Payload Concept Proposal

NOVA

Natural **O**bservation of **V**olcanic **A**ctivity

"To Boldly Go Where No Man Has Gone Before…"

Good Hope High School

Team #1

Interior & **C**omposition for **E**nceladus **E**xploration Mission

Spring 2019

1.0 Introduction

Team NOVA was challenged by UAH to design an autonomous science payload that would complement their Interior & Composition for Enceladus Exploration (ICEE) Mission. The team also had to determine the objective of the payload. In order to accomplish this, the team implemented the engineering design process and communicated with UAH engineering students and the review board. At the same time, the team conducted STEM events within the community to educate the community about the InSPIRESS program, NASA and space exploration.

Team NOVA is a group of fourteen students attending a rural public school in Alabama. The team consists of six seniors, four juniors and four sophomores. Of the fourteen students, eleven participated in last year's mission to the moon, five are taking physics, five are taking Dual Calculus and three are taking Dual Precalculus. NOVA only met as a class on Wednesdays. Most of the work was completed after school and via the use of shared documents on Google Drive.

NOVA determined the team leadership and divided into two groups - Design and ACE. Those on the design team and the chief engineers were tasked to determine the mission objectives and to design a payload that would survive the environment on Enceladus. The ACE team (Activities for Community Engagement) and the project managers were responsible for educating the community about Enceladus by conducting various hands-on activities and presentations to raise excitement for STEM.

The team chose NOVA, which stands for Natural Observation of Volcanic Activity for the team name, and the team slogan is "To Boldly Go Where No Man Has Gone Before." This slogan was chosen because the team consists of members who are fascinated with *Star Trek*. Also, the team mission is to take a "Selfie" of the inside of a cryovolcano -- a task that has never been achieved.

NOVA's mission is to travel to Enceladus on UAH's Lander, *Caesar*. *Caesar* will be on UAH's Orbiter, *Cleopatra*. Once *Cleopatra* reaches Enceladus, it will travel in a polar orbit at 100 km above the surface. *Caesar* will deploy from *Cleopatra* and travel to a cryovolcano at Alexandria Sulci, the outermost Tiger Stripe at the South Pole. After *Caesar* safely lands, it will be operational for 90 days.

The payload for team NOVA is named "*Bullet Bill*". NOVA decided to use two payloads to increase the likelihood of the mission's success. NOVA's payloads will deploy from *Caesar*. As the payloads are falling through the atmosphere and cryovolcano, they will take images of the cryovolcano using the hyperspectral imager and also collect data such as the chemical composition of the plumes, the change in temperature and the payloads' location within the volcano using a mass spectrometer, inertial mass unit (IMU), thermocouple, transceiver, processor, antenna and space battery.

2.0 Science Objective and Instrumentation

The design team decided on three potential missions that would complement ICEE. NOVA used the Science Objective Trade Study provided by UAH to determine which one of the three potential objectives would be chosen for the mission. The first potential mission was to study Saturn's rings. The second potential mission was to study the surface of Enceladus. The third potential mission was to take a picture of the inside of a cryovolcano.

UAH determined the eight Figure of Merits (FOM), as well as the weight of each FOM on the Science Objective Trade Study. The design team used a rating scale of 1, 3 and 9 (1- least desired; 9 most desired) to rate each FOM. Since the team was very interested in taking a "Selfie" inside the cryovolcano, it was given a 9 for "Interest of the Team". The values for "Interest of the Team", "Understood by the Public" and "Creates Excitement in the Public" were the determining factors in the final decision. After completing the trade study and comparing the results, NOVA chose to study the inside of a cryovolcano.

