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Department of Aerospace Engineering Sciences
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Conceptual Design Document (CDD)
REcoverable ProTection After Reentry (REPTAR)

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Project Customers

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Acronyms and Definitions	
Bus	The bus and associated interface that REPTAR is connected to during launch and space phases
CONOPS	Concept of Operations
CW	Continuous Wave
COTS	Commercial Off-the-Shelf
CubeSat	A SmallSat obeying the NASA/CalPoly Cube form factor definitions (1, 3, 6, 12, or 27 U)
Descent	The period of flight when the vehicle is moving at subsonic speeds within the atmosphere
EGSE	Electrical Ground Support Equipment
ELaNa	The Educational Launch of Nanosatellites program
FBD	Functional Block Diagram
Flight	The period between the vehicle's de-orbit burn and successful landing on the surface of the earth
HF	High Frequency (EM Spectrum)
GPS	Global Positioning System
Landing	The point in flight at which the vehicle comes to rest on the surface of the earth
MGSE	Mechanical Ground Support Equipment
NVIS	Near Vertical Incident Skywave
Recovery	The action taken by the ground team to find and collect the vehicle
Re-Entry	The period of the mission during which the vehicle is transitioning from space to the earth's atmosphere
REPTAR	REcoverable ProTection After Reentry
RF	Radio Frequency
SmallSat	A satellite weighing less than 50kg at launch
TPS	Thermal Protection System
U	Standardized Unit Size by CalPoly specifications
UHF	Ultra High Frequency (EM Spectrum Band)
UTTR	Utah Test and Training Range
Vehicle	The REPTAR system, Raytheon Payload, Raytheon Reentry System, and associated structures.
VHF	Very High Frequency (EM Spectrum Band)

I. Project Description

SmallSats can carry expensive equipment and data that may only be useful if recovered. The SmallSat industry is growing rapidly, but expensive SmallSat payloads are typically left in orbit or are allowed to burn up in the atmosphere after their relatively short missions conclude. Successful recovery of SmallSats could reduce the overall cost of missions. Thus, Raytheon has instructed the REPTAR team to investigate and build a vehicle that can safely recover a valuable SmallSat payload.

The overall Raytheon mission will involve a 12U or 6U SmallSat being launched into orbit. After the 1U "Raytheon Unit" payload completes its mission, the SmallSat which contains the payload will be de-orbited and will re-enter Earth's atmosphere. A thermal protection system (TPS) that will be provided by a different team will protect that vehicle during re-entry. Once the vehicle has slowed to subsonic speeds, the TPS will be jettisoned and REPTAR will take over.

REPTAR will descend and land in a way that the payload does not endure any loading higher than the loading it endures during launch. REPTAR will also beacon its location so that an active search party can locate and recover the valuable Raytheon payload.

To complete the mission, REPTAR must also be able to survive all components of the mission that come before the landing phase. This includes launch and a standby period in space where REPTAR will be subjected to high loading, destructive vibrations, and temperature fluctuations.

In order to allow adequate room for the TPS, REPTAR must adhere to strict size requirements. The maximum size that REPTAR may be is 6U including payload, but the team will be designing to keep the size at 3U including the payload. A 6U REPTAR would allow the TPS to be 6U as well, making a 12U CubeSat, including payload, for re-entry. If REPTAR is kept at 3U, the TPS could also be 3U, making the total vehicle 6U, including payload. Figure 1 shows the generic layouts.

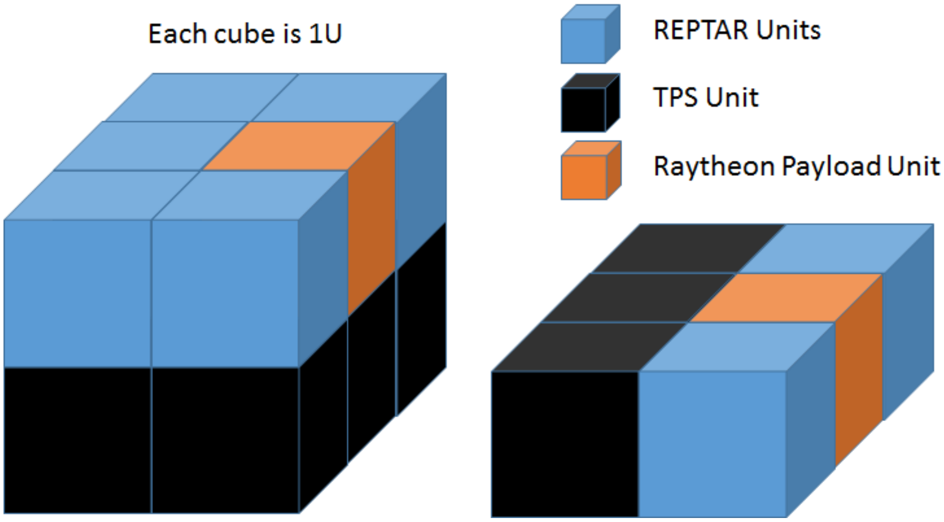


Figure 1: General Layout of REPTAR Configurations

Concept of Operations

Figure 2 shows the overall mission CONOPS that REPTAR will be a part of. The boxes in blue show parts of the mission that are related to the functional requirements, which will be discussed later. As stated previously, all REPTAR must do during the launch and standby phases is survive. However, this stage cannot be overlooked as all aspects of REPTAR must be able to withstand the difficult environments that launch and space provide.

The de-orbit stage will be taken care of by Raytheon, the customer for this mission. The de-orbit maneuver will place REPTAR onto a trajectory bound for the Utah Test and Training Range (UTTR). The re-entry stage will be taken care of by a different team and it is assumed that this team that builds the TPS will keep REPTAR below shock and vibration requirements from launch. This means that if REPTAR survives launch, it will survive re-entry. After the vehicle slows below subsonic speeds, the TPS will be jettisoned and REPTAR's main mission begins.

The land and recovery stage, which is more detailed in the REPTAR CONOPS in Figure 3, is the last stage of the mission. In this stage, REPTAR will bring the payload to the ground and will land it gently in the UTTR. It will then beacon its position and Raytheon will recover REPTAR and the payload.

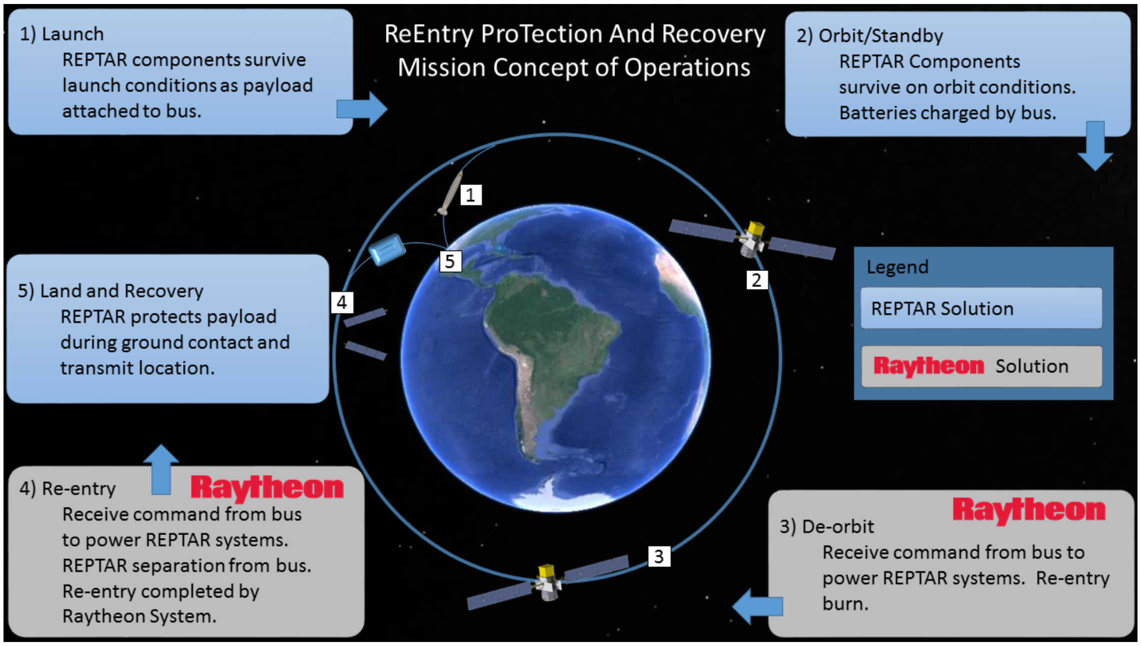


Figure 2: Concept of Operations for SmallSat mission

Figure 3 details the aspects of the mission that REPTAR will actively participate in. The first stage, Descent, is crucial for slowing down the vehicle. Unless something is done to slow down, REPTAR and the payload will impact the ground at terminal velocity. This portion of the mission will be verified using wind tunnels and drop tests.

The landing phase will potentially be the point in the mission where the payload and vehicle experiences the most structural loading. The descent stage will dictate how much speed the vehicle has when it impacts the ground, but after the first two stages, the vehicle and payload will be fully stopped and will no longer be subject to loading.

Though it does not necessarily need to occur exclusively after the vehicle comes to a full stop, REPTAR will begin transmitting its location on or near the ground. This transmission can take many forms, but the overall goal is to contact the search party that will be deployed in the UTTR. The search party, which will be supplied by Raytheon, will receive the transmission from REPTAR and then will go find it. Once found, the payload can be recovered, thus completing the mission.

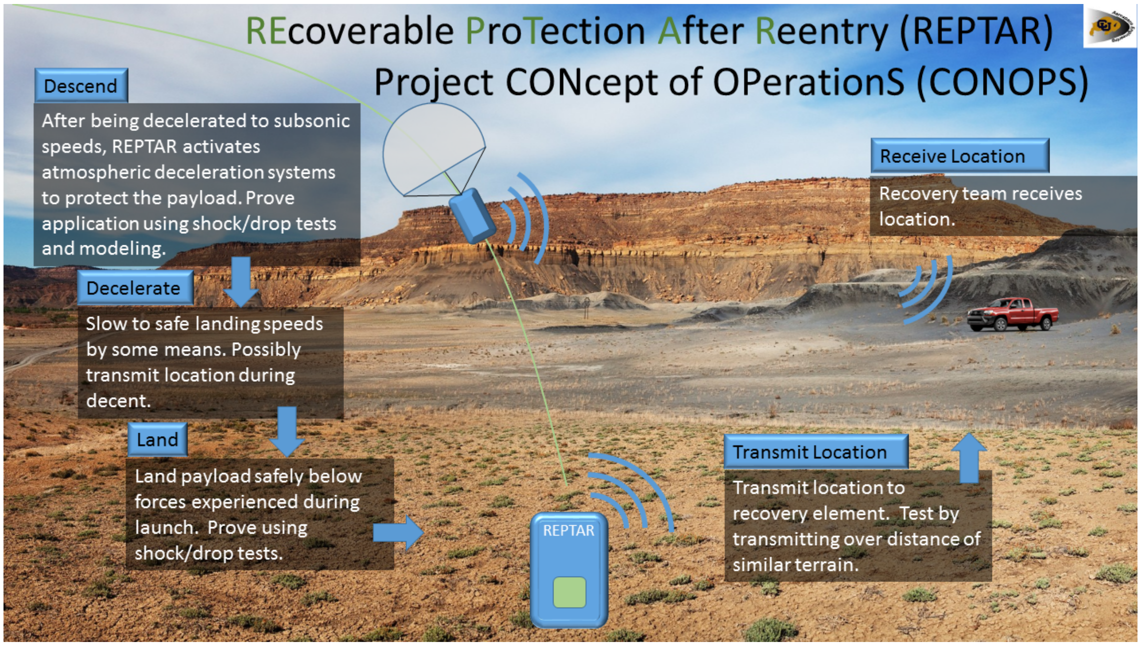


Figure 3: Concept of Operations for REPTAR

Functional Requirements

REPTAR has 4 functional requirements derived from customer requirements and concept of operations. These are the main design drivers of the system as all other requirements will be motivated by these.

- **FR.1** REPTAR shall survive launch and standby period in space.
  - **Motivation**: Customer Requirement. The unit designed needs to survive launch and space environment.
- **FR.2** REPTAR shall conform to industry CubeSat standards.
  - **Motivation**: Customer Requirement. This is to ensure that the customer does not have to change their payload/bus design to accommodate our system.
- **FR.3** REPTAR shall keep the payload safe.
  - **Motivation**: Customer Requirement. The payload needs to be safe in order for it to be used again for future missions or recovery of science and data.
- **FR.4** REPTAR shall be locatable.
  - **Motivation**: Customer Requirement. The search team needs to know its location in order to recover it.

II. Design Requirements

REPTAR's design requirements are based on customer requirements and derived requirements due to the nature of the mission. Each functional requirement can be tied to at least one stage in the mission CONOPS shown in Figure 2, and the requirements flow down from the four functional requirements. Specific numbers were obtained through research regarding launch requirements for SmallSats and from the known space environment.

Mission Statement: REPTAR will land and recover a 1U payload successfully.

- **FR.1** REPTAR shall survive launch and standby period in space.
  - **DR 1.1** REPTAR shall survive vacuum.
    - **Motivation**: Derived from the space environment conditions.
    - **V&V**: Environmental Testing Facility at CU.
  - **DR 1.2** REPTAR shall survive the 8.5 G's that will be experienced during launch.
    - **Motivation**: Derived from the launch environment conditions based on the popular launch vehicles such as Falcon 9 and Delta 4.
    - **V&V**: Simulation/Analysis. Possibility of Vibration Testing at CU or around Boulder area.
  - **DR 1.3** REPTAR's components shall survive environmental temperature as low as 3 Kelvin.[9]
    - **Motivation**: Derived from the space environment conditions.
    - **V&V**: Environmental Testing Facility at CU.
  - **DR 1.4** REPTAR's components shall survive temperatures as high as 400 Kelvin.[9]
    - **Motivation**: Derived. REPTAR should not be more sensitive than the payload to high temperatures. As defined by Raytheon, the payload can survive temperatures as high as 400 Kelvin.
    - **V&V**: Environmental Testing at CU.
- **FR.2** REPTAR shall conform to industry CubeSat standards.
  - **DR 2.1** REPTAR's shape shall be 3U by 2U if it is 6U in volume, 2U by 2U if 4U in volume, and 3U by 1U if 3U in volume.
    - **Motivation**: Derived from the CubeSat industry standards.
    - **V&V**: Inspection.
  - **DR 2.2** REPTAR shall interface with the Raytheon Unit.
    - **DR 2.2.1** REPTAR shall have an electrical interface according to Raytheon provided ICD.

