Spring Final Review

REPTAR
REcoverable ProTection After Reentry

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**Customer:** Steve Thilker, Collin Baukol, Cody Humbargar, Jason Latimer (Raytheon)

**Advisor:** Dr. Brian Argrow, Dr. James Nabity
REPTAR shall assist in the recovery of a de-orbited 1U Raytheon Payload. The mission begins once the SmallSat has re-entered the atmosphere and has reached subsonic velocity. REPTAR shall facilitate the subsonic deceleration, landing, location determination, and location transmission portions of the mission.

Recovery of payload enables:

• Lower mission costs by re-using the payload
• Obtain samples collected by payload on-board
1) Launch
REPTAR components survive launch conditions as payload attached to a bus.

2) Orbit/Standby
REPTAR Components survive on orbit conditions. Batteries charged by bus.

3) De-orbit
Receive command from bus to power REPTAR systems. REPTAR separation from bus. Re-entry completed by Raytheon System.

4) Re-entry
Receive command from bus to power REPTAR systems.

5) Deceleration
Decelerate to subsonic speeds.

6) Land and Recovery
REPTAR protects payload during ground contact and transmit location.
After being decelerated to subsonic speeds, REPTAR activates atmospheric deceleration systems to protect the payload. Slows to safe landing speeds by deploying a parachute. Transmits location during descent. Lands payload safely within launch loading requirements.
## Levels of Success

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Form Factor – DR 1.1</th>
<th>Instantaneous G-Loading – DR 2.1</th>
<th>Communication – DR 3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 1</strong></td>
<td>The form factor of REPTAR including payload shall be 6U Standard</td>
<td>The payload shall endure a maximum instantaneous loading of less than 40 G</td>
<td>REPTAR shall beacon its location over a range of 20 miles</td>
</tr>
<tr>
<td><strong>Level 2</strong></td>
<td>The form factor of REPTAR including payload shall be 4U Standard</td>
<td>--</td>
<td>REPTAR shall beacon its location over a range of 30 miles</td>
</tr>
<tr>
<td><strong>Level 3</strong></td>
<td>The form factor of REPTAR including payload shall be 3U Standard</td>
<td>--</td>
<td>REPTAR shall beacon its location over a range of 45 miles</td>
</tr>
</tbody>
</table>
Executive Summary

- Designed and constructed 3U Recovery Vehicle
  - Parachute for deceleration
  - Aluminum foam for impact absorption
  - GPS and Iridium for location determination and transmission
- Performed thorough subsystem-level validation
- Full system integration incomplete
  - Drop from aircraft not performed
- Performed drop test from a fire tower

CU AES Senior Projects 2016-2017: REPTAR SFR
Design Description
Key Components

- Parachute Housing
- Side Panels
- Avionics Bay
- GPS Antenna
- Raytheon Payload
- Legs
- Iridium Antenna

Dimensions:
- 30 cm
- 10 cm 10 cm
- 10 cm

Raytheon Payload

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10/3/17
## Mass and Volume Budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (g)</th>
<th>Volume (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descent Subsystem</td>
<td>383</td>
<td>1.23</td>
</tr>
<tr>
<td>Landing Subsystem</td>
<td>512</td>
<td>0.41</td>
</tr>
<tr>
<td>Avionics Subsystem</td>
<td>518</td>
<td>0.36</td>
</tr>
<tr>
<td>Frame</td>
<td>437</td>
<td>-</td>
</tr>
<tr>
<td>System Wiring</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>Test Payload and Added Ballast</td>
<td>1300</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>SYSTEM TOTAL</strong></td>
<td><strong>3200</strong></td>
<td><strong>3.00</strong></td>
</tr>
<tr>
<td><strong>SYSTEM MAX</strong></td>
<td><strong>4000</strong></td>
<td><strong>3.00</strong></td>
</tr>
<tr>
<td>Margin</td>
<td>800</td>
<td>-</td>
</tr>
</tbody>
</table>
## Critical Project Elements

<table>
<thead>
<tr>
<th>Critical Project Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parachute Deployment</td>
<td>Without chute deployment, vehicle hits ground at 90 m/s</td>
</tr>
<tr>
<td>Landing Leg and Side Panel Deployment</td>
<td>Without leg and side panel deployment, vehicle experiences more than 40 G upon landing</td>
</tr>
<tr>
<td>Avionics Internal Power</td>
<td>Provides sufficient power at a reasonable line and load configuration to all avionics components</td>
</tr>
<tr>
<td>FET Deployment Triggers</td>
<td>Allows triggering of deployable elements</td>
</tr>
<tr>
<td>Battery Charge - Discharge</td>
<td>Safely provides sufficient power to avionics</td>
</tr>
<tr>
<td>Full System Integration</td>
<td>All components work together in form factor</td>
</tr>
</tbody>
</table>
Testing
Parachute Ejection Modeling