Table 1. Science Objective Trade Study

FOM	Weight	Saturn's Rings		Enceladus' Surface		Cryovolcano	
		Raw Score	Weighted	Raw Score	Weighted	Raw Score	Weighted
Interest of Team	9	3	27	3	27	9	81
Applicability to Other Science Fields	1	9	9	9	9	1	1
Mission Enhancement	1	1	1	9	9	9	9
Measurement Method	9	9	81	9	81	1	9
Understood by Public	9	3	27	1	9	9	81
Creates Excitement in Public	3	9	27	3	9	9	27
Ramification of Answer	3	9	27	9	27	3	9
Justifiability	1	3	3	9	9	9	9
Total			**202**		**180**		**226**

The primary science objective is to take a "Selfie" of the inside of a cryovolcano located at Alexandria Sulci, which is located at the South Pole of Enceladus. This is important because there has never been an image taken of the inside of a cryovolcano. The team was interested in doing this because it has not been done. Therefore, this would be a significant scientific observation.

The second objective is to measure the chemical composition of the ejecta from a cryovolcano. Scientists believe that there is an ocean underneath the surface. The composition of the ejecta could show the composition of the ocean. If the composition of the ejecta is CHNOPS (carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur), this combination of elements implies that Enceladus could support life.

The third objective is to measure the temperature changes within the cryovolcano and the location of the payload as it descends within the volcano. Mapping the changes in temperature as the position changes within a cryovolcano is also noteworthy because it has never been measured.

Table 2. Science Traceability Matrix

Science Objective	Measurement Objective	Measurement Requirement	Instrument Selected
Cryovolcano Image	Picture	Clear picture Survive initial entry Directionality	Hyperspectral Imager
Composition of Cryovolcano	CHNOPS	Take good samples Survive initial entry	Mass Spectrometer
Temperature	Temperature changes within cryovolcano	Take accurate readings Survive initial entry	Thermocouple
Position	Acceleration	Take accurate readings Survive initial entry	IMU

Table 3. Instrument Requirements

Instrument	Mass (kg)	Power (W)	Data Rate (Mbps)	Dimensions (cm)	Lifetime (min)	Frequency	Duration (min)
Hyperspectral Imager	2.00	5.0	10.240 per image	10 x 10 x 10	5	1 min	1/6
Mass Spectrometer	0.230	1.5	22.4	0.45 x 0.50 x 0.80	15	Continuous	15
Thermocouple	0.001	NA	1×10^{-4}	0.2 x 5.0	15	Continuous	15
IMU	0.013	0.22	0.160	2.2 x 2.4 x 0.3	15	Continuous	15

Table 4. Support Equipment

Component	Mass (kg)	Power (W)	Data Rate	Other Technical Specifications
On Board Computer	0.094	0.4	2 x 2 GB	96 x 90 x 12.4 mm; ISIS On Board Computer, 400 MHz, ARM9 Processor
Transceiver	0.085	1.7	Up to 9600 bps downlink; up to 1200 bps uplink	96 x 90 x 15 mm; ISIS VHF/UHF Duplex Transceiver
Antenna	0.100	0.02	(See above)	1 x 98 mm; Cubesatshop.com Deployable Antenna System
Batteries	0.012	NA	NA	8.0 x 42 mm; Mass calculated based on power requirements

3.0 Payload Design Requirements

Before designing the payloads, NOVA was given several requirements from UAH. The first set of requirements is the project requirements. The InSPIRESS program to ensure efficiency and safety for the projects involved in the ICEE mission defined these. The requirements are as follows: 1. The payload must not exceed 10 kg. 2. The payload must fit within a 44 cm x 24 cm x 28 cm volume. 3. The payload must survive the journey to Enceladus and its environment. 4. The payload cannot cause harm to the UAH spacecraft. 5. The payload must complete the mission within the allotted time frame.

The second set of requirements is called functional requirements. There are six functional requirements: 1. Deploy from the UAH spacecraft. 2. House and contain the payloads and the instruments. 3. Provide power. 4. Collect data. 5. Analyze data. 6. Transmit the data to the Lander, *Caesar*.

The third set of requirements concerns the environment. The payloads will be subjected to ejecta from the cryovolcano and a surface temperature of -201°. The temperature of the ejecta is -106°. The payloads must survive the environment on Enceladus, especially the ejecta since it is erupting at 200 kg/s.

