PHOENIX

University of Colorado
Department of Aerospace Engineering Sciences
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Project Definition Document (PDD)

Approvals

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Table of Contents

List of Tables and Figures

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 Problem Statement

Landing on an asteroid provides numerous opportunities for science, research, and commercial purposes. However, designing a spacecraft that can autonomously rendezvous with an asteroid requires a complex control system that can determine the rotational rate of the asteroid and match orientation in order to safely land. Infrared imagery is ideally suited to this task, as 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 ride-share with a GTO, GEO, or interplanetary mission, capture an infrared image of an asteroid, determine the angular rate of the body, and subsequently attempt to rendezvous.

The Phoenix team will design and build a 2U proto-flight[1] level camera payload for the LMCO bus that is capable of imaging simulated asteroid targets in the mid-wave infrared (MWIR) spectrum, processing the imagery, and determining the angular rate of the target with respect to the camera frame (Figure 1). The camera design will include a high-resolution, high-temperature nBn infrared detector provided by Lockheed Martin Santa Barbara Focalplane and a non-proprietary nBn sensor interface provided by Colorado Space Grant Consortium. Should LMCO be unable to procure the sensor within the time constraints of the project, a suitable replacement will be identified. The Phoenix camera will consist of the MWIR nBn sensor, optics assembly, electrical sensor interface, image processing, thermal control mechanisms, and structure. It will be responsible for complete MWIR image capture, processing, compression, and algorithms to determine the angular velocity of a target object. The camera must have an angular resolution of less than 50 μradians.

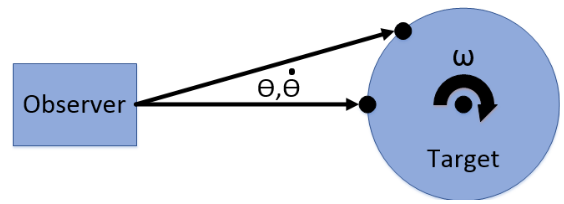

Figure 1: Phoenix will determine $\dot{\theta}$ of a target object

The Phoenix team will be unable to test under flight conditions and will conduct all hardware testing on the ground. All "asteroid" targets will be simulated objects with comparable spectral characteristics, angular velocity, and optical system requirements as the reference asteroid 101955-Bennu (specified by the customer). It is assumed the LMCO bus will be responsible for all power supply, communications, data handling, attitude determination and control, and propulsion systems. Since the LMCO bus is in the early stages of design, the Phoenix team will specify the structural, electrical, and software interfaces between the camera payload and bus. If any bus performance specifications are undefined, a comparable CubeSat technology will be used as a reference by the Phoenix team.

As current technologies for asteroid observation are quite expensive and limited in their abilities, the design of a payload that can be flown on a CubeSat greatly expands the potential for asteroid investigation. Additionally, utilizing the MWIR nBn sensor not only satisfies the needs of the Phoenix camera system, but also gives flight heritage to a burgeoning technology and proves high-temperature IR sensors are suited to the space environment.

2.0 Previous Work

2.1 IR nBn Sensor Resources and Publicity

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). In contrast this nBn sensor can operate at 140 K, allowing the use of much smaller thermal control mechanisms. One company [7] has already prototyped a cooled nBn IR camera with an operating temperature of 135 K and a mass of 0.45 kg; however, it is not space-rated and lacks the form factor and performance requirements for our mission.

2.2 Other IR Systems in Space

The Spitzer space telescope is a space-based IR imagery system able to provide 256 by 256 pixel images at various wavelengths, including the MWIR 3.6 micron band [10]. The satellite used an indium-antimonide (InSb) detector due to its sensitivity in the 1-5 micron wavelengths and is cooled to 6 K. This same detector type is used in infrared guidance systems, FLIR cameras, and other thermal imaging cameras. Numerous other space based telescopes use a passive cooling scheme with heat-pipes attached to a large radiating surface, such as the Kepler Space Telescope. Dutch students at the Delft University of Technology built a CubeSat long-wave infrared camera with an angular resolution of 130 μrad that achieved a temperature resolution of 95 mK [3]. This LWIR camera fit in a 2U CubeSat form factor and used a large, deployable radiative-cooling system.

2.3 Bennu Asteroid Observations

The current knowledge of the shape and rotation of the asteroid 101955-Bennu comes from a series of twenty-three observations from 1999, 2005, and 2011 [8]. Further ground-based observations will not be possible until 2017 and these will be of poor quality. The next good opportunity for ground-based observations does not come until 2037. Even when observations are possible from Earth it requires extensive processing to determine the rotation rate, rotation axis, and shape of the object. This processing involves creating a simulated asteroid, determining what a ground-based observation of the simulated asteroid would look like, comparing the simulated observations to the actual observations, and iterating until the two agree to within tolerances.

