PROJECT HURRISAT

ILLINOIS INSTITUTE OF TECHNOLOGY

ARMOUR COLLEGE OF ENGINEERING

MMAE-412 SPACECRAFT DESIGN

THE NASA CSLI INITIATIVE

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Published on *March* 11th*, 2022*

Produced via LaTeX, Inc U.S.A.
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Contents

1 Introduction

The purpose of this mission report is to provide initial concept design for a cubesat project in response to NASA's CSLI program. NASA's CubeSat Launch Initiative is intended to expand U.S. interest in Science, Technology, Engineering, and Mathematics (STEM), thereby developing future scientists, engineers, and technologists [10]. This proposed Cubesat designated as "HurriSat" is a low-earth orbit (LEO) weather sat intended to study, monitor and track down hurricanes in the U.S south east region. HurriSat's mission relevance is in accordance with the first objective of NASA's Strategic plan listed in sections 1.1 and 1.2. It's first goal is to study the causes and effects of severe space weather events to allow for preparation in a timely manner [8]. Furthermore, HurriSat is designed to transfer, receive, and process various atmospheric data for scientific and educational purposes. It will be utilized by almost all governmental and commercial weather organizations in the years to come.

This report provides a refined look at the mission analysis and concept of operations for HurriSat. The mission goals and objectives are laid out, and the analysis plan is discussed in section 2. Meanwhile, section 3 takes a scientific approach towards the concept of operations. Here the criteria from the NASA CLSI missions are analyzed and turned into either requirements or constraints. Alternate plans for the mission are also discussed. Section 4 discusses the flow from mission to subsystem requirements. It also provides a brief evaluation for each subsystem and its position in the mission flow plan according to the project phase.

1.1 Background in Hurricanes

Hurricanes are among the most destructive weather phenomena that are caused by strong winds and surge effects. They can be fatal, and usually cause destruction of infrastructures. In 2012, Hurricane Sandy led to about $65 billion damage in the northeastern coastal region of the USA and in the Ontario Province of Canada [3]. The severity of the consequences, associates with hurricane activity, has motivated several investigations, attempting to forecast hurricane activity in both near and distant future. Hurricanes are primarily classified based on their speed as seen in Table 1.1, with Category 5 being the most severe. This serves as one of the many reasons that led us bring forward project HurriSat to NASA and its affiliates. Therefore, HurriSat's sole mission will be dedicated to tracking, monitoring and possibly avoiding fatal devastation caused by hurricanes. Additionally, HurriSat will be equipped with high-tech cameras and faster processor to provide accurate weather data with little to zero maintenance cost.

Category	Speed (mph)	Severity
1	$74 - 95$	Minimal damage
2	$96 - 110$	Considerable damage
3	$111 - 129$	Extreme damage
4	$130 - 156$	Devastating
5	> 156	Catastrophic

Table 1.1 – Hurricane Severity

1.2 Stakeholders and Customers

The stake holders partly consist of with an interest with the enterprise of NASA and its affiliates. They are divided into two main categories, Primary and Secondary as listed in Table 5.1. It may include those listed but not limited to:

Table 1.2 – Stakeholders

Primary Stakeholders	Secondary Stakeholders
National Weather Service	NASA
Federal Emergency Management Agency	NOAA
National Environmental Satellite	Department of Education
Department of Defense	Others: Public Safety, Health and Red cross

2 Mission Exploration

The mission of this project is to propose a Low Earth Orbit 6U sized Cubesat in order to track down the hurricanes across the South-Atlantic U.S. Region. The primary target coverage area is about 112,000 square miles across the South East-cost. This Cubesat should be able to track small to big size hurricanes across the given region. This is mainly achieved using high-tech dual cameras. It will try to collect the speed, impact area, changes in temperature, pressure, and air composition of earth's atmosphere for a given radius in miles. By doing so, it has to communicate and transmit data back and forth between local stations effectively. Furthermore, we must ensure the recorded data is shared with the outlined stakeholders and interested parties effectively.

2.1 Mission Objectives

Our primary and secondary mission objectives are as follows.

2.1.1 Primary Objectives

- Data recording (Wind speed, hurricane trajectory, impact radius) and analysis.
- Transmission of data to and from ground station up to 10 external entities.
- Cubesat autonomous tasking if necessary, and warning category level for immediate action.
- Navigation and monitoring hurricane impacted areas. Assessing damage on infrastructures to a certain degree.
- Updating locations using on board GPS or grounds station.