4.0 Payload Alternatives

The design team divided into groups and developed three alternative designs for the payloads. Then, as a whole, the design team discussed the advantages and disadvantages of each design. Initially, all three concepts used carbon fiber, which has a density of 1.75 g/cm^3, and aerogel to house the instruments. Aerogel will act as an insulator and will protect the instruments. The only difference in the designs is the shape of the housing.

Each concept is housed in a 34 cm muzzle and will be launched from *Caesar* using pressurized helium provided by UAH at a launch angle of 75°. Once deployed, space batteries will provide power. Each concept is designed to take "Selfies", measure temperature changes, and determine the chemical composition and position changes while traveling through the cryovolcano. The data will be collected and processed with the onboard processor and transmitted to *Caesar* via the transceiver and antenna.

Concept 1: *Bullet Bill*

NOVA's first concept was named *Bullet Bill* because it is shaped like a bullet. The radius of the probe is 7.8 cm and the height of the cylinder base is 9.0 cm. A positive feature of *Bullet Bill* is that it is more aerodynamic which will keep the hyperspectral imager more stable during flight. A negative feature is that images may be blurred due to its spin.

Concept 2: *Cryo-Sphere*

Concept 2 utilized a spherical shape with a radius of 9.0 cm. A positive feature of *Cryo-Sphere* is that a sphere is remarkably structurally sound. A negative feature is that the hyperspectral imager will be rotated more and the images could be blurry due to the tumbling effect of the sphere.

Concept 3: *Freezie-Cheese*

Since the main goal of the mission is to take a "Selfie," NOVA named the third concept *Freezie-Cheese*, "*Cheese*" because of taking a picture and "*Freezie*" because of the temperature on Enceladus. Concept 3 employed an odd shape that resembles a wedge of cheese. A positive advantage of this design is that it may keep the imager more stable. However, a negative aspect is that its shape will not allow a perfect fit within the muzzle.

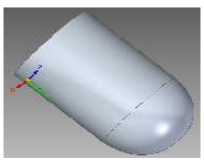

Figure 1. *Bullet Bill*

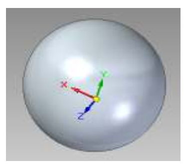

Figure 2. *Cryo-Sphere*

Figure 3. *Freezie-Cheese*

5.0 Concept Selection Trade Study

To determine which of the three concepts for the payloads would be the most efficient, team NOVA developed figures of merit (FOM) for each concept. UAH gave the team seven FOMs and team NOVA developed three additional FOMs - 1. Team Interest, 2. Spin Stability, and 3. Durability. NOVA assigned each FOM a 1, 3, or 9 depending on its importance to the success of the mission with 9 being the most favorable and 1 being the least favorable.

The team decided that achieving the "Science Objective", meeting the "Project Requirements", having the least "Design Complexity" and the "Likelihood of Mission Success" are most important to the success of the mission and assigned a weight of 9 to each. "Science Mass Ratio", "ConOps Complexity", "Spin Stability" and "Durability" were determined to be less important and assigned a weight of 3. The remaining FOMs were determined to be least important and assigned a weight of 1. The arrows up indicate most desired and the arrows down indicate least desired.

Table 5. Payload Concept Selection Trade Study

FOM	Weight	*Bullet Bill*		*Cryo-Sphere*		*Freezie-Cheese*	
		Raw Score	Weight	Raw Score	Weight	Raw Score	Weight
Science Objective ↑	9	9	81	3	27	3	27
Likelihood Project Requirement ↑	9	9	81	1	9	3	27
Science Mass Ratio ↑	3	3	9	9	27	3	9

Design Complexity ↓	9	3	27	1	9	1	9
ConOps Complexity ↓	3	3	9	1	3	1	3
Likelihood Mission Success ↑	9	9	81	1	9	1	9
Manufacturability ↑	1	9	9	9	9	9	9
Team Interest ↑	9	9	9	3	27	3	27
Spin Stability ↑	3	9	27	1	3	1	3
Durability ↑	3	3	9	9	27	3	9
Total			**414**		**150**		**132**

6.0 Payload Concept of Operations

The Concept of Operations (ConOps) is a series of steps the payloads will execute in order to perform a the mission. The Decision Analysis determines the priorities of the payloads. The ConOps paints a clear picture as to what the payload should do as well as how and when it should complete a task. *Bullet Bill's* ConOps includes four phases.