[1] "Proto-flight" refers to hardware that is in flight-form factor but is not required to undergo environmental testing or flight-certification.

3.0 Specific Objectives

As the Phoenix payload is intended to integrate with a 6U CubeSat to provide infrared imagery and angular rate determination measurements of a target object, certain criteria must be met. For use on a CubeSat the project must meet the volume, mass, and power constraints of the CubeSat platform. To produce the required imagery and angular rate determination measurements the captured images must achieve an angular resolution of 50 μradians so that the Phoenix camera image processing software can determine the observed rotation rate. The team will deliver a flight form-factor payload that meets the power and mass constraints of the bus and provides the bus with compressed imagery and an angular rate determination measurement, as determined in a co-rotating frame fixed to the infrared detector as depicted in Figure 1. Table 2 summarizes the major design tasks in each area:

Table 2: Major Design Elements by Content Area

Mechanical (> 25%)	Electrical (> 25%)	Software (> 25%)
• Optical system • Thermal isolation and materials • Support Infrastructure	• Image Sensor Electrical Interface • Power Electronics • Thermal Control Mechanism	• Image Sensor Software Interface • Image Compression • Angular Rate Determination Algorithms

3.1 Levels of Success

The following Figure 2 and Table 3 outline the levels of success for the mission. The achieved levels of success in each content area may not be the same (e.g. the structure could meet form-factor (Level 3), while the image capture capabilities may achieve only Level 2). Additionally, the diagram lays out the levels of success by major project area and shows how the progression of each area depends on the current level of the others. This both explains the functional difference between the levels of success and makes it clear what needs to be completed in each area to allow progression of the others.

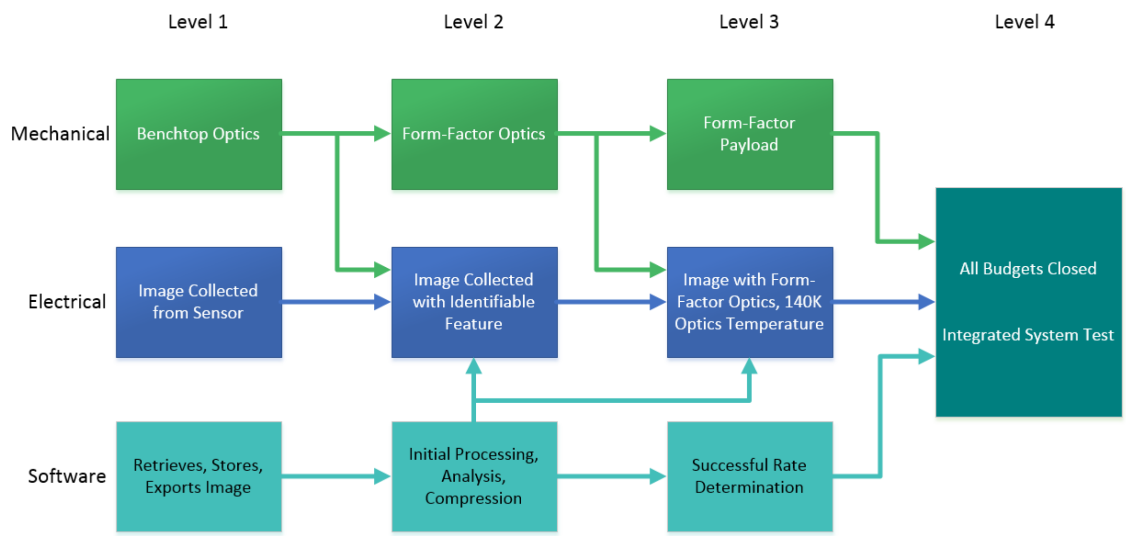

Figure 2: Phoenix Levels of Success Flowdown (See Table 3 for Further Detail)

Assumes each higher level of success adds additional functionality and includes or exceeds all lower level success criteria.