2.1.2 Secondary Objectives

- Recording relevant data (Temperature, Pressure, Humidity) for scientific study .
- Maintaining communication with weather stations every $15 - 20m$ minutes.
- Guidance and Navigation of hurricane free zones.

- Remote sensing capabilities and effective communication with nearby satellites to avoid debris and collision course.

2.2 Requirements and Constraints

2.2.1 Functional

- Performance: Provide images up to 100m resolution, get a 7 degree spread which results in a 200km signal diameter at 800km altitude.
- Responsiveness: Transmitting 24-bit color depth image to the ground station over a single bypass of 10-25 minutes.
- Coverage: ground coverage on this camera is $26x14km$. Compact and within budget.

2.2.2 Operational

- Duration: Will have a mission life of at least 15-20 years
- Availability: 12-hour maximum outage provided feasible space conditions.
- Reliable: Provided no external and uncontrolled space phenomenon.
- Data content: Images, location, relative speed, hurricane radius, impact area, atmospheric data, weather prediction and forecast.

Table 2.1 – Constraints

Internal	External
Project lifetime is only 3 month	Max weight is set at $20kg$ by NASA.
Team Structure and organisation	Budget is limited to $300,000usd$.
Material Availability and Choice (Covid-19)	Able to fit within the rocket launch pod.
Transmission data cap	Max size 12U (10cm x 10cm x 10cm).
Technology Gap	Deadline as per NASA CSLI Rubrics.

2.3 Mission Success Criteria

The success of this project depends on meeting the performance metrics and thereby achieving the goals mentioned in the mission statement. Table 2.1 indicates how those metrics will be for measured and whether the proposal holds true during testing phase.

Table 2.2 – Success Criteria

Target Objective	Success Measure	Control Method
$110,000^2$ miles Coverage	Utilizes a K-band antenna with dual Cameras over 7 degree spread for a 200km signal diameter	STK Simulation
Hurricane speed, and Impact radius	Live Transmission of 24-bit color depth image, with 100m resolution	Sentinel Toolbox
Damage Assessments and response	Transferring data up to 27 GHz, and keeping effective communication with the ground stations.	Analysis Sim
Weather temperature, pressure	Imaging and monitoring data from LIDAR, Temperature and Pressure Sensors.	QGIS Analysis

2.4 Analysis and Trade Studies

To ensure our project results in designing an effective and efficient cubesat, we have made a project plan to provide the best out put parameters in Figure 2.1. After initial mission definition the project is closely followed by trade studies. Numerous data for previous successful missions were collected firsthand. The Japanese XI [5] cubesat, the Freja [12] cubesat, and the Firesat from the Space mission and design [7] reference were used as a basis. Those projects solely match our functionality requirements for a 1U-12U cubesat. Figure 2.2(a) is the volume (density) of cubesats at various altitude. It shows 6U-sats are commonly used for a wide range of altitude. If HurriSat is to be equipped with a faster imaging cameras, and max transfer (bandwidth) frequency as shown in Figure 2.2(b), it will require high throughput (red-accent) power. The tradeoff is an increase in mass size as shown in Figure 2.2(c). The inclination distribution of cubesats is graphed in Figure 2.2(d) in order to provide some insight on satellite footprint with mass and altitude. Once we select the performance metrics, we use STK [1] software analysis to test the values in the simulation. After reading the feedback from the simulation; if the findings are feasible, we proceed to component design phase. If not, we go back to refine our mission definition and operational requirements. This is an agile project managing system where we select the performance parameters and perceive the coverage, operation orbit and bypass simultaneously to decide the best fit. This allows us to be flexible with the little time provided.