• Pressure Gauge:
  • Measured 24 PSI, expected 20 PSI

• Friction Force:
  • 5.29 J of energy: 1079 g dropped from 50 cm

• Parachute Exit Velocity:
  • Velocity measured over 5 inches at 59 FPS
  • Averaged from 3-5 m/s

*Tests performed in Aerospace Welding Shop and Senior Projects Work Shop
Parachute Ejection Testing

• Final Testing with Fiberglass Housing:
  • Ignite black powder for successful ejection

• Purpose:
  • Validate strength of fiberglass
  • Validate parachute ejected

• Results:
  • 9/9 successful ejections
  • No damage to fiberglass

*Test Performed in Aerospace Welding Shop*
Parachute Ejection Conclusion

• Parachute ejection from fiberglass housing:
  • 0.55 g of black powder with cotton sheet protection
• DR 3.2:
  • Parachute helps slow to reduce impact on landing
• Slow REPTAR to safe landing velocity:
  • 4.9 m/s landing velocity with selected parachute
Leg Deployment Testing

- Full Leg System Deployment
  - Power sent to Kanthal coil, system deploys
- DR 2.1
  - 3U volume constraint
- DR 3.1
  - Survive 40 G
- Purpose
  - Validate Kanthal coil cuts wire
  - Validate springs rotate legs into place
  - Validate locking mechanism locks into place
- Model
  - Torque required in 6 m/s wind: 0.065 in-lbs
  - Torque provided: 2.76 in-lbs
Leg Deployment Testing Results

- Simplified system deployed successfully 40/40 times in both no-wind and 6 m/s wind scenarios
- System successfully deployed 7/7 times with full system with final Kanthal coil setup
- Kanthal coils trigger deployments with 3V3 and 4A4

REPTAR

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Leg Crushability Testing

• Single Leg Crushability
  • Simulate ¼ expected system energy – 16.25 J

• Derived Requirement 3.1
  • Survive 40 G

• Purpose
  • Validates 65% compression of leg
  • Validate G-loading

• Model
  • Equating kinetic energy into expected work of leg deformation
Leg Crushability Testing

- Dropped 1 kg mass on single leg from 1.66 m, to achieve ¼ of expected energy
- Tested 5 times
- Estimated G-loading using frame by frame estimate of deceleration
Test Results

- Results
  - Steel on concrete G-loading without leg: 200+ G
  - Expected G-loading: 34 G

Reason for deviation:
- Use of ideal model
- Impact of leg onto concrete

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Building Drop Test Purpose

- **Purpose:**
  - Test impact absorption qualities of landing system in dynamic environment
  - DR 2.1 – Keep payload below 40 G of loading
Results

- Wind speeds during drop: >8 knots
- Vehicle swung in pendulum motion due to high winds
- Impacted ground as speed exceeding expected landing speed due to pendular motion
Building Drop Test Impact on Project

• Side panels need a redesign, they did not act as intended
  • Panels need a locking mechanism and stronger springs

• Necessity of landing system needs to be reinvestigated
  • Stemming from mass tradeoffs

• Chute inflation time needs further testing
  • 10 G upon chute inflation was higher than expected

• Further testing is needed from higher altitudes
  • Allows system to reach steady state before landing, reduces sensitivity to wind upon landing
3V3 Internal Regulator Performance Verification

**Test Scope:**
- Fundamental Voltage Component
- Ripple
- Line/Load Regulation

**Design Requirements:**
- 3.3V Output to within 5%
- Less than 300 [mV] of ripple
- Less than 300 [mV] of combined line and load regulation

**Importance of Validation:**
The 3V3 Internal Regulator is responsible for providing power to:
- MSP430FR – Microcontroller
- Iridium RockBlock Unit
- Venus GPS Unit
- MS5607 – Pressure Altimeter
Subsystem Level Validation:

- 3.34 [V] Realized (Unloaded)
- 160 [mV] Ripple (Unloaded)
- 40 [mV] Load Regulation
- 10 [mV] Line Regulation

Integration:

- 1.5 [V] of ripple observed when RockBLOCK Iridium Module is attached and in a non-transmitting state.
- SPICE Model does not explain performance – issue lies at RF
Microwave Model in ADS
Mitigation and Results

Issues Identified:

• RockBLOCK bias line incorrectly implemented by manufacturer
• Injection locking regulator switching frequency

Mitigation:

• Adjust RF drain Capacitor to 10pF
• Add 180 Ohm Ferrite to board wiring
• 200 [mV] Measured Ripple (from 1.5 [V])
12V and 3V3 Deployment FETs

Test Scope:
- Determine power handling capability of deployment FETs

Design Requirements:
- Handle 28.4 [W] power transfer to black powder charge
- Handle 12.21 [W] power transfer to each Kanthal coil

Importance of Validation:
Critical to ensuring deployment activities can occur
Subsystem Level Validation:
- Handled both Black Powder and Kanthal Coil Deployments successfully [10/10] times with representative load

Integration:
- Failure of the Black Powder Charge FET on test trigger with representative load
- Datasheet assumed one FET grounded for all measurements
- Breakout FET Controller off-ramp used to resolve issue

Final Trench Gap: ~ 2-3 microns
Trench Air Gap Voltage: 6-9 Volts
Battery Performance

Test Scope:
• Li-Ion Battery Stability

Design Requirements:
• Charge-Discharge voltage curve stays within 0.25V of modelled

Importance of Validation:
Battery unit is responsible for providing power to all flight avionics and deployers.

Measurement Error: 10 [mV]
(Not Visible in this Scale)
Flight UART and I2C Communication Tests

**Test Scope:**
Verify Communication from MSP430FR to the following:
- RockBLOCK Iridium Unit
- Venus GPS Unit
- Power Monitor [x2]
- MS5607 – Pressure Altimeter

**Importance of Validation:**
- I2C must work to allow altitude and deployment determination
- UART must work to all location determination and transmission

**Design Requirements:**
- I2C must provide 1Hz Altimeter update rate
- I2C must read power delivered through monitor
- UART Bus 1 must read GPGGA sentence from Venus GPS Unit
- UART Bus 2 must transmit correctly formed packet to Iridium module

**Results:**
All systems performed according to initial MSP430FR emulator model.
Purpose:
To verify the integrated performance of the Avionics Hardware and Software

Deviations From Test Flight:
- Black powder ignition without parachute
- Altimeter readings from EGSE
DITL Results

• Avionics Day in the Life test performed without incident
  • All components performed as expected after mitigation

• Full System Day in the Life test was not run due to complications
  • Control FET triggers mounted incorrectly
  • 12V grounding through structure
    • Iridium suffered from power supply errors following integration
DITL Impact on Project

- Not yet proven system as a flight unit
- Sufficient testing validating each subsystem
  - All deployments functioned properly after trigger FET mitigation
- System not yet proven to meet DR 3.1 (Location Transmission)
  - A functional Iridium module would allow DR 3.1 to be met
Systems Engineering
Functional Requirement Flow Down

- **FR.2**: REPTAR shall conform to industry CubeSat Standards
  - Target form factor is a standard 3U CubeSat
  - Volume becomes the constraining factor in design
- **FR.3**: REPTAR shall keep the payload safe during descent and landing phases
  - Assuming a 40 G loading limit as defined by military standard specifications
  - Landing is the clear critical event, other critical events arise dependent on design
- **FR.4**: REPTAR shall be locatable upon landing
  - REPTAR should be locatable for a search team in the UTTR
  - Reliability of communication is prioritized
Systems Engineering Approach

Fall Semester:
- System Design
- Feasibility and Model Development

Spring Semester:
- Manufacturing
- Testing and Model Verification
### Fall Semester

#### Major Tasks
- Define appropriate project requirements and scope
- Determine levels of success
- Identify feasible designs to accomplish design requirements

#### Major Issues Encountered
- Project initially significantly over-scoped
- Customer unclear on project desires and payload interface

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### Major Tasks
- Model parachute black powder ejection
- Model antennae characteristics
- Model landing impact scenario

#### Major Issues Encountered
- Ensuring proper antennae communication
- Meeting volume constraints
- Managing work amongst team
## Spring Semester

### Major Tasks

<table>
<thead>
<tr>
<th>Integrate full system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full system test</td>
</tr>
</tbody>
</table>

### Major Issues Encountered

<table>
<thead>
<tr>
<th>Full system integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differences between mock system and actual system for avionics</td>
</tr>
</tbody>
</table>

