWins3+1;
        end
      end
    end
  end
end

%Determine percentages
tot=numWins1+numWins2+numWins3;
p1=(numWins1/tot)*100;
p2=(numWins2/tot)*100;
p3=(numWins3/tot)*100;

%Print results
disp('Sensitivity Results')
fprintf('Option 1: %4.3g%% (%3.3g
wins)',p1,numWins1)
fprintf('\n')
fprintf('Option 2: %4.3g%% (%3.3g
wins)',p2,numWins2)
fprintf('\n')
fprintf('Option 3: %4.3g%% (%3.3g
wins)',p3,numWins3)
fprintf('\n')
fprintf('\n')

%Nominal results
disp('Nominal')
s1t=sum(sMat1(2,:).*wVec);
s2t=sum(sMat2(2,:).*wVec);
s3t=sum(sMat3(2,:).*wVec);
fprintf('Score 1: %4.3g',s1t)
fprintf('\n')
fprintf('Score 2: %4.3g',s2t)
fprintf('\n')
fprintf('Score 3: %4.3g',s3t)
fprintf('\n')

[~,win]=max([s1t s2t s3t]);
fprintf('Winner: %4.3g',win)
fprintf('\n')
fprintf('\n')

%% Optics
disp('Optics')
%Weighting vector
wVec=[.19 .15 .13 .11 .11 .10 .09 .08 .04];

%Nominal configuration scoring
sVec1=[8 9 10 9 6 7 6 10 8];
sVec2=[8 7 10 10 3 8 7 10 9];
sVec3=[10 4 10 6 4 9 5 3 3];
sVec4=[10 2 5 4 10 10 10 10 10];
sVec5=[10 10 8 8 9 4 7 8 6];

%Modified scoring vectors
sVec1p=sVec1+1;
sVec1m=sVec1-1;

sVec2p=sVec2+1;
sVec2m=sVec2-1;

sVec3p=sVec3+1;
sVec3m=sVec3-1;

sVec4p=sVec4+1;
sVec4m=sVec4-1;

sVec5p=sVec5+1;
sVec5m=sVec5-1;

%Scoring matrices
sMat1=[sVec1p;sVec1;sVec1m];
sMat2=[sVec2p;sVec2;sVec2m];
sMat3=[sVec3p;sVec3;sVec3m];
sMat4=[sVec4p;sVec4;sVec4m];
sMat5=[sVec5p;sVec5;sVec5m];

%Check all combinations
s1=zeros(size(wVec));
s2=zeros(size(wVec));
s3=zeros(size(wVec));
s4=zeros(size(wVec));
s5=zeros(size(wVec));
numWins1=0;
numWins2=0;
numWins3=0;
numWins4=0;
numWins5=0;
for i=1:length(wVec)
  for j=1:3
    for k=1:3
      for l=1:3
        for m=1:3
          for n=1:3
            %Compute modified vectors
            s1(i)=sMat1(j,i);
            s2(i)=sMat2(k,i);
            s3(i)=sMat3(l,i);
            s4(i)=sMat4(m,i);
            s5(i)=sMat5(n,i);
            %Compute scores
            s1t=sum(s1.*wVec);
            s2t=sum(s2.*wVec);
            s3t=sum(s3.*wVec);
            s4t=sum(s4.*wVec);
            s5t=sum(s5.*wVec);
            %Determine winner
```

```
                [~,win]=max([s1t s2t s3t s4t s5t]);
                if win==1
                    numWins1=numWins1+1;
                elseif win==2
                    numWins2=numWins2+1;
                elseif win==3
                    numWins3=numWins3+1;
                elseif win==4
                    numWins4=numWins4+1;
                elseif win==5
                    numWins5=numWins5+1;
                end
            end
        end
    end
  end
 end
end

%Determine percentages
tot=numWins1+numWins2+numWins3+numWins4+
numWins5;
p1=(numWins1/tot)*100;
p2=(numWins2/tot)*100;
p3=(numWins3/tot)*100;
p4=(numWins4/tot)*100;
p5=(numWins5/tot)*100;

%Print results
disp('Sensitivity Results')
fprintf('Option 1: %4.3g%% (%4.4g
wins)',p1,numWins1)
fprintf('\n')
fprintf('Option 2: %4.3g%% (%4.4g
wins)',p2,numWins2)
fprintf('\n')
fprintf('Option 3: %4.3g%% (%4.4g
wins)',p3,numWins3)
fprintf('\n')
fprintf('Option 4: %4.3g%% (%4.4g
wins)',p4,numWins4)
fprintf('\n')
fprintf('Option 5: %4.3g%% (%4.4g
wins)',p5,numWins5)
fprintf('\n')
fprintf('\n')

%Nominal results
disp('Nominal')
s1t=sum(sMat1(2,:).*wVec);
s2t=sum(sMat2(2,:).*wVec);
s3t=sum(sMat3(2,:).*wVec);
s4t=sum(sMat4(2,:).*wVec);
s5t=sum(sMat5(2,:).*wVec);
fprintf('Score 1: %4.3g',s1t)
fprintf('\n')
fprintf('Score 2: %4.3g',s2t)
fprintf('\n')
fprintf('Score 3: %4.3g',s3t)
fprintf('\n')
fprintf('Score 4: %4.3g',s4t)
fprintf('\n')
fprintf('Score 5: %4.3g',s5t)
fprintf('\n')

[~,win]=max([s1t s2t s3t s4t s5t]);
fprintf('Winner: %4.3g',win)
fprintf('\n')
fprintf('\n')
```