            - **Motivation** Derived. REPTAR will need power and signal interfaces in order to carry out its mission objectives. Therefore, it needs to be charged before re-entry. Hence, it will have an interface with the Raytheon Unit to provide necessary power to perform the mission and signal when the REPTAR unit should activate.
            - **V&V**: Bench Top Test.
        - **DR 2.2.2** REPTAR shall structurally interface with the 1U Raytheon payload.
            - **Motivation** Derived. REPTAR will need to be built in a way that the 1U payload can be added to the vehicle by Raytheon.
            - **V&V**: Demonstration by inspection.

- **FR.3** REPTAR shall keep the payload safe during descent and landing.
    - **DR 3.1** The payload shall not experience loading exceeding 8.5 G's during any stage of the mission.
        - **Motivation**: Derived. The payload can survive the loading experience during launch, therefore it should be kept within the launch limits to ensure its safety.
        - **V&V**: Simulation/Analysis. Possibility of vibration testing at CU facility or around the Boulder area.

- **FR.4** REPTAR shall be locatable.
    - **DR 4.1** REPTAR shall communicate its location over a radius greater than or equal to 20 miles.
        - **Motivation**: Derived from the map of Utah Testing and Training Range(UTTR). The 20 mile range covers half of the range, therefore needing one search team each in the Northern or Southern regions of the range.
        - **V&V**: Demonstration by field test.

III. Key Design Options Considered

Descent

The Descent stage of the mission is crucial for slowing down the vehicle so that the landing is not too violent. The main goal of this stage is to slow down the vehicle as much as possible for landing.

Freefall

The first option to look into for the descent is the most basic: to simply do nothing. This strategy is based largely upon the terminal velocity of the vehicle. In this case, the vehicle is assumed to be a 3U by 1U rectangular box, so the coefficient of drag is estimated to be 2.0. The terminal velocity of an object can be found using Equation 1.

$$V_{terminal} = \sqrt{\frac{2mg}{\rho S C_d}} \tag{1}$$

By using the standard atmospheric conditions for the UTTR (averaging an elevation of 5000 feet) and some standard values for 3U CubeSats, the terminal velocity of the vehicle is found to be roughly 63 (m/s) using the variables in Table 1.

Mass (kg)	Surface (m^2)	C_d	Density (kg/m^3)
3.9	0.01	2.0	1.01

Table 1: Values used to find terminal velocity

Pros	Cons
- Cheap	- Vehicle impacts ground at 63 m/s
- Easy	- No orientation control
- No added mass or volume	

Table 2: Pros and Cons of the Freefall Descent

Drogues and Parachutes

Parachutes and drogues have been used for decades. From the Apollo program[22], to skydivers, to race cars, it is always a go-to when decreasing velocity is a necessity. Drogues are much smaller in diameter than their parachute counterparts but are used for much higher speeds due to stronger lines. A drogue will typically be deployed first to create stability and decrease velocity slightly; it is then followed by a much larger parachute that controls descent and creates a scenario for landing. Due to volume and weight constraints of CubeSats, REPTAR will have to decide which one to use or use both. Since REPTAR will be traveling at high speeds, the concern is a parachute or drogue that can be used at high speeds, but also play the role of landing slowly on the ground without much change to trajectory. Also, the REPTAR team will have to design a mechanism enabling swift and simple deployment of the parachute and drogue.

Parachutes/drogues are packed into a tight volume with four to eight lines attached to the inside of the vehicle it will be deployed from. Lines can be made of materials ranging from Kevlar to Nylon, with the parachute itself generally made of lightweight nylon. At a certain velocity or altitude, it is deployed quickly and will take shape from the force of drag due to air being pressed against it, as in Figure 4. Examining Equation 2, an increase in drag coefficient and increase in surface area will decrease the terminal velocity of the system for landing[2] and the amount of Drag Force the system will experience is equal to Equation 2.

$$D = C_d \frac{\rho V^2}{2} S \tag{2}$$

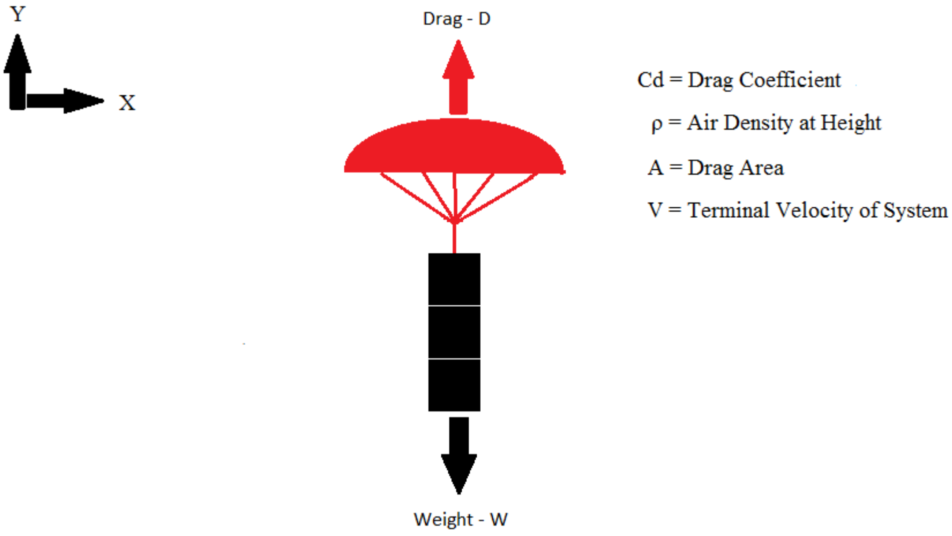


Figure 4: Dynamics of a Parachute and Drogue

Issues with the reliability of a parachute include: if REPTAR is tumbling too much and the drogue does not stabilize it, if the velocity of REPTAR is too large the parachute or drogue can be ripped off, the deployment system could fail and too much loading is experienced. As long as it is protected during launch, orbit and re-entry, temperature and other environmental aspects will not cause the parachute and drogue to fail.

Pros	Cons
- Stabilizes from tumbling	- Will not slow to landing velocities
- Deployed at high altitude and velocity	- Strong lines required

Table 3: Pros and Cons of Drogue without Parachute

Pros	Cons
- Decrease velocity to landing speeds - More control of trajectory - Easy to test - Used on several space missions	- Detach drogue before parachute deployment - Occupy most size and weight of 1U - Multiple moving parts

Table 4: Pros and Cons of Drogue with Parachute

Pros	Cons
- Stability at low speeds - Large decrease in velocity	- Only deployed at low velocity - Can not deploy while tumbling

Table 5: Pros and Cons of Parachute without Drogue

Aerodynamic Braking

Aerodynamic braking is the process in which the area of the spacecraft can be altered to increase drag and slow the spacecraft down. The same principles work for aerodynamic braking as the parachute and drogue. Equation 1 illustrates the effect that expanding the area of the satellite has on the velocity at which it falls. By increasing the area of the spacecraft, the terminal velocity is decreased to a speed that should be more feasible for landing.

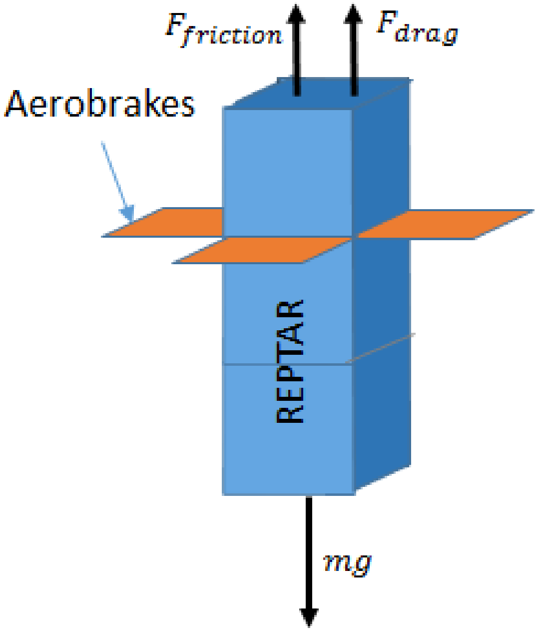


Figure 5: Diagram of Initial Concept

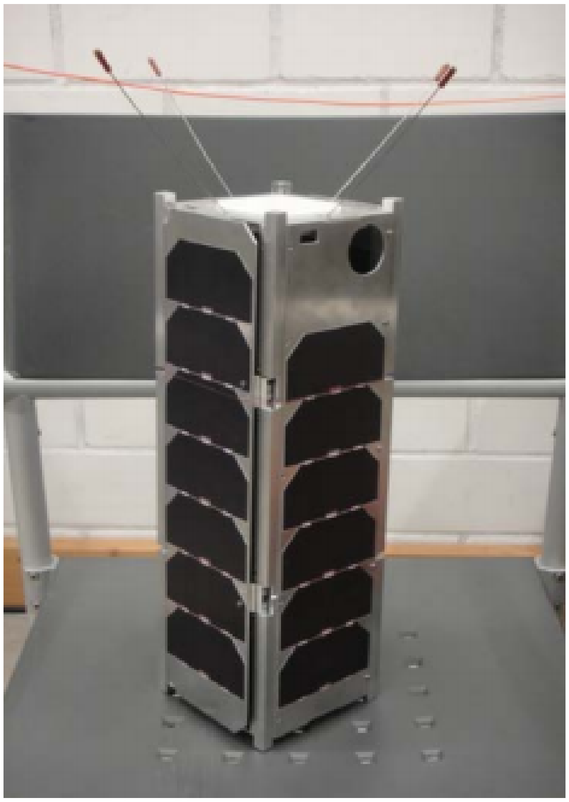


Figure 6: Possible real-world design concept

Figures 5 and 6 above are possible designs for REPTAR in order to increase its area during descent. The initial concept, Figure 5, is a 3U CubeSat design in which drag inducing panels would be mechanically deployed from within REPTAR. Upon researching this option, Baig's paper[1] concerning a deployment mechanism for solar panels on a 3U CubeSat payload was found and can be seen in Figure 6. The same concept is considered in order to increase drag during descent on REPTAR. This method offers a low mass solution that would occupy zero volume inside REPTAR.

The REPTAR payload by itself has an area of 0.01 (m^2), but with the addition of the deployment mechanism the area could at least be doubled. Figure 7 shows the effect of different areas on the terminal velocity of REPTAR:

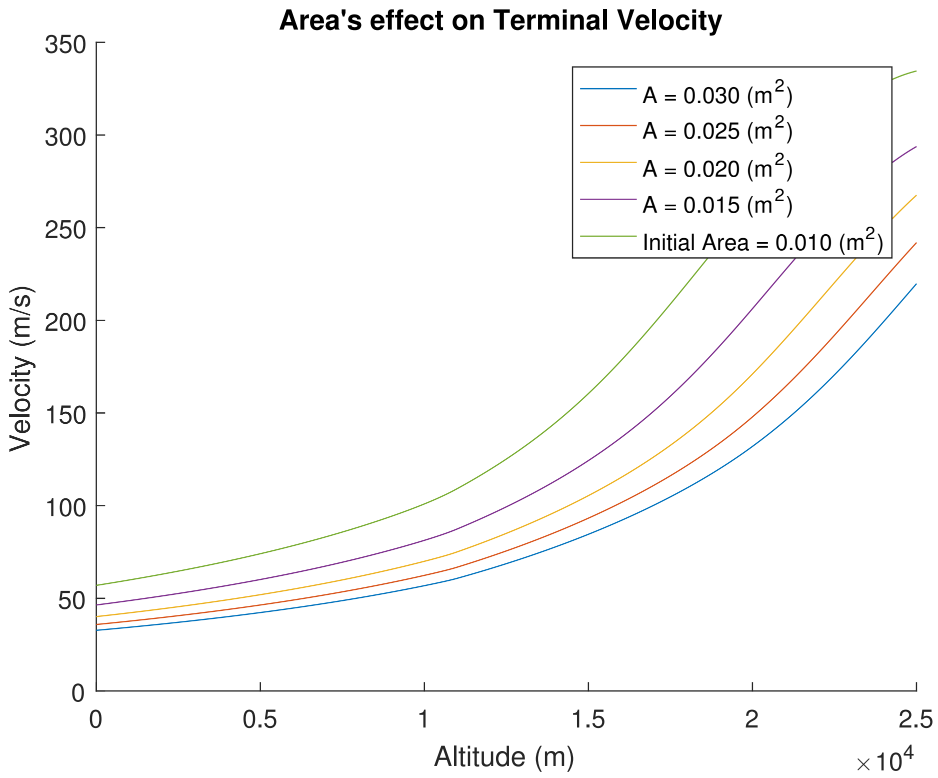


Figure 7: Altitude over Velocity as a Function of Area

Increasing the area to 0.03 (m^2) would slow REPTAR down by roughly 24 (m/s) to a final impact speed of 32 (m/s), or roughly 71 miles per hour. Even if the area was tripled, REPTAR and its sensitive payload would likely be traveling too fast to survive an impact with the ground. In order to ensure minimal shock when REPTAR hits the ground, a different method would need to be chosen.