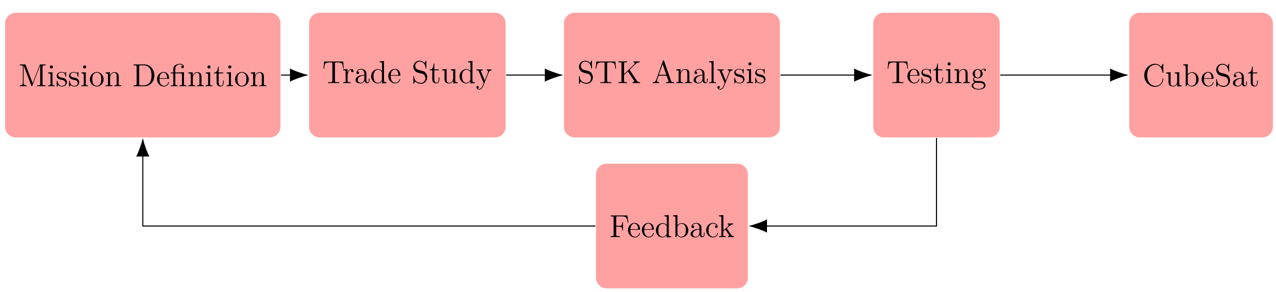
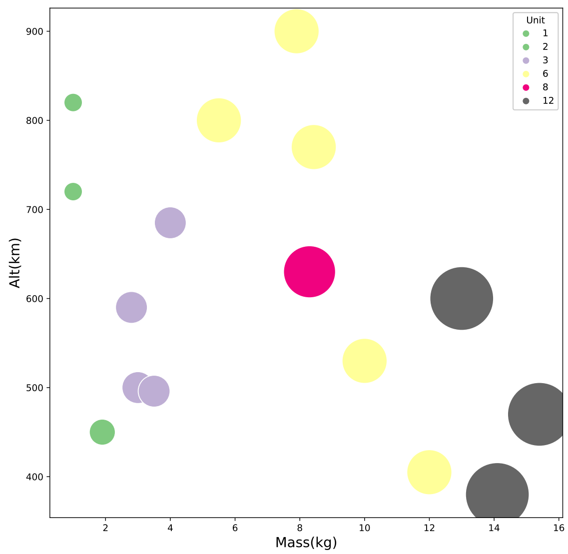


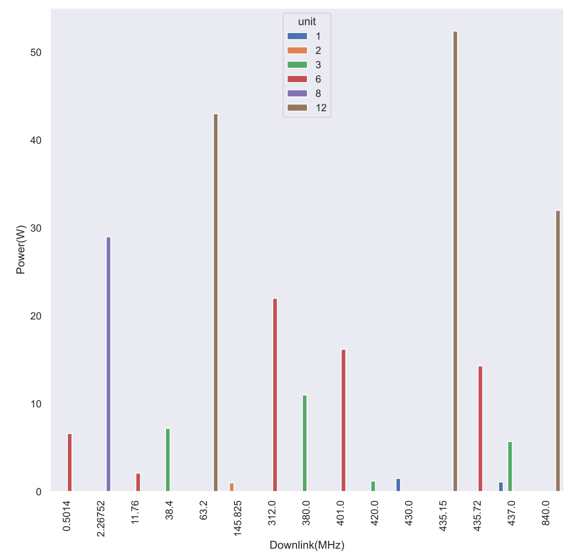
Figure 2.1 – Mission Analysis

2.5 Risk Assessment

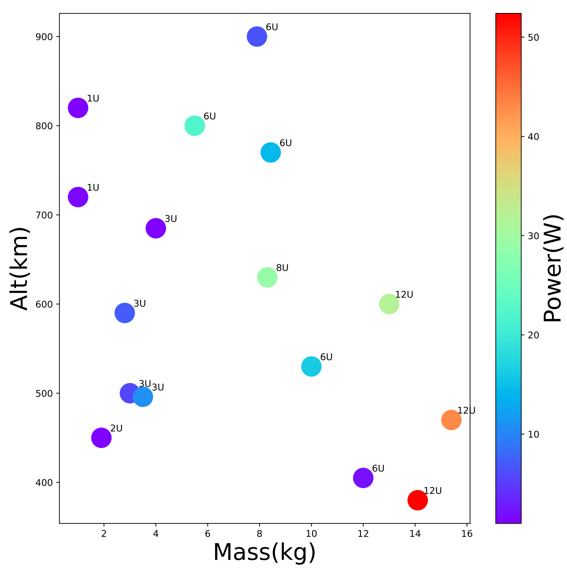
Risk assessment assures the stakeholders whether our cubesat is on track to be hazard free, secure, safe, and scientifically feasible. It is impossible to avoid risks completely. Thus, the team has provided a risk assessment definition in Table 2.3. Those definitions are basic guideline to help assessing the risks and provide some mitigation mechanisms. They are divided in to two sections: probability and severity. Probability is the likelihood of risk to occur, while severity is the effect of the risk. To determine the risk assessments a color grading scale is provided in Table 2.4. Bright red is a high probability and extremely severe. This risk will definitely hinder all types of operation and may even lead to complete failure of the mission. Green on the other hand is quite the opposite. There's is still risk but is either negligible or highly improbable.



