MMAE-412 SPACECRAFT DESIGN

Team-7 Midterm Report

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1 Introduction

The purpose of this mission report is to provide initial concept design for a Cubesat project proposed by the NASA 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]. The proposed Cubesat designated as "HurriSat" is a low-earth orbit (LEO) Cubesat that is capable of studying and monitoring hurricanes in the U.S region. This Cubesat'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 organisations in the years to come.

This report provides an in-depth look at the mission analysis and concept of operations for the cubesat. The mission goals and objectives are laid out and the analysis is discussed in section 2. Section 3 takes an in-depth 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, which can cause severe damage to structures and loss of human lives due to strong winds and surge effects. 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. The severity of the consequences, associates with hurricane activity, has motivated several investigations, attempting to forecast hurricane activity in both near and distant future [3]. So in order to track down the hurricanes we need to study the severity of the hurricanes first hand. They are primarily classified based on the their speed from Cat-1 to Cat-5 with being latter being catastrophic. As listed in the below we have the speed tells us the severity of the hurricane where by our cube sat sensors will immediately pick the signal and starts to broadcast it's path.

Table 1.1 – Hurricane Severity

Category	Speed(mph)	Damage
1	$74 - 95$	Minimal: Damage to building structures possible, primarily to un-anchored older model mobile homes. Damage to poorly constructed signs, shrubbery, and trees. Loose outdoor items become projectiles. Numerous power outages.
2	$96 - 110$	Widespread from very strong winds: Some roofing material, door, and window damage to buildings. Considerable damage to trees, vegetation, mobile homes, and piers. A number of high rise building glass windows dislodged to become projectiles. Widespread power outages up to several days.
3	$111 - 129$	Widespread from very strong winds: Some roofing material, door, and window damage to buildings. Considerable damage to trees, vegetation, mobile homes, and piers. A number of high rise building glass windows dislodged to become projectiles. Widespread power outages up to several days.
4	$130 - 156$	Devastating from extremely dangerous winds: Some wall failures with complete house roof structure failures. Extensive damage to doors, windows, and trees. Electricity unavailable for weeks.
5	> 156	Catastrophic: Complete roof failure on many residences and industrial buildings. Some complete building failures with small buildings blown over or away. Power outages for weeks or months.

1.2 Stakeholders and Customers

The stake holders partly consist of with an interest in an enterprises 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 Redcross

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

- Attitude determination and control (reaction wheel, actuators and sensors).
- Maintaining communication with weather stations every $15 - 20m$ minutes.
- Cubesat autonomous tasking if necessary, and warning category level for immediate action.
- Remote sensing capabilities and effective communication with nearby satellites to avoid debris and collision course.

2.2 Requirements

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 $26x14km$.

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.
- Survivability: Depending on external and uncontrolled space phenomenal only.
- Data content: Images, location, Hurricane radius, Relative speed, and relevant characteristics of hurricane located in the US South Atlantic region.

2.3 Constraints

2.3.1 Internal

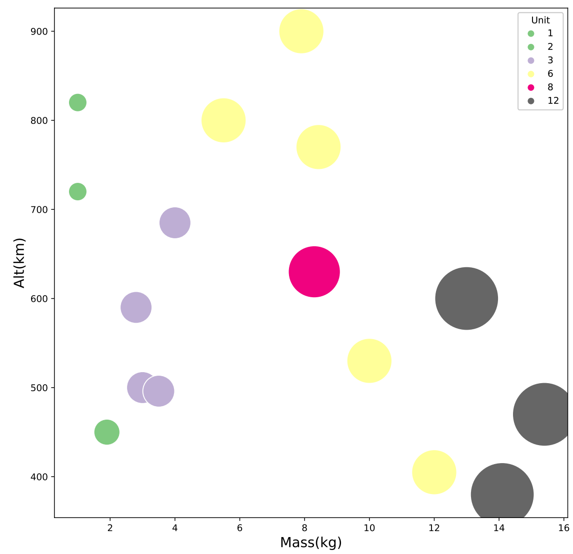
- Cost of sensors and actuators.
- Transmission data cap.
- 2 month Project lifetime.