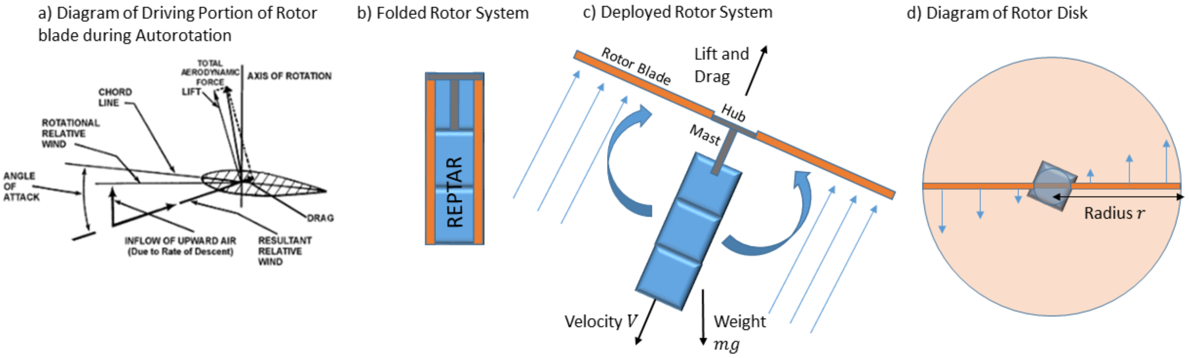
The deployment mechanism that would be utilized for aerodynamic breaking would be designed and built to survive the harsh conditions of space and the extremes of re-entry. It is common practice for solar panels to be deployed in space, so the reliability of this mechanism is something that does not need to be questioned. Table 6 illustrates the pros and cons of aerodynamic braking.

Pros	Cons
- Low mass	- Difficult to manufacture
- Reduces impact velocity	- Difficult to test
	- Many moving parts
	- Not tried and tested
	- Impact velocity still relaitvely high

Table 6: Pros and Cons of a Changing Area Device

Autorotation

Autorotation is an un-powered design option considered for controlling the descent and potentially the touchdown. Autorotation is used by helicopters during engine failure and it is used by gyro-copters for near vertical landings. The system would involve a deployable rotor system. The upward flow through the rotor would cause the rotor speed to increase until the drag on the blades matched the autorotative driving force. The spinning rotor system would generate lift in the direction opposite the flight path, as well as increasing the drag, slowing the SmallSat down. With the ability to control the collective pitch of the blades, the lifting force could be increased right before touchdown to further decelerate the SmallSat and bleed the remaining rotor inertia. The autorotation concept is broken down in Figure 8.[11]



a) Diagram of Driving Portion of Rotor blade during Autorotation

b) Folded Rotor System

c) Deployed Rotor System

d) Diagram of Rotor Disk

Figure 8: Autorotation Concept

This concept has been studied as a re-entry mechanism numerous times by NASA[14] and other entities. While it has been considered for use during re-entry, it has not been implemented in any major scale. The complexity of such a system is a major disadvantage.

Rotor blade material selection, airfoil selection, and manufacturing would add time, cost, and complexity to the design. Rotor systems can be difficult to model and design. Rotor speed control is critical: too slow of a speed and the required lift will not be generated; too fast of a rotor speed and the blade tips encounter compressibility effects and can possibly exceed the critical Mach number leading to intense vibrations and forces on the blades and system. Therefore, rotor speed control would have to be maintained using either an active collective pitch control or a fly-wheel governor-type control. Additionally, rotor imbalance for any reason can cause severe vibrations.

Depending on the inertia of the rotor system at touchdown, if the blades contact the ground or another object, the results can be fairly catastrophic. The forces on the SmallSat would likely be violent and destructive. This would require the vehicle to land on relatively level terrain without obstacles, and have a sturdy landing gear system to ensure the vehicle does not tip over causing such contact.

A system of this design should be very survivable during launch and in the space environment. Survivability during descent would be dependent on control and complexity of design, and margin for strength of materials. While survivability during landing is not required, it is possible that a fast moving rotor contacting the ground would cause forces that exceed limits. Due to the complexity of the design space, the reliability of the system is strongly dependent on the complexity. However, the system would likely be highly robust to wind variances and entry velocities, and the landing survivability would be dependent on landing systems.

In a paper by members of the European Space Agency[15], a simple formula relates the required rotor diameter to the touchdown velocity is written as:

$$r = \frac{1}{2V}\sqrt{\frac{8mg}{\pi\rho C_D}} \tag{3}$$

Since the touchdown location is relatively known in the Utah Test and Training Range, the gravity and density factors are known. Assuming a touchdown velocity from 10 to 20 m/s and a drag coefficient of 2.0. These results are tabulated in Table 7.

While the volume of the SmallSats increases with added units, the standard Cal Poly form factor will not allow the maximum length for deployable rotor blades to exceed a 3U (30 cm) length. Any length beyond what is available in the structure would have to be made up for by telescoping, folding, or inflatable blades. If telescoping blades are used, concerns over blade construction and strength materialize, as well as potential rotor imbalance if the blades do not fully open. If inflatable blades are used, it is not likely that the system would be rigid enough to have collective pitch control, requiring the pitch to be critically preset, and providing no additional thrust prior to touchdown.

			Rotor Radius (m)	
Form Factor	Working Length	Mass (1.33kg/U)	20 m/s	10 m/s
3U	2U (0.2 m)	4 kg	0.17	0.34
6U	3U (0.3 m)	8 kg	0.32	0.65

Table 7: Rotor Diameter for Autorotating SmallSat

Pros	Cons
- Rotor can provide thrust for touchdown - Velocity can be managed - Glide ability	- Potentially complex system - May require rotor speed control - Would require an upright landing - Not readily scalable - Expensive materials and manufacturing - Lack of use and familiarity - Large mass and volume usage

Table 8: Pros and Cons of Autorotation System

Thrusters

The use of thrusters was selected as an alternative for this project to allow for controlled descent and landing. The thrusters would decelerate the payload at a chosen rate for G loadings to be minimized by working in the opposite form of a rocket thruster, such that, it goes against the direction of motion allowing for the deceleration of the payload, as is outlined in Figure 9 below. This figure outlines the forces acting upon an object during a descent phase at an instant velocity of V. The thrusters provide a force in the direction of Earth causing the equal and opposite net force to act in the zenith direction, countering the descent velocity of the object. Due to the nature of the descent and landing of a SmallSat, the orientation of the thrusters would need to be consistent, and therefore would require a minimum of two to obtain the proper control for a safe landing below the G load requirements stated. With these requirements of the descent, this system would require active control due to the nature of thrusters themselves. Thrust may specifically need to be changed throughout the descent to achieve proper orientation for a safe landing. A system with thrusters included would be survivable during launch and space standby. This is due to the amount of previous usage of thrusters within the space industry providing information regarding the survivability in space. It is also survivable during a soft landing as thrusters are quite durable systems on their own.

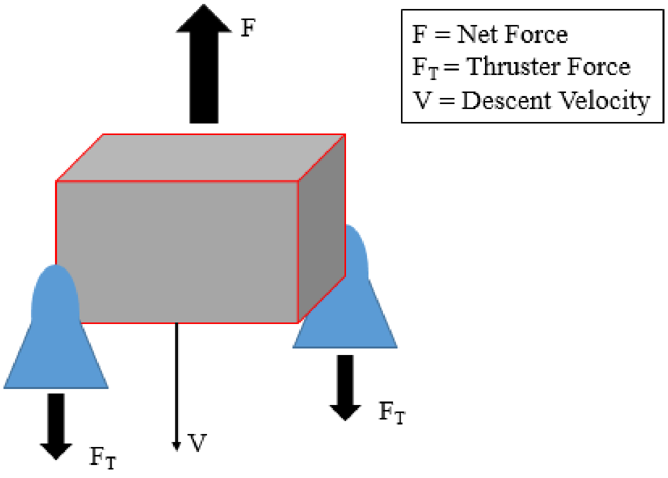


Figure 9: Free Body Diagram of Thruster Forces applied to an object

Thrusters have been used for descent before by both NASA[17] and Roscosmos[21]. They have been utilized on the Curiosity Rover's descent system to allow for a safe descent of the rover as well as on the Soyuz spacecraft for descent from the ISS. However, with these two systems they contained parachutes for the initial descent deceleration; therefore, the thruster systems do not need to be the sole deceleration system for these crafts.

$$\Delta v = v_e ln\left(\frac{m_0}{m_f}\right) \tag{4}$$

Tsiolkovsky's rocket equation, shown in Equation 4 is the basis of a rocket thruster and how it performs its mission, where Δv is the change in velocity the thruster would have to create during the descent, v_e is the exhaust velocity of the thruster, m_0 is the initial mass of the payload including the propellant, and m_f is the dry mass of the system. Manipulating this equation can allow for the calculations of one variable with respect to any of the other variables as was done for the trade study of this project.

Pros	Cons
- Exact velocities can be reached	- Requires active control
- Able to be activated at any velocity	- Very expensive
	- Requires fuel on-board

Table 9: Pros and Cons of Thruster System

As a part of this alternative, the mass component was researched with some calculations as the addition of a propellant would affect the total mass of the system, and potentially cause problems for launch of a SmallSat system should it be overweight. The mass required to perform the maneuver of decelerating the whole system to a velocity low enough for a soft touchdown was found to be Equation 5 when rearranging Tsiolkovsky's Equation (Eqn. 4).

$$m_0 = m_f e^{\Delta v/v_e} \tag{5}$$

Using this equation, the mass was determined with respect to both specific impulse, or varying engine types, as well as the ΔV to be performed. The ΔV was found using a function that calculated the velocity of the cube as it descended by free fall and subtracting the value of 4 m/s for an approximate soft landing velocity. The results of this trade study are visualized in Fig. 10 below.

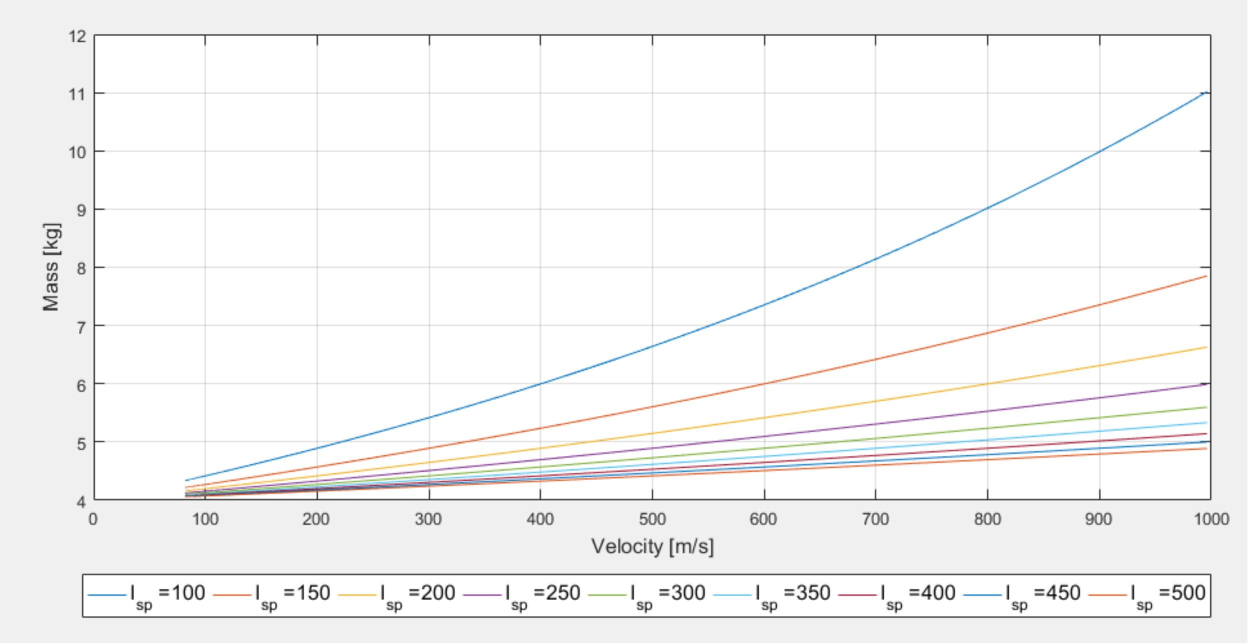


Figure 10: Trade Study of Mass with respect to both I_{sp} and ΔV

Deployable Wings

The use of deployable wings was selected as a means to control the descent of the system. Rigid Foldable wings would be used to stay compacted and minimize interference to previous mission stages prior to operation. The idea is that the vehicle would be at terminal velocity before the deployment of the wings and will be falling at a steep descent angle. This condition would suggest that the drag on the vehicle is greater than or equal to the weight. Deploying the wings would produce a lifting force, perpendicular to the vehicle's velocity, and a drag force, opposite the vehicle's velocity, as can be seen in Figure 11. and eventually reach horizontal flight. The resulting force acts to slow down the vehicle and changes its descent angle. Positioning the wings correctly on the vehicle would cause the system to rotate clockwise in the free body diagram

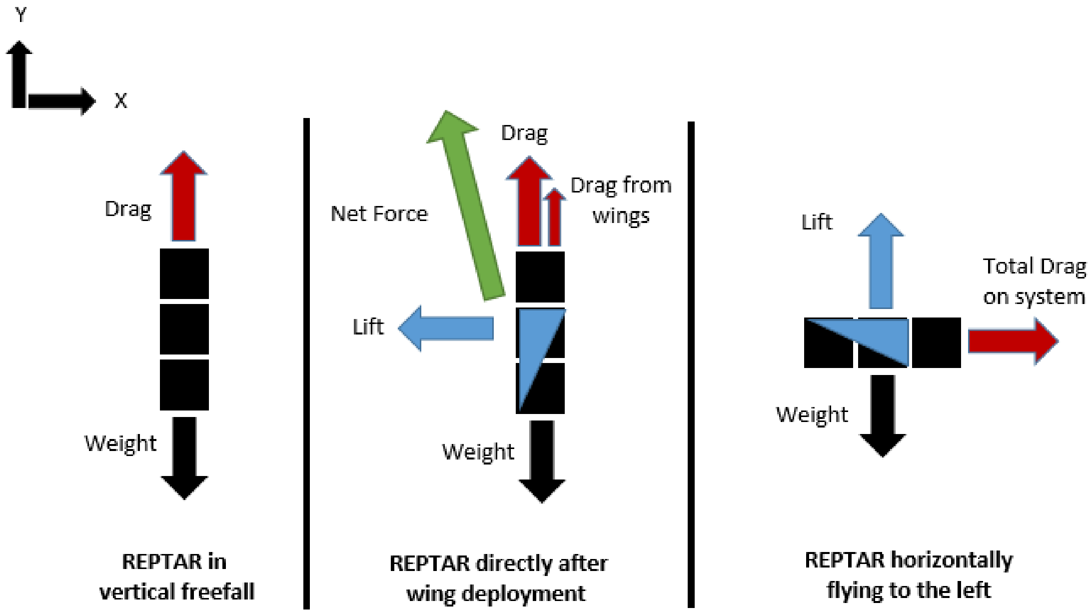


Figure 11: Free Body Diagram of Forces due to Wing Deployment

At this point the vehicle effectively becomes a glider with forward velocity and the system would descend over time as the drag causes it to lose velocity. Being that the system needs to land in the UTTR, navigation and guidance control would be necessary to control the descent. This would require at least a rudder and possibly ailerons too.