Table 3: Levels of Success Explained

Level 1 (Minimum Success)	• Capture image of 500 μrad (TBR) angular resolution from image sensor as commanded by software • Functional bench-top optics design with same focal length and aperture diameter as form-factor • Knowledge of camera sensor temperature • Software can configure sensor, retrieve an image, store the information, and export for analysis
Level 2	• All optics and support structure in form-factor • Capture IR image with software-identifiable object of angular size 100 μrad (TBR) • Initial processing, analysis, and image compression of sensor data
Level 3	• Low temperature (<140 K TBR) image capture and image contains software-identifiable objects of angular size 50 μrads using the form-factor optics • Software can determine observed angular rate of target • All components fit in standard 2U CubeSat Volume
Level 4 (Maximum Success)	• Demonstrate successful integrated system test (from command of image capture to angular rate det.) • Meet mass, power, data, and thermal requirements of the sensor and bus

4.0 Functional Requirements

4.1 High-Level Functional Requirements

Table 4: High-Level Functional Requirements

Req. #	Requirement
1.0	The payload shall integrate into the 2U payload section of the Lockheed Martin 6U CubeSat bus
2.0	The payload shall capture IR images with an angular resolution < 50 μradians
3.0	The payload shall maintain the optics assembly within operating temperature range
4.0	The payload shall determine the angular velocity of an observed object relative to the camera coordinate frame.
5.0	The payload shall compress and store the images as commanded

4.2 LMCO DRM Concept of Operations

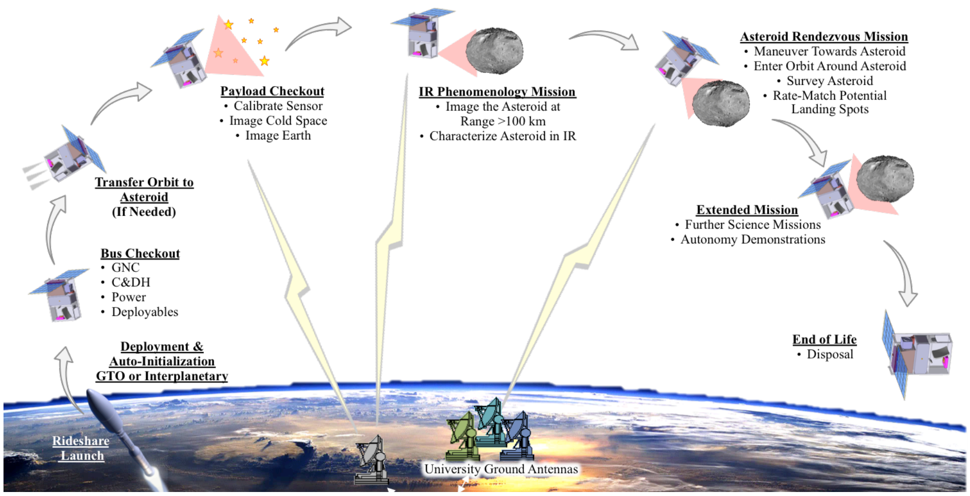

Figure 3: LMCO Bus Concept of Operations

Figure 3 details a Design Reference Mission for the 6U Bus, as described by our customer, LMCO. The bus will rideshare with a GTO, GEO, or Interplanetary mission. Once separated from the launch vehicle the LMCO bus will start up and perform system verification and maneuver towards the target location (the asteroid, Bennu, is used here as a reference target). At this point the Phoenix payload operations will commence.

The Phoenix payload Concept of Operations are limited to validating <u>only</u> the camera payload functional requirements through ground-testing to a proto-flight hardware level, as detailed in Section 4.3.

4.3 Phoenix Concept of Operations

As outlined in Figure 4, the team will perform ground testing to demonstrate that the payload has sufficient resolution and image quality to allow the desired surface surveying and will be able to determine the angular rate of the observed body in the frame of the sensor. The payload will also be able to compress the images as required by the bus to meet the tight data budgets of a mission beyond Earth orbit. For final integrated system testing the MGSE will provide a stable optics platform and a thermal environment representative of space conditions. Phoenix will provide the raw images, health and status for all systems, and the measured angular rate of the target to the simulated bus. A shaft encoder on the test target motor provides the actual rotation rate of the target, which can be used to compute the actual angular rate of the target as observed from the distance of the target. The optics adapter allows the angular size of the test target to be varied without changing the rest of the test setup. Preliminary analysis indicates that the asteroid 101955-Bennu as observed from 100 km could be represented by a ping-pong ball coated in coarse sand observed from 8m and rotating about its center at 0.43 milliradians/s. While the actual test may not use this test setup this analysis shows that a representative test target and test distance are achievable.