### Major Tasks

<table>
<thead>
<tr>
<th>Manufacture system and test rigs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perform subsystem testing</td>
</tr>
<tr>
<td>Compare and reiterate models to test data</td>
</tr>
</tbody>
</table>

### Major Issues Encountered

<table>
<thead>
<tr>
<th>Difficulties modeling parachute ejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure or lack of backup stock for components</td>
</tr>
</tbody>
</table>
# Risk Outcomes

<table>
<thead>
<tr>
<th>Risk</th>
<th>Mitigated</th>
<th>Realized</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD1: Black Powder Ignition</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>RD2: Insufficient Top Break</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>RL1: Bottom Leg Fails to Lock</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>RL2: Side Panels Fail to Orient</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>RA1: Antennae Failure</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>RA2: Regulator / Battery Overdraw</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

- The realized risks were most difficult to mitigate.
- Severity of realized risks had minimal impact to project schedule due to design.
- Unforeseen risks were the most impactful on schedule.
Challenges and Lessons Learned

• Well defined requirements are necessary
  • Poorly defined requirements introduces confusion to system requirements

• Integration and interfacing must be accounted for in design
  • Unaccounted for components can lead to significant redesign
  • Reduces risk as project approaches full system testing

• Off-ramps are critical to project success
  • Multiple issues at subsystem level caused various schedule slips

• Characterize component reliability and complexity
  • COTS components may not perform as expected
  • Custom components may introduce unnecessary complexity
Project Management
Management Approach

- Break team into 3 subsystem teams
  - Mission had 3 unique tasks, allowed team members to focus on single mission task
- Identify and assign team members to critical tasks
  - Primarily allows autonomy while still accomplishing critical tasks
- Employ team members in accordance with their talents
  - Let each team member work to their own strengths
Management Lessons Learned

• Scheduling can be extremely difficult to predict
  • Some tasks were accomplished much quicker than anticipated, some took weeks longer than anticipated

• Tasks must be defined in a way where help can be supplied if needed
  • Team members became knowledgeable about their complex systems, but outside help could not be supplied if needed due to lack of experience with system

• Specific tasks need to be assigned to individuals, not to subsystem teams
  • Tasks were not accomplished efficiently because teams took time determining who would do which task
# Industry Cost

## Assumptions:
- $65,000 annual salary of entry-level aerospace engineers, 2080 hours per year
- Overhead rate of 200%

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Hours</td>
<td>4,560 hours</td>
</tr>
<tr>
<td>Total Direct Labor Cost</td>
<td>$143,500</td>
</tr>
<tr>
<td>Overheard Percentage</td>
<td>200%</td>
</tr>
<tr>
<td>Overhead Cost</td>
<td>$285,000</td>
</tr>
<tr>
<td>Materials Cost</td>
<td>$4,000</td>
</tr>
<tr>
<td><strong>Total Industry Cost</strong></td>
<td><strong>$432,500</strong></td>
</tr>
</tbody>
</table>
Acknowledgments

REPTAR would like to thank:

• Steve Thilker, Collin Baukol, Cody Humbargar, and Raytheon Company
• Dr. Brian Argrow
• Dr. James Nabity
• Trudy Schwartz, Matt Rhode, Bobby Hodgkinson
• Dave Zader
• The Project Advisory Board
Questions?
## Budget Comparison

<table>
<thead>
<tr>
<th>CDR Prediction</th>
<th>Cost</th>
<th>Actual Purchases</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parachute (x3)</td>
<td>$500</td>
<td>Parachute (x2)</td>
<td>$390</td>
</tr>
<tr>
<td>Fiberglass Tubing</td>
<td>$100</td>
<td>Fiberglass Tubing</td>
<td>$293</td>
</tr>
<tr>
<td>Ejection Canister (x25)</td>
<td>$100</td>
<td>Ejection Canister (x75)</td>
<td>$153</td>
</tr>
<tr>
<td>Aluminum Sheets</td>
<td>$190</td>
<td>Aluminum Sheets</td>
<td>$110</td>
</tr>
<tr>
<td>Side Panel and Leg Manufacturing</td>
<td>$600</td>
<td>Side Panel and Leg</td>
<td>$1000</td>
</tr>
<tr>
<td>Aluminum Foam</td>
<td>$400</td>
<td>Aluminum Foam</td>
<td>$100</td>
</tr>
<tr>
<td>Iridium RockBlock2+ and GPS</td>
<td>$300</td>
<td>Iridium RockBlock2+ and</td>
<td>$390</td>
</tr>
<tr>
<td>Populated Boards</td>
<td>$300</td>
<td>Populated Boards</td>
<td>$643</td>
</tr>
<tr>
<td>Aircraft Rental</td>
<td>$250</td>
<td>Aircraft Rental</td>
<td>$0</td>
</tr>
<tr>
<td>Printing</td>
<td>$250</td>
<td>Printing</td>
<td>$300</td>
</tr>
<tr>
<td>Other</td>
<td>$420</td>
<td>Other</td>
<td>$853</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$3,410</strong></td>
<td><strong>Total</strong></td>
<td><strong>$4,232</strong></td>
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</tbody>
</table>
## Battery and Regulator Statistics