A similar successful concept was used by the ARES Mars Airplane[4] which utilized two key components that prove the effectiveness of these aspects. The ARES was able to deploy at a high velocity of Mach 0.7 and deployed foldable rigid wings slightly after the ARES deployment. The airplane also used active control to navigate its course. Rather than just assuming the role of a glider however, the ARES had a propulsion system on-board. This airplane was much larger than this intended system, having a span of 6.25 (ft), but proved the concept of operation.

Successful demonstration of gliding descent from high altitude has also been tested. An example using inflatable wings is demonstrated by BIG BLUE Flight Experiments[5]. Their experimental mission ends with a gliding descent that begins above 95,000 ft. Their descent begins with no velocity and their average descent rate was about 8 (m/s). Their experiment proves the feasibility of a gradual descent, although the REPTAR system will activate at a high initial velocity.

Based on understood principles and similar operations, the survivability of the wing system in space and during launch seems justified. During descent, the reliability could be affected by descent conditions. If there are high wind speeds, the ability of the wings could fail. Also, if the system is tumbling, and the wings are deployed at a weird angle, the lift produced would be in the wrong direction. These are a few concerns to be considered for using wings.

Pros	Cons
- Low cost	- Requires active control
- Familiar concept	- Complex system
	- Trade study to choose wings

Table 10: Pros and Cons of Deployable Wings

Landing

The landing portion of the mission is concerned with making the touchdown with the ground as gentle as possible. By the end of this stage, the vehicle will no longer be in motion. The main goal of this mission stage is to bring the vehicle to a stop while subjecting the payload to the least amount of structural loading possible.

Net

The idea of landing REPTAR in a net was inspired by Luke Aikins' jump on July 30^{th}, 2016 in which he safely landed in a polyethylene[3] net without a parachute after he jumped from an altitude of 25,000 (ft). A 100 by 100 meter net would be set up in the UTTR before REPTAR even enters the Earth's atmosphere. In order to protect the payload from the harsh impact with the ground, the same idea can be implemented with REPTAR. A polyethylene net would add zero mass and zero volume to REPTAR while ensuring minimal impact with the ground. Although impacting the net would certainly be better than hitting the ground, the net adds complexity to REPTAR since an automatic control system would be necessary in order to get REPTAR to the location of the net. The net would definitely be a survivable option of landing since it would never have to go through the rigors of space. Testing would ensure the reliability of the net being able to safely catch an object the size of REPTAR traveling at the velocity that it is able to slow down to. The pros and cons of a net system for landing are detailed in Table 11.

Pros	Cons
- No mass on REPTAR	- Expensive fabric
- No volume on REPTAR	- Small landing area
	- Active control necessary

Table 11: Pros and Cons of Net Landing

Crushable Structure

Another method of landing REPTAR without damaging the payload is to simply absorb the energy upon impact. For a high speed impact, a structure could deform plastically to absorb a significant amount if not all the energy of the system. The amount of energy required to be absorbed would be the kinetic energy upon landing. The amount a structure would have to deform would then be based on its material and structural properties. This relationship is shown below in Equation 6 and diagrammed in Figure 12.

$$\frac{1}{2}mV^2 = Fd = \sigma A d \tag{6}$$

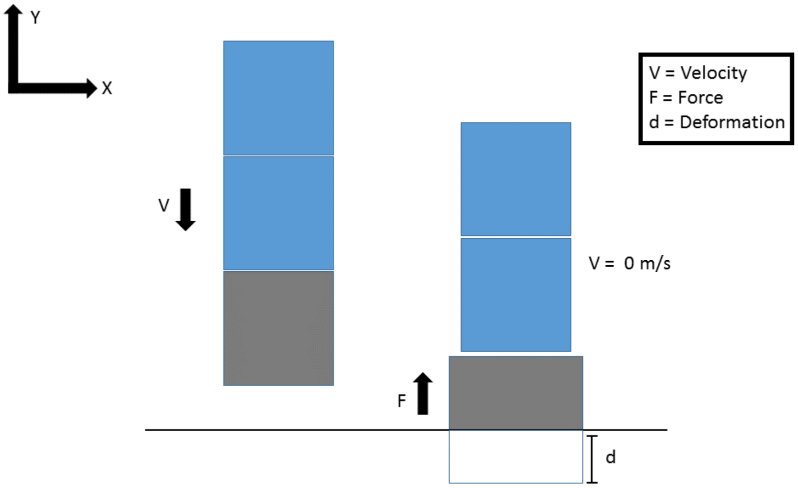


Figure 12: Diagram of Energy Absorbing Crushable Structure

From Equation 6, if the velocity of REPTAR during impact on the ground can be determined, a structure allowing a certain range of deformation can be used to absorb the energy and protect the payload. It is important for the structure to absorb the energy and not simply store it temporarily like a spring. Storing the energy temporarily may introduce unpredictable behavior to REPTAR after landing and danger the payload. However, energy storing devices may be a viable option for small amounts of energy. A basic stress strain curve for an ideal energy absorbing material is shown in Figure 13 showing how a structure absorbs energy as it is strained.

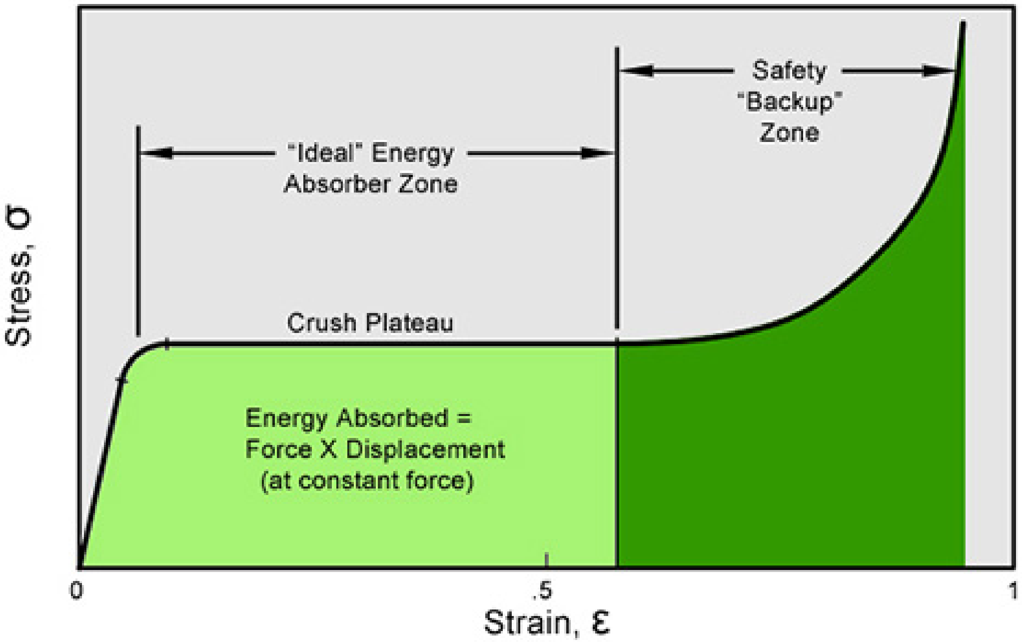


Figure 13: Energy Absorption from Stress-Strain of Ideal Energy Absorber[8]

During the compression of the structure, the stress remains relatively constant in the ideal energy absorption area. By crushing under an allowable loading for a large strain, a significant amount of energy can be absorbed while only subjecting the payload to a force determined by the crush plateau stress. Figure 14 shows how having more material to deform would allow faster landing velocities with a max loading of 6.5 G's.

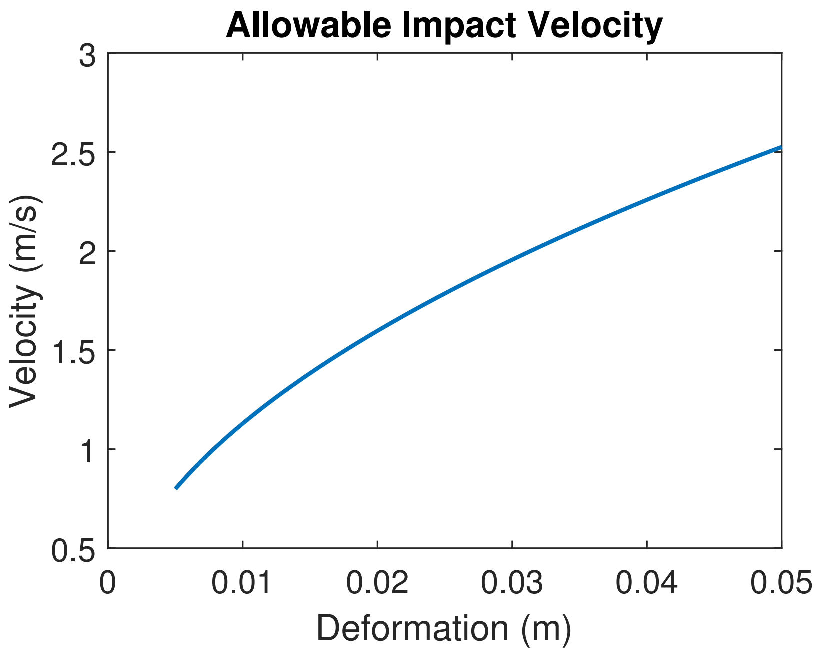


Figure 14: Study of Allowable Landing Speed depending on Structural Deformation

Due to the size constraints of the 3U system, the amount of possible deformation is restricted. In order to properly absorb all the energy in the system without damage to the payload, the system would need to be decelerated significantly or have another system to absorb any extra energy the structure is unable to. The energy absorbing structure must be carefully chosen both in form and in material to absorb the energy effectively. For instance, honeycomb materials have high crush strengths but only when the loading is applied directionally into the cell structure. Due to the potentially high velocity of impact, a certain orientation during impact may not be guaranteed. Additionally, although many materials may be suitable as energy absorbers, it is important that the material can survive both launch and the space environment without degradation.

Risks involved with using a crushable structure are mainly based on how accurately the velocity can be predicted. With the kinetic energy being proportional to the square of velocity, any errors in determining the velocity could quickly cause the structure to be inadequate in protecting the payload.

Pros	Cons
- Potentially simple structure	- Requires accurate prediction of velocity
- Easy to test	- Possible orientation requirements

Table 12: Pros and Cons of Crushable Structure Landing

Airbags

Similar to the crushable structure, airbags can be used to absorb the energy upon impact. Instead of using the kinetic energy of the system to perform work and deform a structure, airbags would transfer the kinetic energy of the system to the gas inside the airbag[7]. Airbags have been used for various spacecraft missions such as Project Mercury, Luna 9, Luna 13, the Mars Pathfinder, and the Mars Exploration Rover[7]. Additionally, for the Orion Crew Module, an airbag landing system has proven effective at safely landing the system at a speed of 40 (ft/s)[20]. With previous application in space missions, an airbag that can survive both space and launch conditions should be feasible.

There are two methods of using an airbag for landing. The methods differ by the decision to either vent the gas or not. If the gas is not vented, the kinetic energy is transformed into potential energy based on the elasticity of the airbag[7]. The potential energy of the airbag is then converted back into kinetic energy and would cause a bouncing behavior. Over time, losses would cause the bouncing to stop. Upon impact, this system would effectively be equivalent to a disturbed spring system oscillating until returning to steady state.

If the gas is vented, the kinetic energy is transferred to the gas in the airbag and is then the gas exits the airbag to the surrounding environment[7]. By venting the gas to the surroundings, the energy transferred to the airbag and the gas inside leave the system and minimizes energy transfer to the payload. Although this method prevents any danger from bouncing the previous method described would case, it requires time sensitive deployment.

Pros	Cons
- Allows higher speed landings	- Possible time sensitive deployment
- Previous use in space missions	- Sensitive to landing surface
	- May danger payload if gas is not vented

Table 13: Pros and Cons of Airbag Landing

Location Determination

The location determination stage of the mission is the beginning of the recovery phase. The goal of this stage is for either the vehicle or the recovery team to determine where REPTAR is. REPTAR cannot be found if neither REPTAR nor the search party know its location, so this stage is crucial for successful recovery.

Global Positioning System

Global Positioning System, commonly known as GPS, is a global navigation satellite system that provides location and time information anywhere or near the Earth. It calculates the location and time by solving equations to compute the precise position of the receiver and the deviation from true time. To solve for the four unknown quantities (three position coordinates and time), it needs a minimum of 4 satellites in receiver's line of sight. The GPS operates independent of telephonic or Internet connection[6].

The receiver uses messages received from satellites to determine the satellite positions and time sent. The equations for location determination is in the form of a traditional 3-D distance calculation equation with an additional term to account for the receiver clock bias. This process is visualized below in Figure 15.

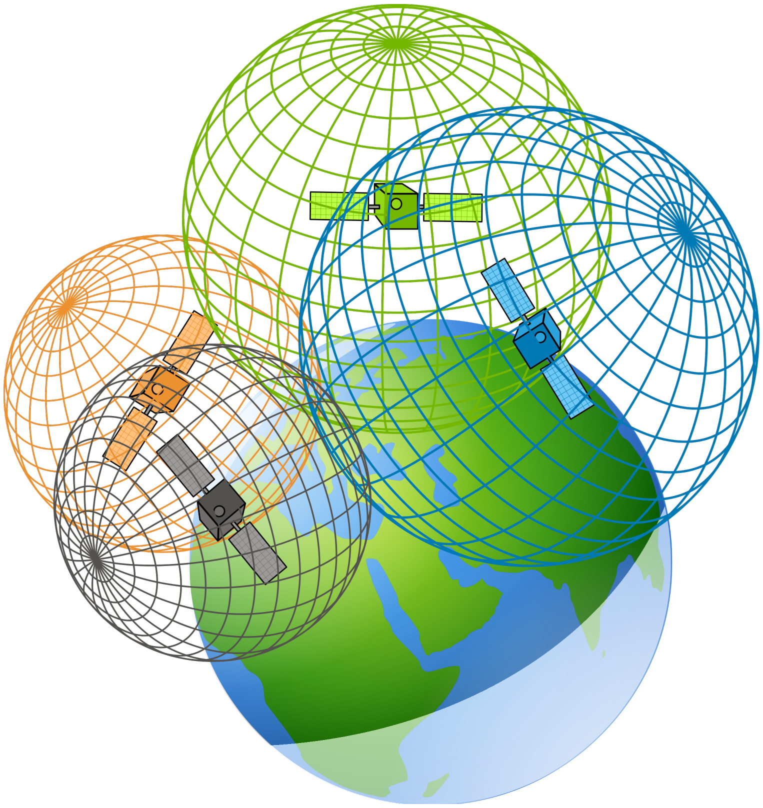


Figure 15: Four Satellites allow Accurate Position Determination

The equations for distance from a satellite and clock bias are solved by numerical or algebraic methods. This is also known as pseudo-ranging method. Multiple combination of satellites with relative sky directions are used for getting results with better resolution. This allows the accuracy of up to a meter. The output of the receiver is a latitude and longitude.