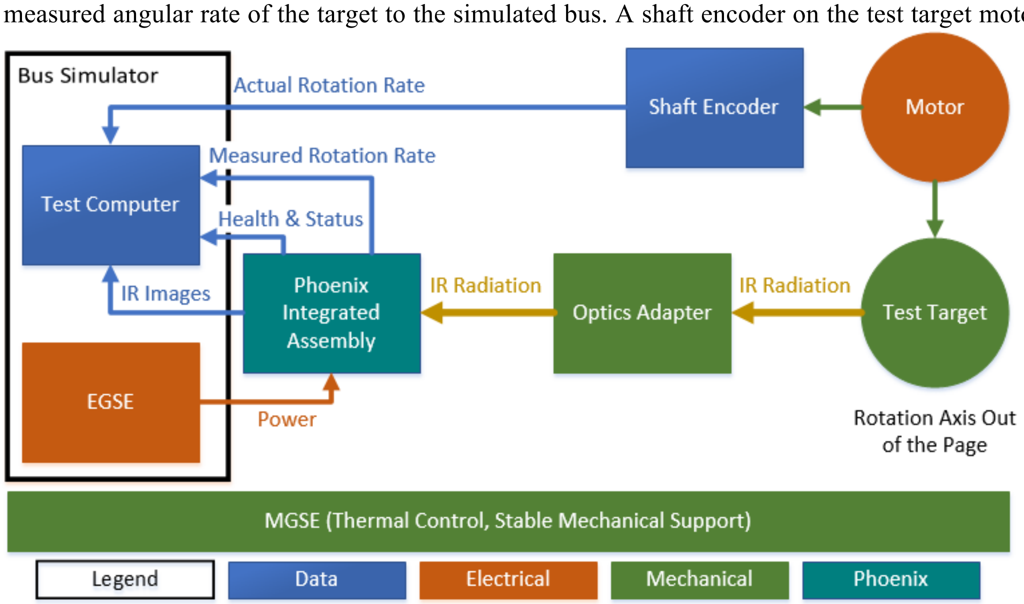

Figure 4: Phoenix Concept of Operations and Integrated System Test

4.4 Phoenix Payload Functional Block Diagram (FBD)

The Phoenix payload, as illustrated in Figure 5, 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.

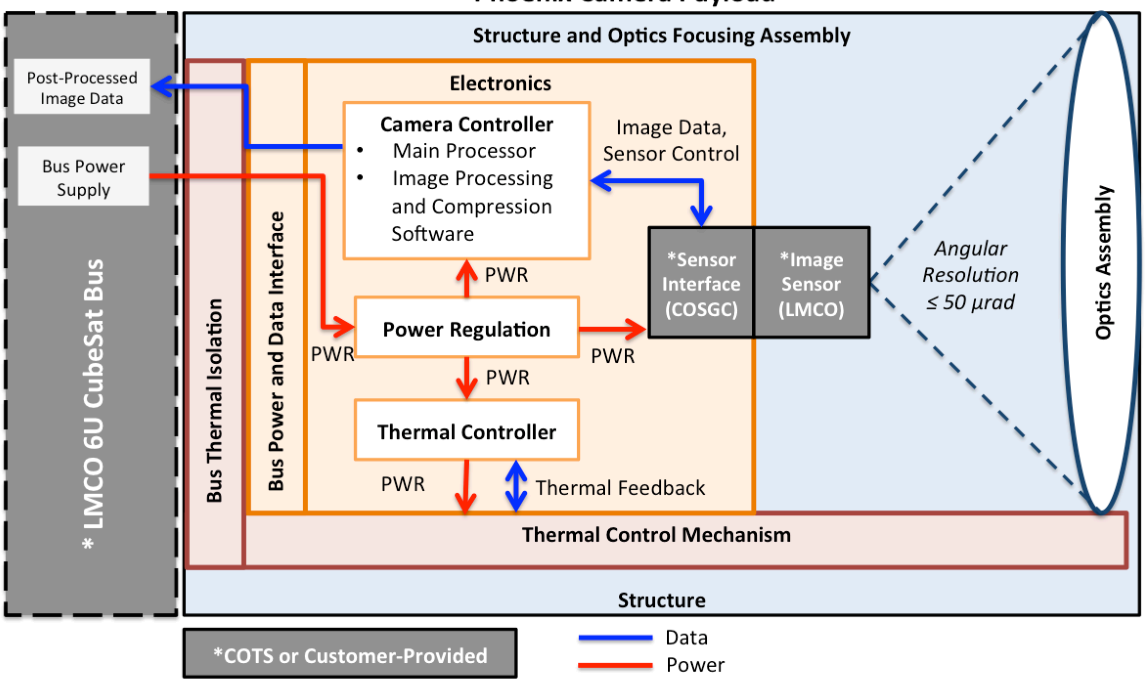

Figure 5: Phoenix Functional Block Diagram showing all major camera systems.