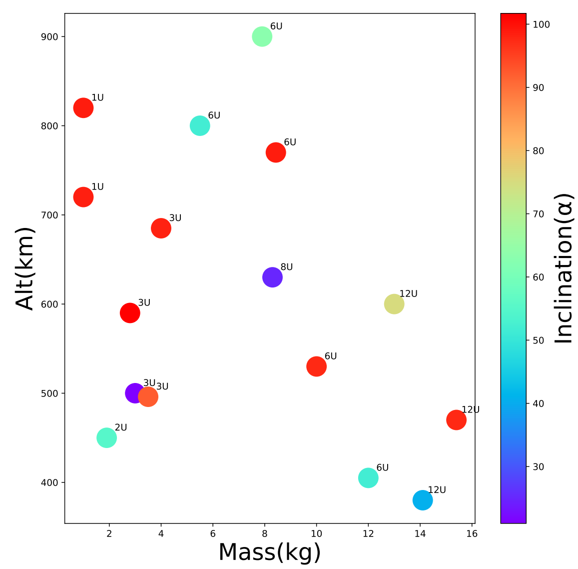
(a) Cubesat size scatter vs altitude.



(b) Downlink Freq over power per unit size.



(c) Power Loading



(d) Inclination

Figure 2.2 – Trade Studies

Table 2.5 is where we listed out every possible risk. While most of the risks are accounted for, there might still be an unforeseeable event due to radiation exposure or space debris. HurriSat will be utilizing its propulsion driven ADCS, using active software tracking to avoid debris. It will also feature a double wall bumper in the structures to sustain slight damage. Similarly, some parts of the IC transistors will have to be embedded with carbon nanotubes to resist radiation exposure.

Table 2.3 – Risk Definitions

Risk Probability	Description
Frequent	Consistent threat to mission. Requires deliberate and active planning.
Occasional	May occur a couple-three times.
Improbable	Highly unlikely to occur.

Risk Severity	Description
Catastrophic	Would cause complete mission failure. It's a no-go situation.
Major	Would cause significant complication to mission.
Minor	Would causes a minor hindrance to mission.
Negligible	Minimal effect on mission.

Table 2.4 – Risk Color-grading

		Risk Severity			
		Catastrophic (4)	Major (3)	Minor (2)	Negligible (1)
Risk Probability	Frequent (A)	A4	A3	A2	A1
	Occasional (B)	B4	B3	B2	B1
	Improbable (C)	C4	C3	C2	C1

Table 2.5 – Risk Assessment

Risk	**Risk Assessment**	**Hazard**	**Mitigation**
Pre Launch			
Environmental (Dust,Humidity, Weather)	A1	Hinder launch-day, minor damage to Cubesat	Controlled and designated-construction environment
Cost	B3	Financial Problems	Clear focus on fund acquisition
Transportation	A1	Damage to CubSat or team	Route Planning, safe access to traffic
Team injury	B1	Damage to team member and legal liability	Safe workspace guidelines
Technology Limitation	B1	Longer time and overhead	Mindful design
Post Launch			
Space Debris and Micrometeoroids	B4 to B2	Fatal destruction or damage of the Cubesat	Double Wall Bumper, Active space debris tracking software
Thermal Damage	A2	Electrical, mechanical component damage	Selecting the best Thermal resistant shield
Radiation Exposure	A3	Electronic systems, causing circuit damage or system shut downs	Transistors, IC's and circuits will be embedded with carbon nanotubes.
Foreign Satellites	C4	Longer time and overhead	Active tracking of other Satellites
Solar Flares	C3	Damage or destruction of CubSat	Active tracking of solar threats. Selective Solar flare resistant design, Course correction mechanisms.
Launch			
Acceleration	B2	Damage due to increasing drag and friction	Minimized induced drag, using thrusters and controllers
Mechanical Vibration	B3	Structural and payload damage	Incorporate shock observant if possible. Distribute static loads.
Acoustic Energy	B2	Structural damage	Use sound suppression system and pressurized leveling.