The GPS is a very reliable system as it is used for military, civil and commercial users around the world. Due to its heavy usage in the aerospace industry it has been implemented in appropriate form factors for small satellites. Therefore, it is available commercially off the shelf at reasonable prices, which makes it even a more compelling solution. The pros and cons of a GPS unit are summarized in Table 14.

Pros	Cons
- Low mass and volume - Easy interface - Accuracy of up to 1 m - Small form factor - Low cost - Good flight heritage	- Requires open access of sky

Table 14: Pros and Cons of GPS

Pseudo-Noise Ranging

There are several types of ranging that have been researched and implemented on on-orbit location determination system. For example, pseudo random noise, tone, sequential ranging etc. Each ranging transmits and receives data with different encryption code. PN range in particular was chosen as one of the options for trade study due to its common use and familiarity.

Pseudo-noise ranging is used for satellite identification, ranging and mitigation of reflection and interference effects[23]. It uses an encrypted code for protection against spoofing. The range is calculated using the time delay of line of sight radio signals from when they are transmitted to when they are received. PN has been used extensively by the Deep Space Network to support interplanetary missions.

It is a key feature of GPS, as GPS uses multiple PN ranges instead of one for higher precision. Implementing a custom PN range system would require building a simple GPS from scratch with significant accuracy, form factor, and performance degradation relative to an existing GPS solution. The pros and cons of PN ranging are summarized in Table 15.

Pros	Cons
- Low mass and volume	- Difficult to implement
- Small form factor	- Difficult to test
- Good flight heritage	- Time consuming
	- Limited by line of sight

Table 15: Pros and Cons of PN Ranging

Radar Signature - Reflective Paint

The idea of increasing REPTAR's radar signature is a passive solution to location determination. Rather than use electronics to compute a position solution, an object with a higher radar signature becomes detectable by ground solutions such as radar antenna. More formally, the Radar Cross Section (RCS) of an object describes the measure of the target's ability to reflect radar signals in direction of the radar receiver[19].

$$\sigma = \frac{4\pi r^2 S_r}{S_t} \tag{7}$$

Mathematically, the radar cross section is computed using Equation 7 where σ is the RCS, r is the distance from the antenna, S_r is the scattered power density in the range, and S_t is the power density intercepted by the target. Equation 7 assumes the object is in free space. Due to ground signal interference, the signal will be significantly degraded. However, the values found using Equation 7 can be considered a best case scenario. More qualitatively, σ is dependent on three factors: the projected cross section area of the object, the reflectivity, and the directivity of the object. The size and orientation of REPTAR will be fixed by the functional requirements, thus its cross section area cannot be modified. Increasing directivity also involves changing the shape of REPTAR to direct some of the power back to the radar. Thus, the quantity left to modify would be reflectivity. A coat of reflective radar paint would increase REPTAR's reflectivity according to the reflectance value of the paint. Paint coatings have been used on numerous other CubeSat missions and spacecraft in general, meaning they have sufficient launch heritage.

Pros	Cons
- Negligible mass and volume	- Low position solution accuracy
- Simple to implement	- High background noise from ground
	- Requires direct line of sight

Table 16: Pros and Cons of Reflective Paint

Location Transmission

The location transmission stage of the mission is the final part of the recovery phase in which the REPTAR system will broadcast its location (as determined in the Location Determination phase) to a Raytheon recovery team located in a pickup truck (or similar vehicle) parked along the side of I-80 in the middle of the UTTR. The Location Transmission system on REPTAR will be responsible for forwarding on a set of location coordinates to the recovery team.

Near Vertical Incident Skywave (NVIS)

One of the biggest challenges the location transmission system faces is being able to transmit the signal clearly over a relatively large area (a circle of a radius up to 50 miles) while the antenna can be no more than 30cm above the ground (the maximum length on an edge of the CubeSat volume). A solution to this problem is an NVIS transmitter which uses the ionosphere (specifically the D and F layers) to "bounce" low frequency signals (2-10MHz) back towards the earth. By making the waves' incident angle on the ionosphere very small it is possible to communicate with receivers located within 200-400km of the transmitter (regardless of the surrounding terrain)[16]. Figure 16 shows a typical raytracing of an NVIS system operating.

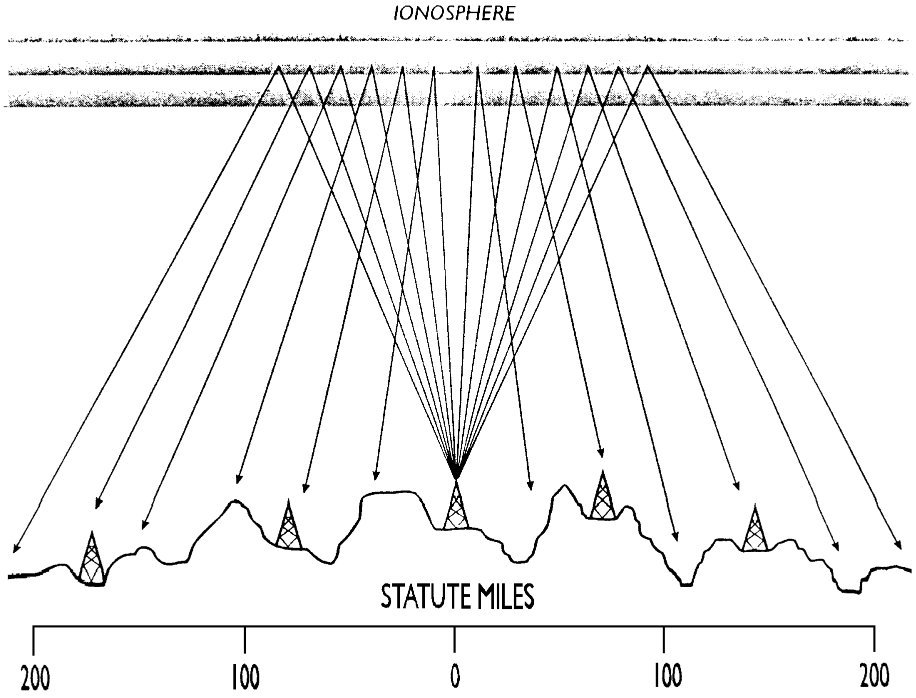


Figure 16: NVIS Communication System Operation[10]

A typical NVIS communication system block diagram is laid out in Figure 17. The communication link needed for the REPTAR system to communicate its location is unidirectional so the REPTAR radio will only need to transmit and the recovery team radio will only need to receive. This situation gives the team a larger number of possible implementations of each radio as many COTS components in the HF band are unidirectional.

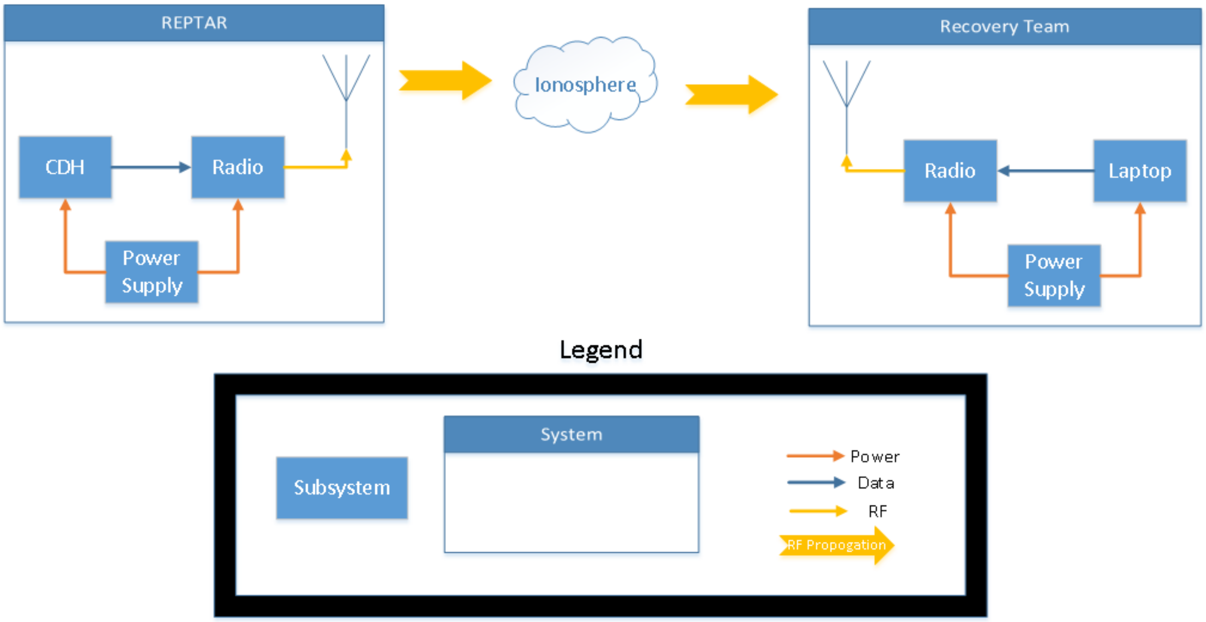


Figure 17: NVIS Communication System Block Diagram

There is a large variety of possible communication protocols that have been successfully demonstrated at HF frequencies. The US Army has successfully demonstrated internet over HF in an NVIS configuration at an effective data rate of 25 (kbps)[16]. These high data rates are possible due to a relatively high power operation of the transmitting system in order to overcome the high susceptibility of the signal (even at small bandwidths) to environmental noise sources. It is possible for the REPTAR system to use a continuous wave (CW) Morse code signal in order to send coordinates to the recovery team. This approach allows REPTAR to operate at very low power levels (0.25-0.5 Watt)[18] but limits the data rate significantly (0.83 bps at 4Hz bandwidth).

Pros	Cons
- Low frequency makes testing easy	- Requires a large antenna
- Long communication range	- Location and time dependant RF propagation
- Extensive commercial and military use history	- Low data rates
- Team experience with technology	- High environmental noise susceptibility
- No required external contracts	
- Low power draw in CW operation	

Table 17: Pros and Cons of NVIS Communication System

Microwave Line of Sight Communications System

The REPTAR team has considered a microwave line of sight communication system (most likely with carrier frequencies in the VHF/UHF range) in order to meet the needs of the location transmission phase of REPTAR's operation. Such a communication system is outlined in Figure 18. This system is very similar to the block diagram outlined for an NVIS system in Figure 17 but the operation of the radios, antennas, power supplies, and control systems will be different given the different operational frequencies.

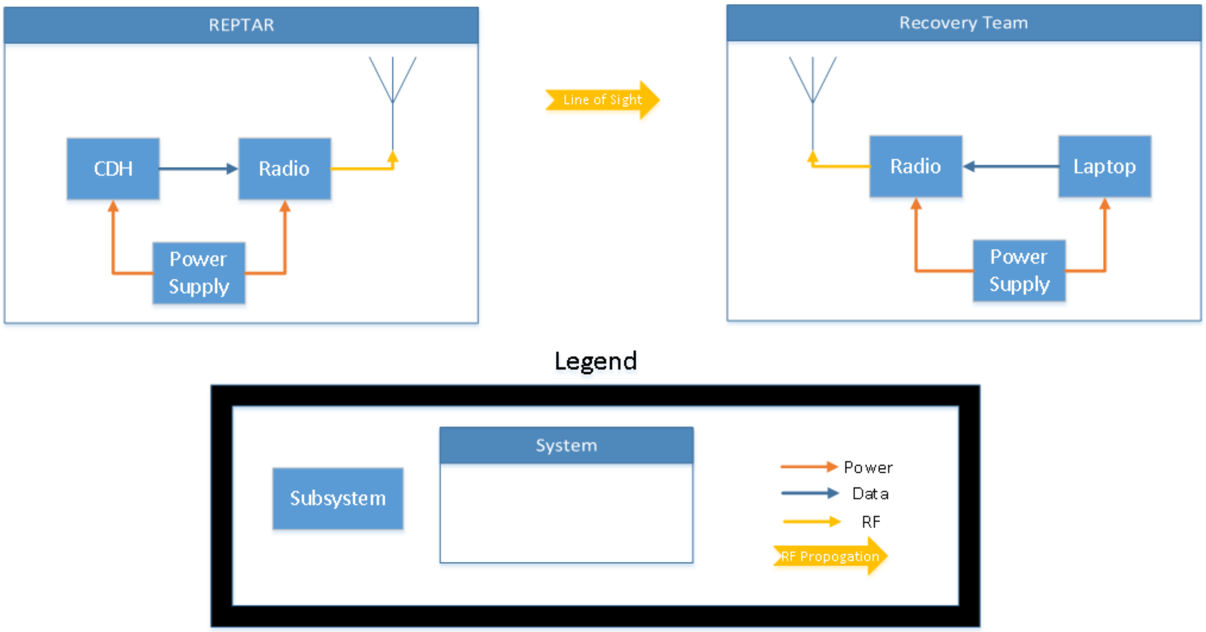


Figure 18: Microwave Communication System Block Diagram

An important factor in a microwave communications link is the effective line of sight available to the transmitting antenna. In a microwave communication system both transmitting and receiving antennas must have line of sight to each other. Unfortunately the effective line of sight of the transmitting antenna on REPTAR is limited by the maximum possible height the antenna can be placed at. As REPTAR is being designed to fit into either a 3U or 6U CubeSat form-factor, the antenna can be placed at a maximum of 30 cm above the surface of the earth (assuming no deformation of the structure).