5.0 Critical Project Elements

Table 5: Critical Project Elements and Descriptions

#	CPE	Description
		Technical CPEs
T1	Machining Optics Support Structure	Potential for high-tolerance, delicate components and/or difficult materials.
T2	Design of IR Optics Assembly	Must fit in very constrained 2U form factor and provide angular resolution and FOV properties.
T3	Thermal Control Mechanism	IR Sensor (and possibly optics) must be cooled with passive and/or active mechanisms that fit in < 2U form factor
T4	Rate-determination and Image Processing Software	Extensive design work required, critical to Level 2 success.
		Logistical CPEs
L1	IR Sensor Procurement (LMCO nBn sensor or alternative)	High-resolution, high-temperature IR Sensor required. Some concern with procurement and project time constraints. Reliant on Customer/3rd Party.
L2	Sensor Interface Procurement and Documentation (COSGC)	Use of nBn sensor reliant of obtaining non-proprietary interface board from Customer/3rd party.
L3	Lead time to obtain materials or solutions for optics and thermal components	Custom or high-tolerance parts tend to have long lead times that can delay the project schedule.
L4	Liquid Nitrogen procurement and setup.	LN_2 will likely be required to cool testing targets and equipment. Special procurement and handling procedures required.
		Financial CPEs
F1	Budget to purchase COTS or Custom Optics Assembly.	High quality or non-standard size optics can be cost-prohibitive.

6.0 Team Skills and Interests

Table 6: Team Member Skills, Interests, and Relevant CPEs

Name	Major	Skills/Interests	CPEs
J. Broadway	ASEN	Structure analysis and CAD design, extensive machining experience (CNC, mills, lathes, saws, 3D-Printing, and drills), millimeter-wavelength microwave optics bench testing.	T1, T2, L3
J. Ellison	EE	Advanced embedded systems, PCB design, assembly, and testing, vacuum systems, power electronics, machining experience, and systems engineering.	T3, T4, L2, L4
T. Hardon	ASEN	Program management experience, including design reviews, leading meetings, and communicating with mentors. Satellite mission operations, STK modeling, and data analysis. Interest in EMC/EMI Analysis.	F1, L1, L3, T3
F. Hinckley	ASEN	Test design and execution, model validation, mechanical and electrical test fixture design, PCB design and testing. Machining experience.	T1, T2, L2, L4
B. Hogan	ASEN	Thermal modeling (via Thermal Desktop) for multiple satellites, setup and conduction of thermal vacuum testing. Machining experience and interest in structure design.	T1, T3, L4
G. Massone	ASEN mCSCI	Experience with project management and systems engineering, including requirement flowdown/verification, concept of operations, budgets, design reviews, integrated system testing. Interest in thermal control mechanisms and electrical systems design/testing.	T3, L1, L3, F1
C. Parker	CSCI ECEE	Extensive embedded software architecture, algorithm design, applicable languages experience (C/C++, python), and testing. Interest in DSP, some experience from ECEE course.	T4, L2
L. Smith	ECEE	Strong background in FPGAs, embedded systems software, Matlab Simulink/System Generator for design analysis and synthesis, DSP. Actively completing software engineering certificate.	T4, L2
J. Stewart	ECEE	Extensive experience in optics design, simulation, construction, and testing, data filter programming in Matlab and C, some experience with high-efficiency voltage converters, FPGA programming, thermal control systems	T1, T2, T3, L1

7.0 Resources

Table 7: Resources required for each CPE

CPE	Resources Required	Anticipated Sources
	Technical CPEs	
T1	• Machine Shop • Composites lab • Laser Cutter and 3D Printer (for prototyping or test setup)	• Aerospace shops • ITLL facilities
T2	• ASAP and APEX plug-in for Solidworks • Optics Mentorship	• ASAP license (COSGC) • LMCO Mentors, Faculty Mentors
T3	• Thermal Desktop • Thermal Mentorship	• Thermal Desktop (COSGC) • LMCO Mentors, Faculty Mentors
T4	• Time, Software Mentorship	• LMCO ADCS Mentors, Faculty Mentors
	Logistical CPEs	
L1	• nBn MWIR Detector	• LMCO Santa Barbara Focalplane
L2	• Non-Proprietary Interface Board and ICD	• COSGC
L3	• Reliable Optics Supplier • Schedule Buffer	• Edmund Optics or Similar
L4	• Supplier • Safety training	• TBD
	Financial CPEs	
F1	• Sufficient funding	• Customer funding

8.0 References

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