3 Concept of Operations

After analyzing STK and selecting parameters using trade studies, the stage is set for concept exploration and risk assessment. Our operation is closely dependent on the possible launch stages (see Figure (3.1). Launch sites for previous missions include Cape Canaveral Air Force Station,Pacific

Missile Range Facility, Kennedy Space Center, Mojave Air and Space Port, and Rocket Lab Launch Complex [11]. According to the NASA CubeSat 101 [9] the possible launch rockets are in Minotaur I or IV, Taurus XL, Falcon Heavy, Falcon 9, Atlas V, Delta II, or Electron. We chose the Kennedy Space Center (28.573°N and 80.649°W), for the safest and most reliable launch site in present day. This also determines the pre-launch budget. It is highly probable a NASA Rocket or NASA associated rocket will be used to launch the cubesat. Based on the findings from Space Flight [6] HurriSat is estimated to cost around $48 - 50k$ USD per unit excluding labor costs.

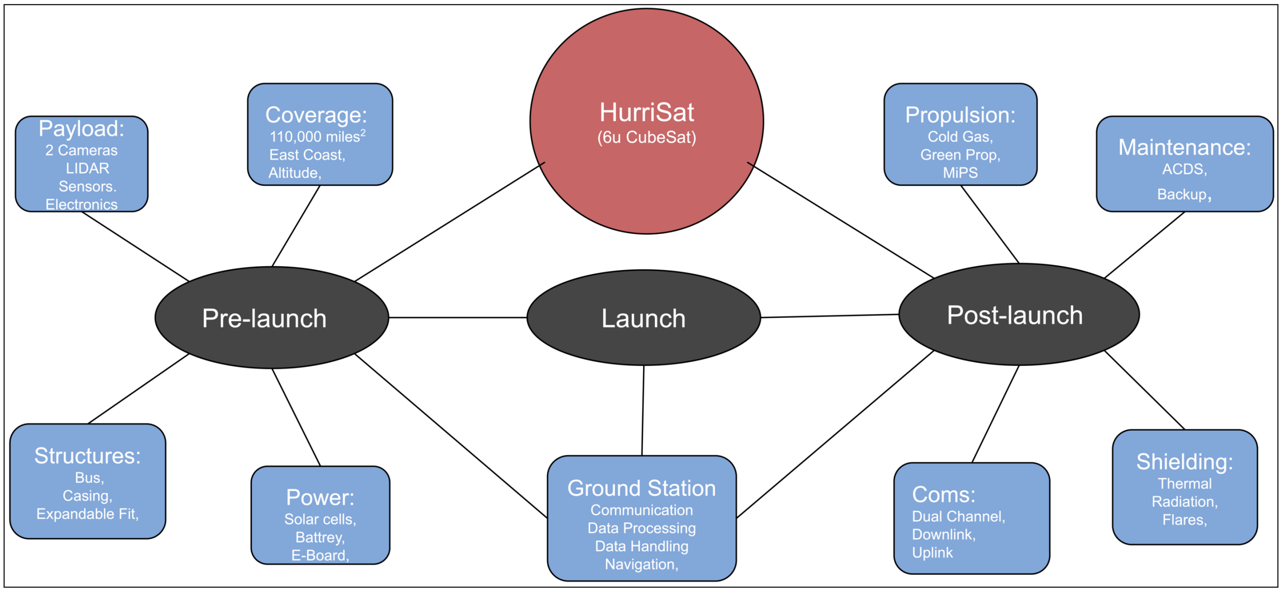


Figure 3.1 – Concept Diagram

3.1 Delta V design (Δv_{design})

The Delta V design required for the spacecraft was observed over a range of possible altitudes and inclination angles. The range was selected after a thorough research of LEO Cubesats that operate on the the optimum orbit. Table 3.1 shows the values with the best parameters listed. The intersection cell (highlighted cell in bright red) is our optimum $\Delta v_{design} = 11.729$. Selected choice of altitude is $h = 800km$, and the inclination angle is $\alpha = 35$.