2.3.2 External

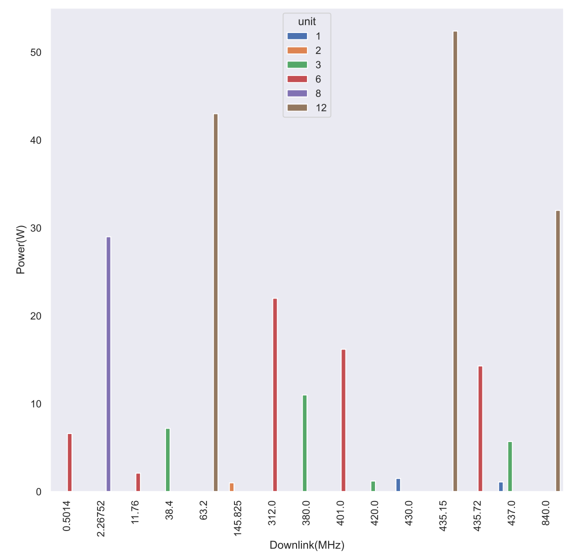
- Max weight $20kg$.
- Budget is limited to $300,000usd$.
- Able to fit within the launch pod
- Size is limited to 12 units of each (10cm x 10cm x 10cm).
- Submission deadline proposed by NASA CSLI Rubrics.

2.4 Analysis and Trade Studies

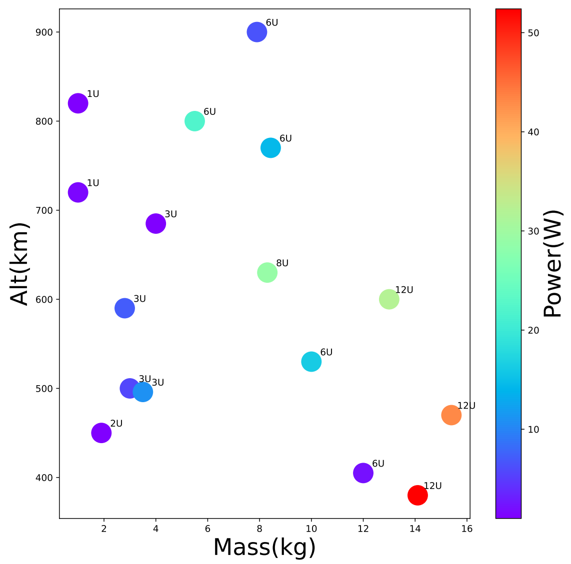
To ensure our project results in designing an effective and efficient Cubesat, we have made a project plan to provide the best out put parameters in Figure 2.2. After initial mission definition the project is closely followed by trade studies. Numerous data for previous successful missions were collected 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 for a 1U-12U cubesat project. Figure 2.1(a) is the volume (density) of cubesats at various altitude. It shows 6U are commonly used for a wide range of altitude. If HurriSat is to to be equipped with a faster imaging cameras, and data transfer (bandwidth) frequency as shown in Figure 2.1(b) that would mean it will require high (red-accent) power. The trade off is to increase mass as shown in Figure 2.1(c). Additionally the inclination distribution of cubesats is graphed in Figure 2.1(d) provides an insight of how the inclination aligns with altitude and coverage. Once we chose those performance parameters, we use STK [1] software analysis to test the values in the simulation. Based on the feed back of the simulation output, if the findings are feasible we proceed to component design phase. If not we go back to refine and tune our mission definition and operational requirements. This is an agile project managing system where



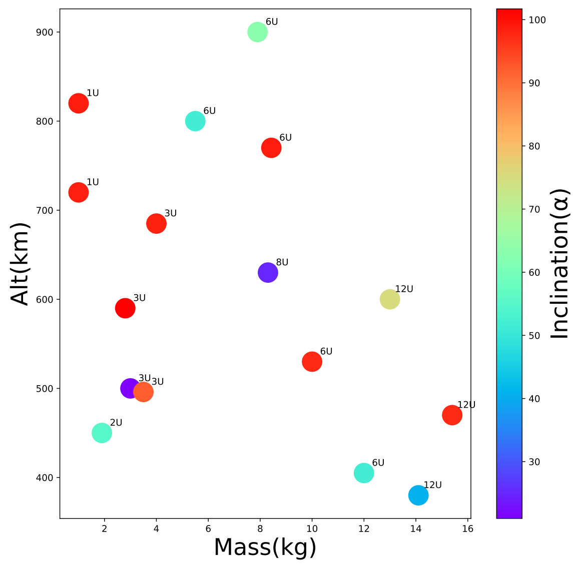
(a) Scattering of Cubesat size based on altitude.



(b) Downlink Freq over power per unit size.



(c) Power Loading



(d) Inclination

Figure 2.1 – Trade Studies

we choose parameters and perceive the coverage, operation orbit and bypass simultaneously in order to decide the best fit. This allows us to be flexible with the project life time provided.