During Phase 1, *Bullet Bill* will travel on UAH's Lander, *Caesar* that will be transported on UAH's Orbiter, *Cleopatra*. *Cleopatra* will orbit around Saturn for two Earth years. After studying Saturn, *Cleopatra* will travel to Enceladus and orbit for two more Earth years at a 100 km orbit. *Caesar* will deploy from *Cleopatra* and land at the south pole of Enceladus within 5 km from Alexandria Sulci. Alexandria Sulci is one of the Tiger Stripes and contains numerous cryovolcanoes. The payloads (*Bullet Bill*) will be housed in two muzzles, similar to a double barrel gun.

During Phase 2, the first *Bullet Bill* will deploy from *Caesar* at 75°. NOVA chose 75° to allow for a longer hang time so the imager will have time to take more images. The initial velocity of the payloads will be 35 m/s. After five minutes, the second payload will deploy from its muzzle at the same angle of the first payload.

After deploying, Phase 3 will begin. The payloads will begin collecting data concerning chemical composition of the ejecta, temperature changes within the cryovolcano, as well as changes in position and acceleration. After the payloads reach the maximum height of 5.055 km, the imager will begin taking "Selfies" every minute for 10 seconds.

During the final phase, the payloads will fall through a cryovolcano at Alexandria Sulci. They will continue collecting and transmitting data to *Caesar*. Eventually, the payloads will crash without causing harm to UAH's Lander, *Caesar*.

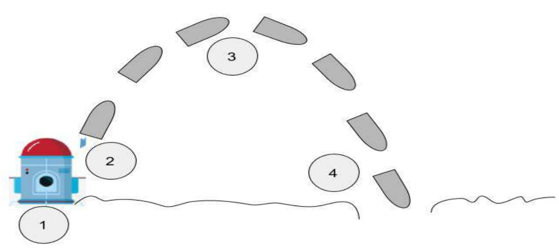

Figure 4. Concept of Operations

7.0 Engineering Analysis

The engineering analysis consisted of four phases: Initial Conditions, Deployment, Trajectory, and Ending conditions.

Initial Conditions

Bullet Bill will travel to Enceladus on-board UAH's Lander, *Caesar*. Once landing *Caesar* will be stationary. NOVA assumed that *Caesar* will land near the South Pole and will be within 5 km of Alexandria Sulci. Alexandria Sulci is the outermost Tiger Stripe and houses cryovolcanoes. The dimensions of Alexandria Sulci are 2 km wide, 0.5 km deep and 35 km long.

Deployment

Initially, NOVA planned to deploy from UAH's Orbiter, *Cleopatra*. However, the chief engineer found the velocity of the payloads to be very high. Consequently, the design team decided to complete a Deployment Trade Study to determine the best method for deployment. NOVA considered three methods of deployment: 1. Orbiter - Downward, 2. Orbiter - Backward, 3. Lander. The design team developed three FOMs - 1. Clearest Images, 2. Increase Likelihood of Surviving, and 3. Better Accuracy. The team assigned each FOM a 1, 3, or 9 depending on its importance to the success of the mission with 9 being the most favorable and 1 being the least favorable. The team chose to launch from the Lander, *Caesar*, since this would provide a lower velocity and increase the likelihood of producing a clearer image.

Table 6. Deployment Trade Study

FOM	Weight	Orbiter - Downward		Orbiter - Backward		Lander	
		Raw Score	Weight	Raw Score	Weight	Raw Score	Weight
Clearest Images ↑	9	1	9	1	9	9	81
Increase Likelihood of Surviving ↑	3	3	9	3	9	1	3
Better Accuracy ↑	9	3	27	3	27	9	81
Total			**45**		**45**		**165**

For deployment, NOVA made several assumptions. First, there will be constant pressure and acceleration inside the deployment barrel. Second, friction will be negligible inside the barrels. Third, there will be a perfect fit. Fourth, there will be rifling in the barrel to help prevent the payloads from tumbling and to maintain their orientation.