### Battery

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pack Configuration</td>
<td>2 Panasonic NCR18650BF cells in series</td>
</tr>
<tr>
<td>Pack Voltage</td>
<td>7.2 V (3.6 V per cell)</td>
</tr>
<tr>
<td>Max Discharge</td>
<td>10 A</td>
</tr>
<tr>
<td>Internal Resistance</td>
<td>154 mOhm (77 mOhm per cell)</td>
</tr>
<tr>
<td>Capacity</td>
<td>3350 mAh</td>
</tr>
</tbody>
</table>

### Regulator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3V3 Avionics</th>
<th>3V3 Deployer</th>
<th>12V Deployer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>80%</td>
<td>93%</td>
<td>92%</td>
</tr>
<tr>
<td>Max Current</td>
<td>1.2 A</td>
<td>8 A</td>
<td>10 A</td>
</tr>
<tr>
<td>Junction Temperature Max</td>
<td>100°C</td>
<td>125°C</td>
<td>120°C</td>
</tr>
<tr>
<td>Part Number</td>
<td>MCP1632</td>
<td>LTC1775</td>
<td>LTC3786</td>
</tr>
</tbody>
</table>
Battery and Regulator Performance

Power Dissipation over Flight

<table>
<thead>
<tr>
<th>Regulator</th>
<th>Max Rated Junction Temp. [C]</th>
<th>Max Modelled Junction Temp. [C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3V3 Avionics</td>
<td>125</td>
<td>85</td>
</tr>
<tr>
<td>3V3 Burn Wire</td>
<td>125</td>
<td>100</td>
</tr>
<tr>
<td>12V Black Powder</td>
<td>125</td>
<td>120</td>
</tr>
</tbody>
</table>
Full System Drop Test
# Full System Drop Test

<table>
<thead>
<tr>
<th><strong>Scope</strong></th>
<th>Drop REPTAR from airplane in controlled environment</th>
<th>• Requires aircraft, large drop zone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rationale</strong></td>
<td>Full system drop test is the culminating test that provides proof of concept and full integration testing</td>
<td>• Testing high speed parachute deployment • Location determination during descent • G-Loading profile</td>
</tr>
<tr>
<td><strong>Risk Reduction</strong></td>
<td>Reduces risk by validating in-flight performance before real flight with expensive payload</td>
<td></td>
</tr>
</tbody>
</table>
Comparison of Actual Descent to Test Drops

- **Actual Flight**
- **Ideal Drop**
- **Proposed Drop 12500 ft**
- **Min Alt Drop 11500 ft**

**Axes:**
- **Altitude [1000 ft]**
- **Velocity [m/s]**

**Legend:**
- Black line: Actual Flight
- Blue line: Ideal Drop
- Green line: Proposed Drop 12500 ft
- Red line: Min Alt Drop 11500 ft
Drop Test Measurement Unit

- Where?
  - Housed where Raytheon Payload would be stored in actual mission

- How?
  - Accelerometer (ADXL377, +/- 200G with an error of 1G)
  - Raspberry Pi Camera

- Quantities from the main avionics:
  - Altitude (Altimeter)
  - Location (GPS)

- Mass and Volume
  - Mass: 177 g of instruments + 1157 g of ballast
  - Volume: 1U

- Additional Measurements will be taken from the plane
Expected G-Model

**G Loading During Descent**

- Time [s]
- G Loading

- Chute Deployment

**G Loading during Landing**

- Percent Leg Deformation
- G Loading
Monte Carlo Parameters

- Initial Velocity = 32.0 [m/s]
- Initial Velocity Variance = 5.0 [m/s]
- Min Alt = 12500 [ft], Alt Variance = 200 [ft]
- Heading Range = 20 [deg]
- Pos. Variance (x) = 500 [m]
- Pos. Variance (y) = 500 [m]
- Pos. Shift (x) = -250 [m]
- Pos. Shift (y) = -250 [m]