Table 3.1 – ΔV_{design} in (km/s)

Altitude (km)	Inclination Angle $\alpha(degrees)$					
	30	32	35	40	45	52
800	11.709	11.717	11.729	11.752	11.778	11.817
850	11.836	11.843	11.856	11.879	11.904	11.943
900	11.958	11.966	11.978	12.001	12.026	12.065
950	12.077	12.084	12.097	12.119	12.144	12.183
1000	12.191	12.199	12.211	12.234	12.258	12.297
1100	12.410	12.418	12.430	12.452	12.476	12.514
1200	12.617	12.624	12.636	12.658	12.682	12.720

3.2 Mass sizing

The mass estimate for HurriSat is based on previous successful 6U cubesat missions and commercial data sheet for sub-components weights [2]. Table 3.2 shows our mass sizing, based on an initial payload mass. The payload is estimated to be approximately 3.1kg after trade studies. This includes dual high-tech cameras, LiDAR, IC electronics, and censors outlined in the payload section.

Subsystem	%Amount	Mass (kg)
Payload	30	3.100
Structure	11	1.137
Thermals	2	0.207
Power	17	1.757
TT&C	15	1.550
ADCS	8	0.827
Propulsion	17	1.757
10%Margin included		1.033
Total	100	11.367

Table 3.2 – Mass Sizing

4 Conceptual Approach

After selecting a configuration, the preliminary design phase aims to find the optimum design parameters that provide us the desired functionality. Our primary focus is to maximize field of view to track down the hurricane changes over a specified region. Numerous forecasting ways, trade studies, software analysis, and numerical solvers were utilized to appropriately size and compare the performance of various design configurations.

4.1 Payload

The payload comprises two visible spectrum imagers, a LIDAR sensor, both fixed in orientation on the spacecraft and a K-band Patch antenna. A signal transmission from the ground station or on board wind tracking software would provide the satellite with orientation requirements to pin point the camera and track the target area. Cameras and electronics weigh around 600 grams and the LIDAR weighs around $2.5kg$ bringing the total payload mass to $3.1kg$.

To achieve the ground resolution requirement of at least $10m/pixel$ the camera sensor has a resolution of $4112x2248pixels$ and a size of $3x2mm$ with a pixel size of $0.64\mu m$. Pixel size was selected based on the smallest available scale pixel technology considering technological gaps. Lens focal length was selected to equal $90mm$ to achieve a zoomed in image. With these specifications overall camera ground resolution is $6.5m/pixel$ which exceeds initial requirements[7]. Ground coverage on this camera is $26x14km$.

The second camera has an identical sensor behind a fisheye lens at a focal length of 1mm which results in a large half cone angle. Its purpose is to locate possible hurricane formations and providing the system with data to direct the focused camera and LIDAR at the phenomenon. It has a ground resolution of $584m/pixel$. Area coverage on this camera is $2400x1312km$ which meant that in specific cases, HurriSat can cover the entire target area with a single pass[11].

4.2 Communications Architecture

The satellite communication system will consist of a single patch antenna array with $66x66x11mm$ dimensions. The signal is set in the K-band at 27GHz frequency (at PSK modulation), meaning that the signal bandwidth will equal the data bandwidth. Given the wide signal spread of patch antennas, the satellite won't have to adjust its orientation to transmit data to the ground station. For a single image, the antenna is expected to transmit a $24-bit$ color depth to the ground station over a 10-minute period, with an overall power consumption of only $3.44mW$.

4.3 Structures

Structure configuration for HurriSat requires a lightweight material capable of withstanding environmental elements; such as aerodynamic, gravitational, and solar torques that could arise during liftoff and transonic periods. Endurosat[4] and ISISPACE[14] have cubesat structure designs that fulfill our requirements for this mission. Endurosat is made out of Aluminum 6082 with PC104 full compliance and an approximate mass of $850g$ having a simple modular design with dimensions of $100x227x366mm$. The ISISPACE cubesat structure weighs around 1100 g having a modular design with dimensions of $100x227x341mm$.