Most microwave communication systems and their components are rated at or above MILSPEC standards for thermal, shock, and vibration.

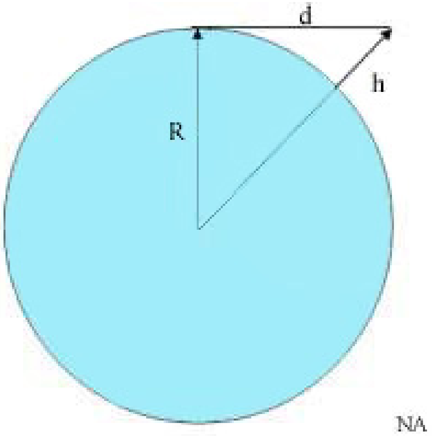


Figure 19: Effective Line of Sight Horizon for Microwave Communication System

In order to better understand the performance of a Microwave antenna operating at this height, the maximum possible line of sight available is calculated. Figure 19 shows the geometry associated with determining the maximum communication radius of the proposed microwave transmit antenna. Since the antenna is so close to the ground relative to the radius of the earth calculating the distance d (distance to the horizon) is approximately equivalent to the effective radius of coverage of the antenna. Based on the above geometry, d is calculated using the Pythagorean theorem as in Equation 8.

$$d^2 = (R+h)^2 - R^2 = 2Rh + h^2 \rightarrow d = \sqrt{2Rh + h^2} \tag{8}$$

Assuming that the antenna is mounted at the top of a 3U or 6U CubeSat bus, the parameters are:

$$R = 6,371,000m \tag{9}$$
$$h = 0.3m \tag{10}$$

Plugging in the above parameters to Equation 8, d = 1955 meters or 1.21 miles. This is significantly short of the 20 miles of effective communication that the REPTAR system is required to communicate over (DR4.1) and as such a microwave communication link is not feasible without some sort of deployable mast to elevate the microwave antenna.

In order to determine the size of this mast for a line of sight range of 20 miles (32186.9 meters) we rearrange equation 8 to solve for h and get the below equation 11. Using the values of d and R already identified we get that the antenna would need to be 81.3 meters above the ground in order to meet DR4.1. This is a very large deployable to fit into a 6U or 12U structure and makes practical implementation of a microwave line of sight link very difficult.

$$h = \sqrt{d^2 + R^2} - R \tag{11}$$

Pros	Cons
- Many COTS options	- Cannot meet DR4.1 without large deployable mast antenna

Table 18: Pros and Cons of Microwave Communications System

Spot Tracker Beacon

A possible solution for location transmission is to utilize a Spot Tracker beacon. A Spot Tracker is a COTS component that allows a predetermined message containing the current location of the Spot Tracker to be sent via satellite so that the message can be viewed by anyone with Internet access via a web portal. A block diagram for this system is shown below in Figure 20.

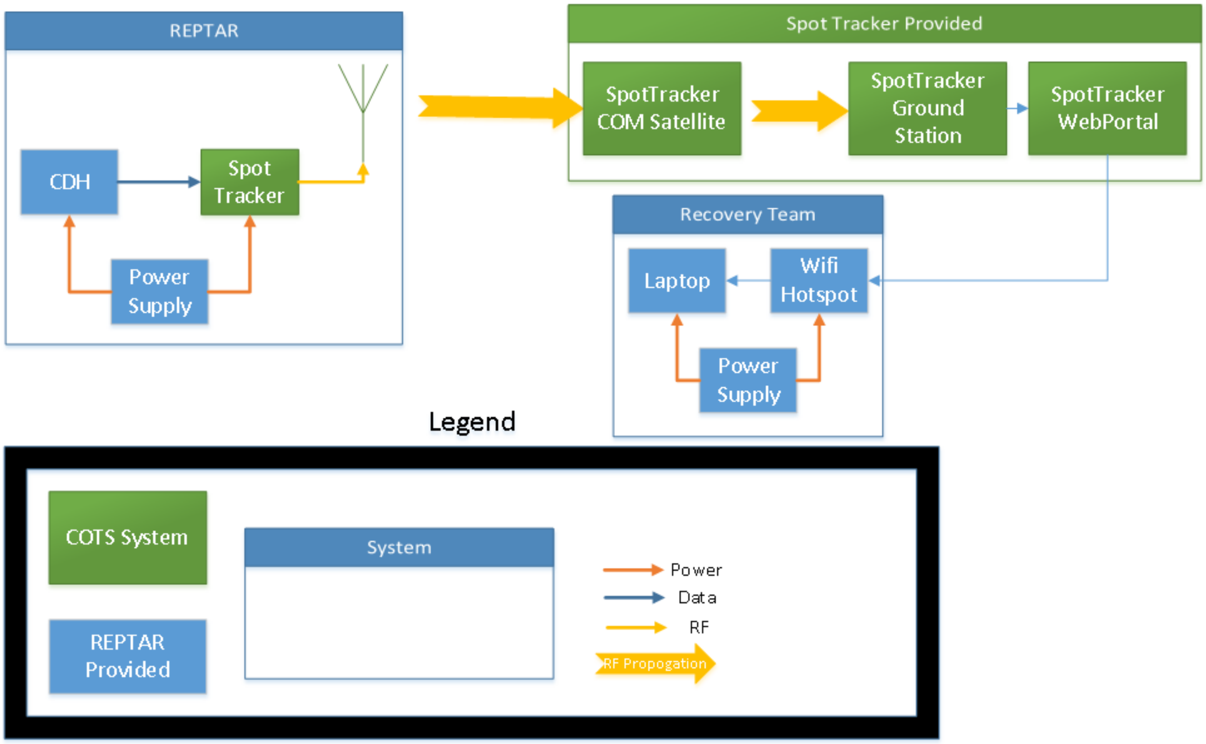


Figure 20: Spot Tracker System Block Diagram

The spot tracker is an easy solution to implement that guarantees communications coverage with very little work needed by the REPTAR team to ensure communications capability. Unfortunately, the spot tracker does not have a built-in electrical interface to control this system with an external command and data handling system because the spot tracker was designed to consumer use. The spot tracker is also a relatively large and heavy system (approximately the size and mass of smart cellular phone) which would pose problems in integrating the unit. Additionally, the Spot Tracker does not utilize encryption. This could prove problematic if Raytheon wants to use REPTAR to recover classified payloads.

Pros	Cons
- Guaranteed Coverage - Easy to implement	- Requires custom electrical integration - Relatively large mass and volume requirement - Utilizes a public, unencrypted network

Table 19: Pros and Cons of Spot Tracker

Cellular Phone Communications System

A more integrated COTS solution to the location transmission phase of REPTAR's operation is a smart cellular phone which has been configured to send a text message with REPTAR's current position as determined in the location determination phase. Figure 21 shows how such a system would operate.

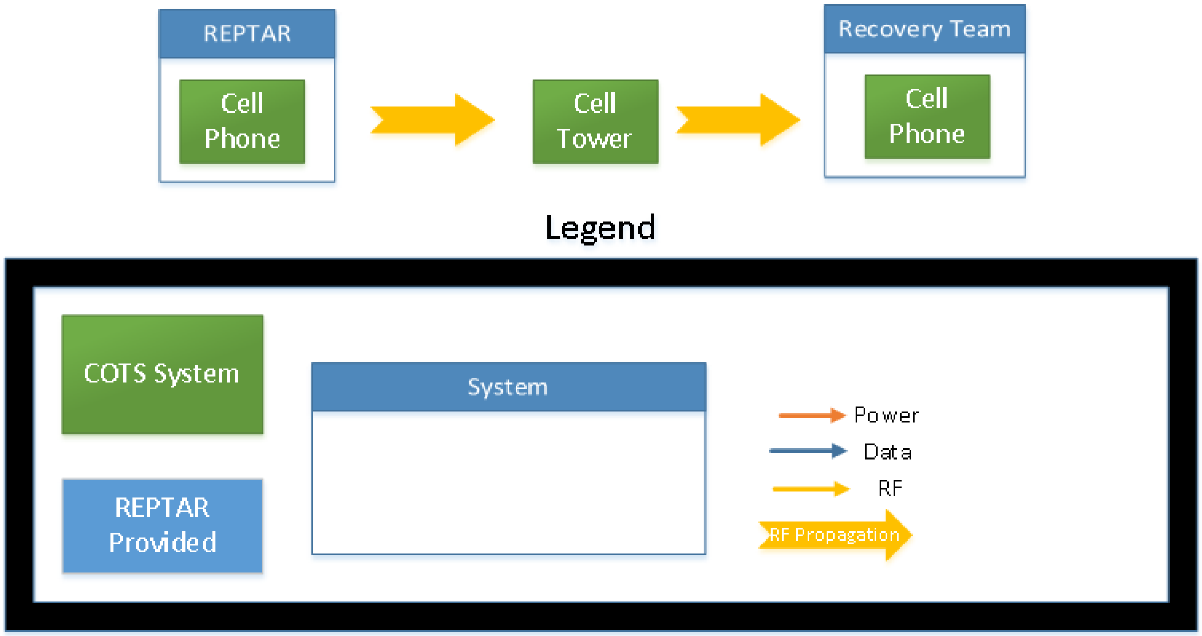


Figure 21: Cellular Phone System Block Diagram

This communication system would be relatively low cost and easy to implement as a smart cellular phone provides its own power source, signal processing, GPS, and transmission system in one convenient package. This system does not have independent inhibits as required by DR4.2 but such inhibits could be implemented relatively easily. Unfortunately smart cellular phones are relatively expensive from a mass and volume perspective and have a fixed form factor which does not lend itself well to CubeSat integration. Despite these drawbacks smart cellular phones have been used by NASA on previous CubeSat missions successfully.

Testing the cellular link system to ensure that it can provide coverage anywhere within the UTTR is much more problematic. Cellular providers do not have good signal strength maps in the public domain and what little information available is not enough for the REPTAR team to understand if a cellular provider provides adequate coverage in the UTTR. Should this method be selected the team would likely have to determine the signal strengths of different cellular providers in the UTTR on its own.

Pros	Cons
- Low cost to implement - Simple to implement	- Would require custom RF inhibits - Large mass and volume requirements - Difficult to verify communication performance

Table 20: Pros and Cons of Cellular Phone

Iridium Network

Another possible location transmission approach would be for REPTAR to utilize the Iridium communications network in order to guarantee communication once REPTAR has landed. A block diagram for an example communication system utilizing the Iridium network is detailed in Figure 22.

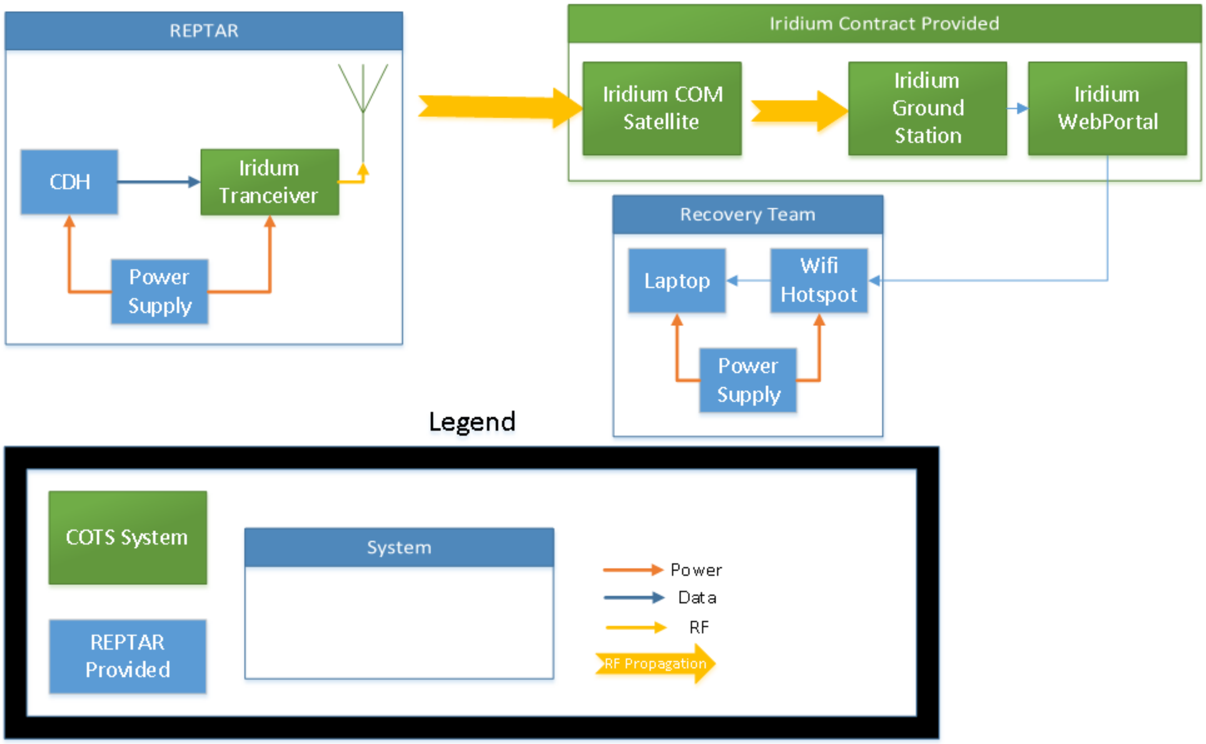


Figure 22: Iridium Communication System Block Diagram

Figure 22 is very similar to Figure 20 because both the spot tracker and Iridium network operate very similarly, the biggest differences being the Iridium network's greater possible data transmission capabilities and the fact that the Iridium network does not have a location determination capabilities. The Iridium network provides guaranteed communications coverage at any time in a very simple to implement system. The Iridium network is also very expensive to gain access to (both for the transceiver and for the subscription based access to the transmitted data). Most available Iridium transceivers are also very bulky which would pose several mass and volume challenges in integration.