The team decided to launch at 75^o for a longer time of flight so the imager will be able to take multiple images as it descends into the cryovolcano. Since *Caesar* will be 5 km away and the launch angle is 75^o, the payloads will need a muzzle velocity of 35 m/s to travel 5.057 km (the Tiger Stripe is 2 km wide). The muzzle is 34 cm long with an outside radius of 16.7 cm; the inside radius is 15.7 cm. The mass of one muzzle is 1.51 kg. To obtain a muzzle velocity of 35 m/s, NOVA will use 378 kPa (54.96 psi) of pressurized helium, which will be provided by UAH.

The dimensions of the hyperspectral imager (10 cm x 10 cm x 10 cm) determined the size of the housing. The payload is composed of a hollow right cylinder composed of carbon fiber and a half sphere nose cone made of plexiglass. Carbon fiber has a density of 1.75 g/cm^3 and plexiglass has a density of 1.18 g/cm^3. The total volume of the instruments is 1241.08 cm^3 which means the inside volume of the payload has to be at least that amount. The inside radius of the cylinder is 7.3 cm and the height is 8.5 cm. The outside dimensions are 9.0 cm with a radius of 7.8 cm. The inside radius of the nose cone is 7.3 cm and the outside radius is 7.8 cm. The total mass for one housing is 0.637 kg. Since the temperature of Enceladus is -201^{o}C and the temperature of the ejecta is -106^{o}C, the team decided to use aerogel to insulate and to protect the instruments. The mass of the aerogel is 0.019 kg.

Trajectory

NOVA assumed gravity will be constant, there will be no drag, *Caesar* will be 5 km from Alexandria Sulci and the payloads will enter a cryovolcano. The launch velocity of each payload is 35 m/s at 75°. The initial y-velocity will be 33.8 m/s and the x-velocity will be 9.06 m/s. The total flight time is 598.36 s for each payload. The range for each payload will be 5.057 km and the maximum height will be 5.055 km.

Since the depth of the Alexandria Sulci is 0.5 km, it will take about 15 s to reach the bottom. Using the total time of the descent, NOVA calculated the battery mass by multiplying the power and operational time of each instrument, adding those and then dividing by the battery specific mass 400Whr/kg. The calculated mass is 0.003 kg. NOVA decided to use a mass of 0.010 kg to ensure there will be enough power to operate the instruments.

After deployment, the mass spectrometer, IMU, and thermocouple will begin taking measurements. After reaching the maximum height of 5.055 km, the imaging system will begin taking images every minute for 10 seconds. The data will be collected by the on-board processor and then immediately be sent to the Lander via the transceiver and antenna.

Ending Conditions

NOVA made several assumptions concerning ending conditions. The team assumed gravity will be constant, the payloads will enter a cryovolcano and the payloads will not encounter too much ejecta from the cryovolcano. By using two payloads, this will increase the probability of taking a clear image during the mission. As long as the data is sent immediately, the payload does not have to survive impact.

8.0 Final Design

The final design of NOVA's mission is essentially Concept 1, *Bullet Bill*; however, the team made a few changes that will greatly enhance the mission goal of taking a "Selfie". Instead of using only carbon fiber for the housing, NOVA decided to use plexiglass in the nose cone. This will increase the likelihood that the hyperspectral imager will take clear images of the cryovolcano.

The cross-section of the payload in Figure 5 below shows the internal instruments and their placement within the carbon fiber shell. The hyperspectral imager is placed at the front of the payload with a plexiglass, spherical shield to act as clear yet sturdy lens. On one side, a mass spectrometer is placed directly on the inside of the payload with a very size-insignificant scoop running to the external side of the plexiglass lens. This scoop will gather samples from the ejecta during the payloads' descent. On the other side of the imager is a thermocouple running through a small, insulated and sealed hole to the outside. The thermocouple will receive more accurate readings this way. As seen in Figure 5, the IMU, processor, and transceiver are placed behind the imager and are insulated with aerogel.