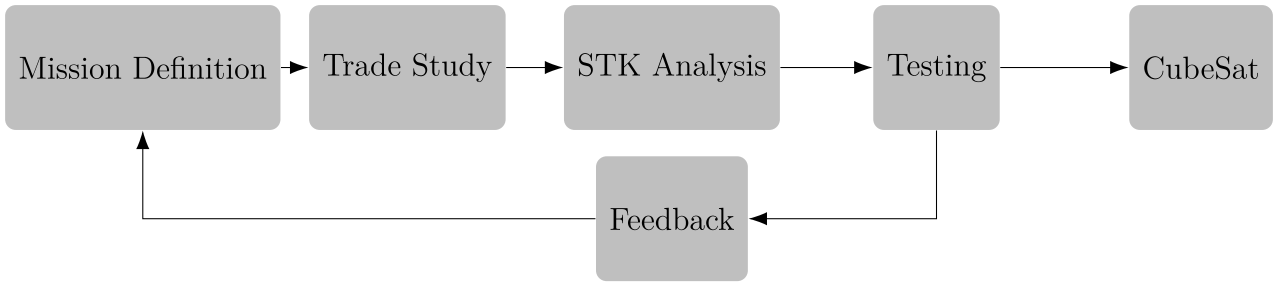


Figure 2.2 – Mission Analysis

2.5 Risk Assessment

Risk assessment takes a deep dive into whether our cube sat project is on track to be hazard free, safe, and feasible It is impossibly to avoid risks completely. With that in mind we have provided a risk assessment mechanisms in Table 2.1,Table 2.2 and Table 2.3.

Table 2.1 – 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.

After defining the risk mechanism terms we assign a color grading as shown in Table 2.2. This color grading is then used for a probable risk assessment and mitigation in the table to that follows. Finally, the overall risk assessment results are shown in Table 2.3.

Table 2.2 – 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 2.3 – Project Stage Risks

Risk	Risk Assessment	Hazard	Solution
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	Safe workspace guidelines
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 sites. 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 $48 - 50kUSD$ per unit excluding labor costs.

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 $\Delta v_{design} = 11.729$ is, there and our choice of altitude is $h = 800km$, and our 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

Similarly the mass estimates are for a 6U based projects based on prior Missions, and commercial data sheet for sub-components weights [2]. Table 3.2 shows our mass sizing, based on an initial payload mass. The initial payload is found to be approximately 3.1kg after trade studies.

Table 3.2 – Mass Sizing

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

4 Preliminary Design

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 hurricane recognition software would provide the satellite with orientation requirements to point the camera and track the target. 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 in order to avoid 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. 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. This camera has the purpose of locating possible hurricane formations and providing the system with data to point the focused camera and LIDAR at the phenomenon. It has a ground resolution of $584m/pixel$. Area coverage on this camera is $2400x1312km$ which means that in specific cases the satellite can cover the entire target area with a single pass.

Given the low power requirement and the mission objective the focused camera only takes single images before the antenna is tasked to transmit. Given that the satellite passes over the target area multiple times per day, the ground station will receive sufficient images and LIDAR information about the hurricane as it progresses

4.2 Communications Architecture

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

4.3 Structures

Structure configuration for our CubeSat mission within a 3U configuration requires a lightweight material capable of withstanding environmental conditions such as aerodynamic, gravitational, and solar torques that could arise during liftoff and transonic periods. Endurosat has a cubesat structure design made out of Aluminum 6082 with PC104 full compliance and an approximate mass of $290grams$ [4]. A simple modular design with dimensions of $100x100x340.5mm$ is selected for our current mission.

4.4 Propulsion

4.4.1 Thrusters

The spacecraft will use Green Monopropellant hot gas CubeSat propulsion for 5 - 6 U CubeSat with Isp of $200sec$ or higher and total Impulse of 3320 N-Sec. ADN/AF-M315E propellants can be utilized to produce thrust of $50mN$ to $1N$. The propulsion system is to be mounted on the end of the CubeSat and can take up size of $0.5 - 1U$. Cold gas thrusters are utilized for vector thrust and attitude control. The VACCO [13] 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 upto $880,000$ firings occupying a space of about $0.3U$.

This set of thrusters allows for spacecraft attitude control and change in velocity (delta-V) while carrying 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

4.5.1 Power Supply

The spacecraft will utilize solar cells across the face of the cubesat in order 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].

4.5.2 Power Efficiency

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].

4.6 Thermal

4.6.1 Thermal Shield

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 achieved through a combination of surface finishes and internal heaters.

4.6.2 Radiation Shield

For 35 degree 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

In the next project phase we'll begin a detailed component design based on the numbers provided 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 highly developed tech ensures the desired result. However the trade off 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 Mass	$3.100 kg$
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 be equipped with dual high tech cameras, LiDARs and power budget to fully operate the spacecraft. It's mission is to meet one of the goals of proposed by NASA in monitoring, tracking and alerting the public about possible hurricanes in the U.S. east coast region.

7 Appendix

7.1 List of Tables and Figures

7.2 Keywords

CSLI: Cubesat Launch Initiative
GPS: Global Positioning System
K-Band: a radio frequency band from 18 to 27 GHz
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
STK: Space Mission Toolkit by AGI Solutions

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