Pros	Cons
- Guaranteed coverage	- High cost
- Simple to implement	- High mass and volume requirements

Table 21: Pros and Cons of Iridium Communications System

IV. Trade Study Process and Results

Trade studies were conducted with five different metrics considered to compare the options. The first option, which is always common with any space mission, is mass. Lower mass means lower cost to put into orbit. Lower mass also means that the terminal velocity of the vehicle will be slower, which is very important for the descent and landing portions of the mission. This metric was weighted at 0.15, lower than the 0.2 baseline, due to the fact that there were not explicit mass requirements from the customer.

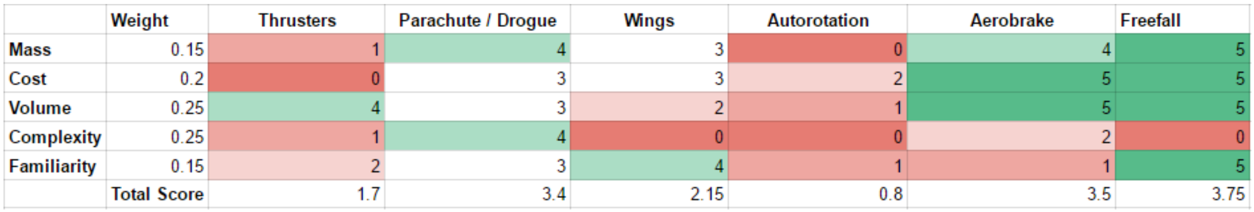
The second considered metric was cost. The budget for this project is $5,000, and it is important that adequate funds are left over for testing and validation. This means that components need to be inexpensive enough to be tested and potentially replaced in certain situations. Cost was weighted 0.20, which is the baseline weight, due to the fact that cost is a tight constraint on the project. The team cannot exceed the budget, so inexpensive options deserve more weight toward the final score.

The third metric is volume. The maximum size REPTAR may be is 6U, but the team is designing for a 3U size including payload. This means that the team may only have 2U to fit all components to complete the mission. With space a rare commodity, small components and solutions are crucial. This metric was weighted 0.25, above the 0.2 baseline, and this is due to the fact that the group fully intends to keep REPTAR within 3U including payload. To make this happen, high volume solutions cannot be considered.

The fourth metric is complexity. With less than nine months to complete the project and with many missions phases to focus on, individual solutions cannot be overly complex. Complexity is defined not only by the technical complexity of the solutions, but also by the time it would take to implement the solutions. This metric also received a 0.25 weight, which is again above the 0.2 baseline. This was done because the schedule for the project is tight and inflexible. Complex options would jeopardize the team achieving its goal on schedule. Additionally, simple options would allow the team to perform more testing and optimization.

The fifth and final metric is familiarity. It will be easier for the group to design using concepts that they have experience with, so it is important that familiarity be considered when picking a solution. This metric was weighted 0.15, below the 0.2 baseline, because the group has faith that it can learn new technologies and techniques. Though scheduling would be easier if the team is familiar with all of the design options it chooses, the team can likely stay on schedule if they end up working with foreign concepts.

Descent



	Weight	Thrusters	Parachute / Drogue	Wings	Autorotation	Aerobrake	Freefall
Mass	0.15	1	4	3	0	4	5
Cost	0.2	0	3	3	2	5	5
Volume	0.25	4	3	2	1	5	5
Complexity	0.25	1	4	0	0	2	0
Familiarity	0.15	2	3	4	1	1	5
	Total Score	1.7	3.4	2.15	0.8	3.5	3.75

Figure 23: Descent Trade Study Results

Freefall

Mass - Rating (5/5) Since no extra components are needed for freefall, all mass would be allocated to protecting the payload during landing.

Cost - Rating (5/5) No extra components are needed to protect payload.

Volume - Rating (5/5) REPTAR would consist of only landing systems.

Complexity - Rating (0/5) The required landing system would need to save the payload when the vehicle impacts the ground at roughly 150 mph and be extremely flexible to account for any orientation during landing.

Familiarity - Rating (5/5) All members of REPTAR have taken dynamics and orbital control. Basic understanding of drag is needed.

It is noted that the freefall option, though high scoring in almost all categories, is ultimately not a feasible option due to the high speeds that it would allow the SmallSat to impact the ground. With an impact speed surpassing 60 m/s, it would be impossible for the group to keep the payload under the required 8.5 G's of loading.

Drogues and Parachutes

Mass - Rating (4/5) Parachutes and drogues are typically made of nylon and can come in lightweight forms designed for mass constraints. The mass of the lines holding the parachute or drogue in place will use most of the weight. Since REPTAR will be moving at higher than normal velocities, more sturdy and heavy lines will be required to ensure the parachute does not get ripped off due to drag force.

Cost - Rating (4/5) Parachutes and drogues are available from COTS. From research, these prices will not harm REPTAR's budget. REPTAR team could also design and build their own.

Volume - Rating (3/5) Parachutes and drogues when packed can occupy a large amount of the 1U CubeSat. Both together may be to much volume for REPTAR constraints. When including the lines into the volume count, everything will have to be tightly packed.

Complexity - Rating (4/5) Parachutes have been used for decades and the research and technology is simple enough that the resources available will create a successful use of them. It consists of a deployment mechanism and ensuring the lines are held in place that the sudden increase in drag force will not tear them out.

Familiarity - Rating (3/5) Only a few members of REPTAR have worked with parachutes, but not at high velocities. Due to their low complexity, REPTAR team would be able to learn and implement parachutes and drogues with the help of resources and advice from COTS vendors.

Aerodynamic Braking

Mass - Rating (4/5) The system that was researched is a low mass option to decrease the velocity of the system.

Cost - Rating (5/5) The amount of materials that would be required to purchase for an aerodynamic braking system is low. Much of the cost of the system would be from manufacturing but this would be performed mostly in-house and would be relatively low cost.

Volume - Rating (5/5) Due to the system of rails being placed on the outside of the SmallSat, the proposed method of aerodynamic braking would not take up any volume inside of REPTAR.

Complexity - Rating (2/5) The rail system along with the deployable panels would be quite complex to design and build. Having moving parts with additional testing to confirm that they could survive the force of deploying could be difficult.

Familiarity - Rating (1/5) The deployable rail system has only been integrated on a 3U CubeSat system in a lab. It has never flown in space and the REPTAR team members have no familiarity with a system such as this.

Autorotation

Mass - Rating (0/5) Due to the light weight nature of SmallSats (1.33 kg per 1U), the mass of a rotor system that has hub, hinges, mast, blades (that are potentially telescoping), and bearings, all of which must survive rapid deployment and high aerodynamic and rotational forces would be a very significant portion of the mass of the SmallSat.

Cost - Rating (2/5) Expenses in materials and manufacturing of lightweight and precise components capable of withstanding aerodynamic and rotational forces and imbalances would likely be very high. Replacement if damages also expensive.

Volume - Rating (1/5) Based on required rotor diameter, mast diameter, with a reasonable chord length, the volume required would be a large portion of the SmallSat. Additionally, it would span all available units reducing flexibility in placing other components.

Complexity - Rating (0/5) Rotor systems are very complex to design. Small angle approximations, dis-symmetry of lift across the span of each blade as well as across the disk itself are inherently difficult to model. Blade tip speed and rotor speed control are extremely important to prevent severe vibrations and forces. Due to these factors, the rotor system is not readily scalable.

Familiarity - Rating (1/5) Typical aircraft wing design if fairly well known by team members and faculty, but rotor systems are much more complex. There is not a significant knowledge base to guarantee success.

Thrusters

Mass - Rating (1/5) The mass for a system of this type will vary, however, with options of thrusters online being themselves light, the addition of propellant is the main concern. This can be verified to fit the systems weight requirement quite easily with an engine of a large specific impulse, however as the efficiencies of these engines decrease, the amount of propellant will increase.

Cost - Rating(0/5) The cost of thrusters is the biggest driver for this alternative as the budget allocated for this project is unable to purchase thrusters that provide enough thrust for a safe descent and landing. The price tag for a 1N thruster is upwards of $50,000 and is out of reach for this project's budget.

Volume - Rating(4/5) The ability to find smaller, more powerful thrusters nowadays allows this study to be at a higher value. The inclusion of the propellant will lower this value slightly, as the densities of different propellants allow for smaller packaging to be used and lower the volume required to hold the propellant on-board.

Complexity - Rating(1/5) A thruster system would be quite difficult to integrate into an autonomous system with respect to the small amount of experience this team possesses regarding thrusters as a whole.

Familiarity - Rating(2/5) The familiarity of thruster systems within this team is not as high as was expected. With the propulsion course being the only real familiarity for any sort of propulsive system for this team the thruster system doesn't obtain a high familiarity rating.

Wings

Mass - Rating (3/5) Wings tend to be light weight to produce optimal lift for their size. The avionics will contribute additional mass.

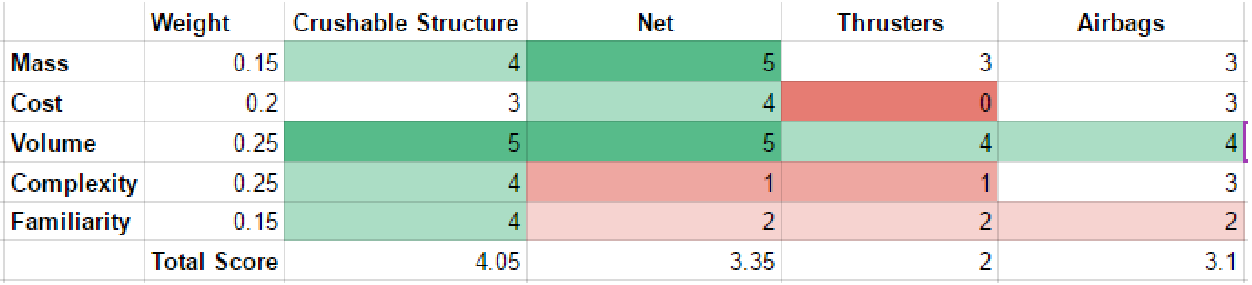
Cost - Rating (3/5) The general cost of wings of with a span around 50 cm will be inexpensive, but the necessary avionic components will increase the cost. This would ultimately be dependent on a trade study of different wings however.

Volume - Rating (2/5) Space would be used for the wings, rudder, and avionics needed for active control. The front of REPTAR may require material to make it more aerodynamic too. This would ultimately be dependent on a trade study of different wings however.

Complexity - Rating (0/5) Creating the active control system and being able to land in the UTTR after altering the trajectory would be extremely challenging. Other methods not requiring active control are much simpler.

Familiarity - Rating (4/5) The familiarity towards wing designs and the principles of flight are well known, but there is little familiarity with developing the active control system necessary for this method.

Landing



	Weight	Crushable Structure	Net	Thrusters	Airbags
Mass	0.15	4	5	3	3
Cost	0.2	3	4	0	3
Volume	0.25	5	5	4	4
Complexity	0.25	4	1	1	3
Familiarity	0.15	4	2	2	2
	Total Score	4.05	3.35	2	3.1

Figure 24: Landing Devices Trade Study Results

Net

Mass - Rating (5/5) Since the net will be completely ground based it would have no negative implications on the overall mass of REPTAR.

Cost - Rating (3/5) Deploying a polyethylene net is a middle of the road method in terms of cost for landing REPTAR safely in the UTTR. A net that is 100 m^2 is quite large and difficult to ship which would also drive up the overall price of acquiring the net.

Volume - Rating (5/5) Once again, the net would not be implemented within REPTAR. For this reason the net would require no volume and receives the highest volume rating.

Complexity - Rating (1/5) In order for REPTAR to safely land in the net, an active control system would be required to guide REPTAR to the landing area. This requirement would add a whole new level of complexity to the mission and therefore receives a low rating for the complexity.

Familiarity - Rating (2/5) In July 2016, Luke Aikins jumped from 25,000 ft and landed safely into a polyethylene net[3] without a parachute. There is available research on the subject, and the group members have experience with structures.

Thrusters

Mass - Rating (4/5) The mass for a system of this type will vary, however, with options of thrusters online being themselves light, the addition of propellant is the main concern. This can be verified to fit the systems weight requirement quite easily with an engine of a large specific impulse, but in this case the smaller ΔV's experienced during a landing sequence would allow for thrusters as a viable option in regards to the mass of the system.

Cost - Rating(0/5) The cost of thrusters is the biggest driver for this alternative as the budget allocated for this project is unable to purchase thrusters that provide enough thrust for a safe descent and landing. The price tag for a 1N thruster is upwards of $50,000 and is out of reach for this project's budget.

Volume - Rating(4/5) The ability to find smaller, more powerful thrusters nowadays allows this study to be at a higher value. The inclusion of the propellant will lower this value slightly, as the densities of different propellants allow for smaller packaging to be used and lower the volume required to hold the propellant on-board.

Complexity - Rating(0/5) A thruster system would be quite difficult to integrate into an autonomous system with respect to the small amount of experience this team possesses regarding thrusters as a whole as well as the combination of thrusters and another method could cause complications to arise in the timing/implementation of the thruster system.

Familiarity - Rating(2/5) The familiarity of thruster systems within this team is not adequate enough to implement such a complex system. as high as was expected. With the propulsion course being the only real familiarity for any sort of propulsive system for this team the thruster system doesn't obtain a high familiarity rating.

Crushable Structure

Mass - Rating (4/5) Mass required may be minimal if material is carefully selected. However, depending on descent capabilities mass may not be able to be minimized effectively.

Cost - Rating (3/5) For simple structures that would essentially be a block of material, minimal manufacturing is required so costs would simply be for materials. Due to the size and weight of the system, any material required would be minimal which would have costs be minimized. However, due to the system being designed to fail, the structure can only be used once. For testing alone, at least two copies of the structure will be needed for static testing and drop testing. Although an individual structure may be inexpensive, requiring multiple copies of the structure will add up.

Volume - Rating (5/5) If the material or structure used would have a high compression strength, a minimal amount of material may be required depending on landing velocities.

Complexity - Rating (4/5) The simplest structure to absorb energy would simply be a plate of material that was placed on the face where REPTAR would expect to land. However, impact analysis is difficult and there is a large amount of possible materials that may be valid. Extensive research must be conducted to determine a suitable material for absorbing energy in addition to being suitable for being put in space.

Familiarity - Rating (4/5) The idea behind using a crushable structure is simple and quickly understandable based on previous work the REPTAR team has been exposed to. However, there is a large amount of possible materials that could be valid to use. Extensive research would be required to pick a material that is ideal for REPTAR's mission.