4.4 Propulsion

The spacecraft will use Green Monopropellant hot-gas cubesat propulsion for 5 - 6 U cubeSat with I_sp of $200sec$ or higher and total Impulse of 3320 N-Sec. ADN/AF-M315E propellants can be utilized to produce a thrust of $50mN$ to $1N$. The propulsion system is to be mounted on the two end of the cubeSat and can take up size of $0.5 - 1U$. Cold gas thrusters are utilized for vector thrust and attitude control (ADSC). The VACCO [14] Standard Micro-Propulsion System (MiPS) is considered for the cubeSat as a low-cost module with a complete set included for the propellant storage, pressurization, distribution, and control. It is a lightweight closed-loop system that is capable of producing a total Impulse of $44N - Sec$ for up to $880,000$ firings occupying only a space of about $0.3U$. This set of thrusters allows for spacecraft attitude control and change in velocity (ΔV) whilst carrying a non-toxic R134a propellant in an aluminum alloy housing. A smart controller within the system reduces re-entry hazard and increases control by utilizing the sensor suits within and closed-loop thrust vector control.

4.5 Power

The spacecraft will utilize multi solar cells across the face of the cubesat, to generate and store power during daylight periods of the orbit. The use of solar cells, as opposed to alternative power supplies such as fuel cells or radioisotopes, provides an extended mission life through a virtually unlimited fuel source [7]. For the solar cells, Indium Phosphide voltaic cells were chosen due to the extended time before 15% degradation compared to other types of voltaic cells. These cells also demonstrated excellent efficiency [7]. The total power requirement of the payload is estimated to be approximately $24W$, consisting of $20W$ for the LiDAR and IC, $1.5W$ for the cameras, and $2.5W$ for the temperature and pressure sensors. The lower power requirement for the LIDAR can reached through operation at reduced duty cycles [13].

4.6 Thermal

Since the internal instruments are assumed to not have an optimal operational temperature the optimal temperature of the battery will be targeted as $15°$ degrees Celsius. This can be done through a combination of surface finishes and internal heaters. For $35°$ inclination angle approximately $218 - 257\frac{w}{m^2}$ is expected for radiation interference. MLI (Multi-layer insulation) blanket can be used as insulation to minimize the effects of the radiation on the internal components [7].

5 Further Work

The next project phase will focus on detailed component design based on numbers listed in the summary Table 5.1. The goal is to aim for the safest and efficient spacecraft design possible. The analysis shows minimizing the payload whilst equipping it with a highly developed tech ensures the desired result. However, the tradeoff would mean a higher power generation, that includes the collecting and gathering data as well as transferring to ground stations. Our next step is going to solely focus on designing a feasible structure that supports and maintains the component parts.

Table 5.1 – Summary Table

Parameter	Value	Parameter	Value
Cubesat Size	6U	Delta V design	$11.729 km/s$
Altitude (h)	$800 km$	Estimated Payload	$3.100 kg$
Inclination (α)	$35 degrees$	Estimated Mass	$11.367 kg$
Launch Latitude (L_0)	$28.6 degrees$	Estimated Cost	$\$288,000 usd$

6 Conclusion

All listed findings of the HurriSat are subject to change provided there's evidence of additional information. Each component will be going under a detailed evaluation prior to design phase. The payload system will be modeled along with the support structure to verify its integrity. We will be conducting a full simulation of the launch mission to ensure expected performance goals are met. The HurriSat project is the overture for NASA's CSLI program. It will implement exceptional engineering design and manufacturing technology that will result in making a fully operational cubesat. HurriSat will be utilized to create a safe mode of tracking and monitoring Hurricanes for NASA in the near future. The administration will also be able to collect weather data in order to combat climate change the effect of global warming.

7 Appendix

7.1 List of Tables and Figures

7.2 Keywords

AF-M315E: Hydroxyl Ammonium Nitrate fuel/oxidizer blend
ADCS: Attitude Determination and Control System
ADN: Ammonium dinitramide
CSLI: Cubesat Launch Initiative
GPS: Global Positioning System
K-Band: a radio frequency band from 18 to 27 GHz
LiDAR: laser imaging, detection, and ranging
MLI: Multi-layer insulation
NASA: National Aeronautics and Space Administration
NESDIS: National Environmental Satellite, Data, and Information Service
NOAA: National Oceanic and Atmospheric Administration
NWPC: National Weather Prediction Center
NWS: National Weather Service
PSK: Phase-shift keying
STK: Space Mission Toolkit by AGI Solutions
TT&C: Telemetry, Tracking and Command

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