In terms of the entire mission, there will be two *Bullet Bill* payloads and two launching muzzles in the fashion of a double barrel gun. The payloads will be launched from *Caesar* five minutes apart at the same velocity and angle using pressurized helium provided by UAH. The payloads will travel in a parabolic trajectory towards the cryovolcano.

By taking measurements of the chemical composition, the payloads will determine if there is a possibility of life by looking for carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur. This combination of elements implies that Enceladus could support life. The payloads will also collect data concerning temperature, acceleration and position changes. Mapping changes in temperature as the position changes within a cryovolcano is also noteworthy because it has never been measured. After reaching the maximum height of the trajectory, the hyperspectral imager inside each payload will begin taking "Selfies" every minute for 10 seconds. This is most important aspect of NOVA's mission because there has never been an image taken inside a cryovolcano. As soon as the data is collected and processed, it will be sent to *Caesar* via the transceiver and antenna.

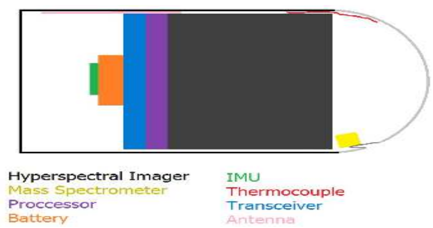

Figure 5. Cross Section of Final Design

Table 7. Final Design Mass Table

Function	Components (2)	Mass (kg) (2)
Deploy	*Bullet Blaster*	3.028
Measure	IMU, Hyperspectral Imager, Mass Spectrometer, Thermocouple	4.488
Collect Data	Processor	0.188
Provide Power	Battery	0.020
Send Data	Transceiver & Antenna	0.370
House/Contain Payload	*Bullet Bill* and Aerogel	1.312
	Total	**9.406**

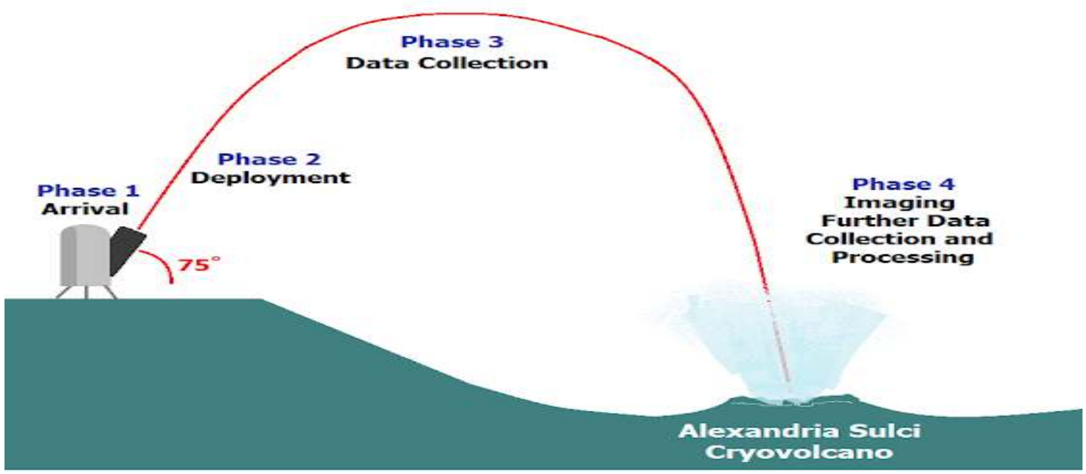

Figure 6. NOVA's Mission

Table 7. NOVA's Payload Requirement Compliance

Requirement	Verification	Compliance
Mass ≤ 10 kg	9.198 kg	✔
Volume of 44 cm x 24 cm x 28 cm	33.4 cm x 34 cm	✔
Survives Environment	Carbon Fiber, Plexiglass	✔
Deploy	Lander (*Caesar*)	✔
Not Harm Spacecraft	Pressurized Helium	✔
Collect Data	Hyperspectral Imager, Mass Spectrometer, IMU, Thermocouple	✔
Complete Mission within Timeframe	15 min < 90 days	✔