Airbags

Mass - Rating (3/5) Due to the size of the system, an airbag required to land the system safely would not be too large or heavy. Still, due to the mass and limitations an airbag would likely still take up a significant amount of possible mass.

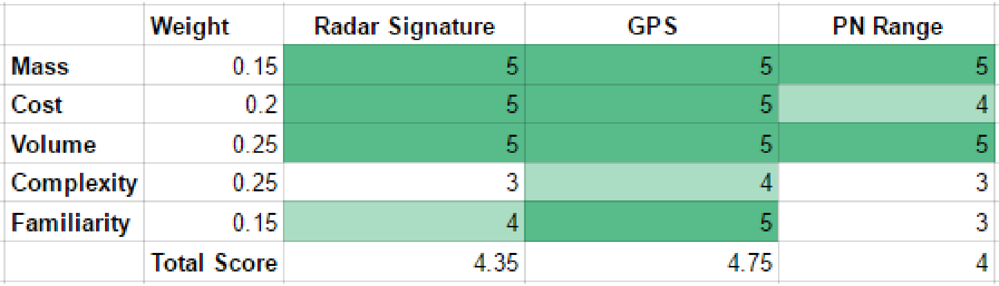
Cost - Rating (3/5) Constructing and testing a resilient airbag could prove to be rather costly. Additionally, if the airbag were to be damaged during testing or tested for possible failure scenarios multiple airbags would quickly affect the budget.

Volume - Rating (4/5) The size of the airbag required would not need to be too large due to the low mass of the system. The gas to fill the airbag would most likely be a solid material until a signal is sent to start the chemical reaction to create gas.

Complexity - Rating (3/5) Airbags are typically used in automobiles and there exists a large amount of literature on there tests and design. There are various methods to consider on how to signal deployment of the airbag depending on design. Analysis and verification of the airbag may prove difficult.

Familiarity - Rating (2/5) Airbags and the basic concepts behind them are common knowledge due to them being a common feature in most automobiles. However, the REPTAR team has no direct experience in developing or analyzing airbag systems.

Recovery Location Determination



	Weight	Radar Signature	GPS	PN Range
Mass	0.15	5	5	5
Cost	0.2	5	5	4
Volume	0.25	5	5	5
Complexity	0.25	3	4	3
Familiarity	0.15	4	5	3
	Total Score	4.35	4.75	4

Figure 25: Location Determination Device Trade Study Results

GPS

Mass - Rating (5/5) Typical GPS modules for a CubeSat weigh about 1 – 2grams.

Cost - Rating (5/5) The cost of the module can vary anywhere between \$50 to \$250 depending on the model chosen for the application. This would be well within the project's budget.

Volume - Rating (5/5) The volume of the module is fairly small compared to the volume of the CubeSat. It will also vary based on the model chosen, however it will have volume in the range of $5 * 5 * 2\ mm^3$ to $25 * 25 * 2\ mm^3$.

Complexity - Rating (4/5) GPS is a fairly simple device for location determination as it can be bought off the shelf. Therefore, the only complexity left in the system would be the interface between the GPS and the transmission system.

Familiarity - Rating (5/5) The entire group has experience with GPS from the electronics course taken in junior year.

Pseudo Noise Ranging

Mass - Rating (5/5) The mass of the needed PN Range device would be relatively small. However, exact numbers cannot be worked out as it would be a custom system built by the team.

Cost - Rating (5/5) The PN Range system is relatively low cost(<250) as well, well within our budget.

Volume - Rating (5/5) Since it will be a custom system, the form factor can be adjusted accordingly.

Complexity - Rating (3/5) This will be difficult to implement as the entire ranging code will need to be developed and tested. This would cause significant scheduling issues for the team.

Familiarity - Rating (3/5) Only a few team members have experience with this type of ranging.

Radar Signature - Reflective Paint

Mass - Rating (5/5) A coating of reflective paint around a 3U CubeSat would have mass less than 1 g.

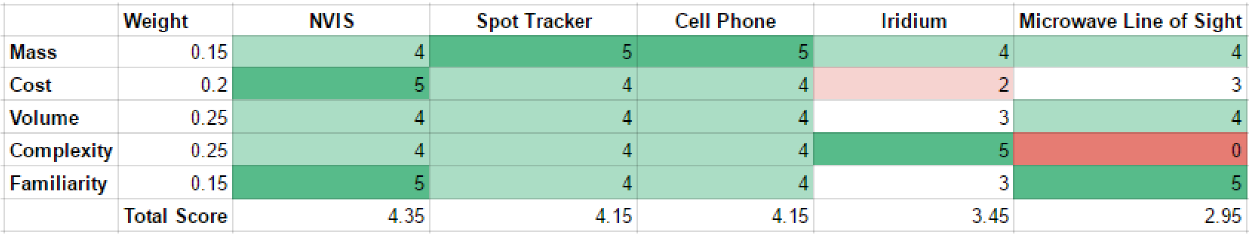
Cost - Rating (5/5) The typical cost of a spray can of paint would be around \$30-\$50, depending on the vendor selected, which is well within the project's budget.

Volume - Rating (5/5) A coating of reflective paint around a 3U CubeSat would have negligible volume.

Complexity - Rating (3/5) The implementation of the paint job for the CubeSat would be simple. However, operation of a radar antenna and subsequent location of the CubeSat adds additional work and complexity to the task.

Familiarity - Rating (4/5) Many team members will handle painting with ease, with a couple being experienced in radar antenna operation.

Location Transmission



	Weight	NVIS	Spot Tracker	Cell Phone	Iridium	Microwave Line of Sight
Mass	0.15	4	5	5	4	4
Cost	0.2	5	4	4	2	3
Volume	0.25	4	4	4	3	4
Complexity	0.25	4	4	4	5	0
Familiarity	0.15	5	4	4	3	5
	Total Score	4.35	4.15	4.15	3.45	2.95

Figure 26: Location Transmission Trade Study Results

NVIS

Mass - Rating (4/5) Most commercial High Frequency(HF) transmitters have a mass of around 500g with higher data rate systems having higher mass.

Cost - Rating (5/5) HF electrical components and systems are very inexpensive because of the low carrier frequency. COTS systems can be purchased for less than \$100.

Volume - Rating (4/5)

Complexity - Rating (4/5) An NVIS system is conceptually and physically simple to implement with much of the difficulty being placed on selecting the correct operational parameters[18].

Familiarity - Rating (5/5) The REPTAR electronics lead has significant experience operating HF stations and has designed and implemented multiple HF radios and antennas.

Microwave Line of Sight Communications System

Mass - Rating (4/5) Commercial microwave COM systems typically have a mass of 500 grams.

Cost - Rating (3/5) Good microwave communications systems operating in the VHF/UHF range cost around $700 as COTS solutions.

Volume - Rating (4/5) A typical microwave communications system will be around 0.5U in volume (with some variation depending on frequency.

Complexity - Rating (1/5) A microwave communications sytem would require an antenna elevated 81.3 meters above the ground in order to meet the minimum transmission distance requirement (DR 4.1). A deployable of this size would be very difficult to implement in a 6U or 12U form factor.

Familiarity - Rating (5/5) Almost every member of the REPTAR team is familiar with the theory of operation of a microwave communications link and several members of the team have experience implementing them.

Spot Tracker

Mass - Rating (5/5) A spot tracker has a mass of around 150 grams.

Cost - Rating (4/5) A spot tracker retails at $100, but the additional custom electronics to interface with the spot tracker would likely cost around the $150-$200 range bringing the total cost to $250-$300 in implementation.

Volume - Rating (4/5) A spot tracker unit is about the same size as a commercial smart cellular phone.

Complexity - Rating (4/5) The spot tracker itself incorporates both the location determination and transmission in a pre-implemented package but would require some development to interface our own command and data handling system to.

Familiarity - Rating (3/5) Several members of the REPTAR team have used spot trackers or similar GPS beacons but the team does not have any experience integrating one with another electronics system.

Cellular Phone Communications System

Mass - Rating (5/5) A typical smart cellular phone has a mass of around 200 grams.

Cost - Rating (4/5) A smart cellular phone with pay-as-you-go data plan will cost between $200 and $800 depending on plan and phone selected.

Volume - Rating (4/5) Most smart cellular phones come in a standard form factor of approximately 14.5cm by 4.5cm by 0.09cm. This form factor is unchangable and will take up a fairly large portion of the space allocated to us.

Complexity - Rating (3/5) A cellular phone is an integrated system that we can use to reduce the complexity of the software and electrical interfaces. Unfortunately these phones will require some rework to follow CubeSat acceptance testing[13] because they do not feature 3 independent RF inhibits. It will also be very difficult to verify that the chosen data plan will provide adequate coverage in the UTTR as available coverage maps from major network providers do not provide enough detail for the team to ensure communication.

Familiarity - Rating (4/5) Members of the REPTAR team have experience developing software for cellular phones but the team does not have experience with performing electrical rework of these devices.

Iridium Network

Mass - Rating (4/5) Iridium 9602 transceiver(common baseline) weighs about 30 grams with a compatible power supply weighing about 500grams, bringing the total to around 530 grams[12].

Cost - Rating (2/5) The Iridium network requires REPTAR purchase both a transceiver and data plan from the Iridium corporation. Due to the high demand for the Iridium network's limited bandwidth these transceivers and data plans can be very expensive (easily in the $1000-$1500 range).

Volume - Rating (3/5) Iridium transceivers are typically slightly larger than cellular phones by a factor of about 50%.

Complexity - Rating (5/5) An Iridium communication system comes out of the box ready to operate with our system.

Familiarity - Rating (3/5) Members of the REPTAR team have been part of teams that have used Iridium links but no one has worked directly on the Iridium link.

V. Selection of Baseline Design

Descent

Parachute and Drogue

Even though Freefall scored the highest in the trade study, the final decision for the descent mechanism came down to aerobrake and parachute/drogues due to the fact that Freefall was determined to not be feasible. Aerobrake did not win because the coefficient of drag would be too low to efficiently slow the vehicle down to landing speeds. A combination of parachute and drogue will provide a velocity that will not make the landing system too complex.

All design options for descent had the ability to survive launch and orbit, so survivability was removed from the trade study and not used as a deciding factor. Also, reliability was not added to the trade study because it is similar to survivability in that most possibilities are dependent on the investment of resources and testing put into the solution and not upon the actual design decision.

The deciding factors for the trade studies were complexity and volume. The size of the CubeSat is limited and typical parachutes and drogues will be able to be packed inside the tight volume with space available for a deployment mechanism. Parachutes and drogues have been used on numerous space and re-entry missions, and skydivers consistently use them without difficulty. Once deployed, the upward drag force will expand the canopy and begin to decrease the velocity. The rate of expansion will have to be controlled to limit the amount of loading the payload experiences. Also, before the main parachute can be deployed, REPTAR must be stabilized and the velocity decreased so drag force does not disable or rip off the parachute. Since there are plenty of COTS parachutes to buy, the cost is not high, and there are plenty of resources and documentation on how to deploy, use, and test parachutes and drogues. Based on research, parachutes and drogues will ensure REPTAR is at speeds that will not make landing too complex and out of reach. With the consistent use of parachutes in different scenarios it is a reliable option compared to the other possibilities for the descent phase.

Landing

Crushable Structure

Complexity is the main driving factor for the landing process. The other landing mechanisms seen in Figure 24 were determined to be extremely complex systems. When systems are overly complicated, there is too large a risk in landing failure. Additionally, with the selection of a parachute and drogue to slow down REPTAR, the viability of a crushable structure is increased as less energy will be needed to be absorbed due to a slower descent. The parachute and drogue also allow for a predictable speed and orientation before touchdown, allowing the crushable structure to be designed around expected landing conditions. There is also the consideration of volume added to the system. The parachute and drogue will take a significant amount of space so a simple structure that requires minimal space is ideal. There are limitations to how effective a crushable structure can be due to size and mass limitations. Depending on how effective the parachute and drogue are at decelerating REPTAR, supplemental means of ensuring a safe landing may be required.

Location Determination

GPS

Figure 24 shows a summary of the trade study performed for the location determination system. The most important parameters while choosing a solution for location determination are volume and complexity of the solution, therefore they are weighed the most, followed by the cost, mass and familiarity. As it can be seen that the top choice is GPS for this system due to its high reliability and accuracy. GPS has been used extensively in small satellites, giving it a good flight heritage and guaranteeing launch and space survivability. Implementing a custom PN range entails a significant amount of work which is not viable due to schedule constraints. The majority of the PN range implementation would entail designing a custom GPS with the same performance parameters. Due to GPS' readily availability (commercially) at reasonable prices, it becomes an even more compelling solution as it saves the team a considerable amount of effort from reinventing the wheel. The second choice is the radar signature which scored very close to GPS. Therefore, the final system would be a GPS, with a possibility of reflective paint for radar signature for redundancy.

Transmission

NVIS

Based on the parameters considered, the NVIS communication system was determined to be the best possible solution primarily due to its low cost of implementation and the team's high familiarity with the technology. Figure 26 shows a summary of the considered design options.

The location transmission systems can be grouped into two kinds of operational approaches: communication to ground based antennas and communication to satellite antennas. The technologies that rely on communication to satellites (Spot Tracker and Iridium) are characterized by high integration requirements (mass, volume, and mounting complexity) and easy implementation of the actual transmission link. The Iridium link scores lowest of the four considered solutions because of its high cost and integration requirements which would severely limit the budget and volume available for the rest of the REPTAR system. The Spot Tracker rates significantly better than the Iridium system because of its significantly cheaper cost and less taxing mass and volume requirements. Compared to the two satellite communications solutions, the Cellular phone performs better than an Iridium transmission link (largely due to its greatly decreased cost) but worse than a Spot Tracker given its greater difficulty in integration. All of these results are reasonable given the systems considered and the importance the team places on maximizing our available volume and minimizing complexity.

Of the reviewed solutions, the NVIS HF communications link scored the highest because of the team's familiarity with the system, its low cost, low mass, low volume, and low complexity. This solution makes the most sense for the REPTAR system as it provides a verifiable communications system in a small form factor at a lower cost than the other solutions reviewed by the team. Like the other solutions NVIS communication is also a well researched and understood communications technique that the team had great familiarity with. Overall this makes NVIS the obvious choice for REPTAR's location transmission phase.

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