- Wind Vel. min = 5 [kts]
- Wind Vel. Variance = 5 [kts]
- Wind Dir. min = 230 [deg]
- Wind Dir. Variance = 40 [deg]

- Chute Open Alt Min = 1900 [m]
- Chute Open Variance = 200 [m]
- Standard Deviation = 213.5 [m]

Known Winds: 2520, 2530, 2540, 2545
Entire drop zone is accessible for recovery

1.5km radius Reference Circle
## Consequences Table

<table>
<thead>
<tr>
<th>Quantities</th>
<th>All golden!</th>
<th>Location Transmission Fails</th>
<th>Landing Fails</th>
<th>Parachute Fails</th>
<th>All fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>G's experienced</td>
<td>37</td>
<td>37</td>
<td>52</td>
<td>840</td>
<td>840</td>
</tr>
<tr>
<td>Location Determined?</td>
<td>Yes</td>
<td>No</td>
<td>Likely</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Time to Land (s)</td>
<td>~86 s</td>
<td>~86 s</td>
<td>~86 s</td>
<td>~32 s</td>
<td>~32 s</td>
</tr>
<tr>
<td>Data survived</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Likely</td>
<td>Likely</td>
</tr>
</tbody>
</table>
Post Flight Analysis

Compare:

• G-loading experienced during flight
• Expected drift vs actual drift
• Expected time to land vs actual time to land

Review:

• Leg deployment footage
Summary of Confidence for Drop Test

• Descent System:
  • 85% confidence of parachute deployment

• Landing System:
  • High confidence that legs and side panels will properly deploy
  • 95% confidence towards aluminum foam landing characteristics
  • Concerns towards uncontrollable landing environment

• Avionics System:
  • High confidence in avionics system as designed
  • Flight environment can introduce issues in communication

• Overall:
  • Current: 81% confidence that full system will perform successfully in drop test
  • Future: Further testing to reduce variance
Launch Inhibit Considerations

- **CPE:**
  - Interfacing to Deployment Mechanisms

- **Requirements:**
  - FR1: REPTAR shall survive launch and standby phase in space
  - FR2: REPTAR shall conform to industry CubeSat standards

- **Concerns:**
  - None at this time
Altimeter Considerations

• CPE:
  • Altimeter Accuracy

• Requirements:
  • DR 3.1: REPTAR shall survive an instantaneous G loading of 40 G’s

• Concerns:
  • Errors – Inherent inaccuracies in CDH subsystem
  • Delays – CDH tasks that take time, during which REPTAR has traveled some distance
# CDH Error Stackup

<table>
<thead>
<tr>
<th>Delay Source</th>
<th>Description</th>
<th>Altitude [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Update Delay</td>
<td>Distance traveled between measurement samples</td>
<td>0.8</td>
</tr>
<tr>
<td>Transmission Delay</td>
<td>Distance traveled during the transmission from Altimeter to Microcontroller</td>
<td>order of millimeters</td>
</tr>
<tr>
<td>Calculation Delay</td>
<td>Distance traveled during a computation cycle of the flight code</td>
<td>0.9</td>
</tr>
<tr>
<td>Equilibrium Delay</td>
<td>Distance traveled during the time taken to equilibrate the ambient and internal pressures</td>
<td>1.3</td>
</tr>
<tr>
<td>Parachute Delay</td>
<td>Distance traveled during the parachute deployment</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>4.0</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Description</th>
<th>Altitude [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altimeter Error</td>
<td>Smallest altitude reading resolved by the altimeter</td>
<td>0.7</td>
</tr>
<tr>
<td>Calculation Error</td>
<td>Interpolation error in standard atmosphere lookup tables</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>5.7</strong></td>
</tr>
</tbody>
</table>

\[ h_{\text{margin}} = 2 \sum h_{\text{delay}} + \sum h_{\text{error}} = 13.7 \text{ m} \]
# Key Altitudes

<table>
<thead>
<tr>
<th>Altitude [m]</th>
<th>Description</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPS Jettison</td>
<td>Begin altitude sensing</td>
<td>REPTAR terminal velocity becomes subsonic</td>
</tr>
<tr>
<td>5900</td>
<td>Upper Bound for parachute deployment</td>
<td>Parachute deployment at higher altitudes induces greater than 40 G’s</td>
</tr>
<tr>
<td>3513.7</td>
<td>CDH target for parachute deployment</td>
<td>Builds in margin from CDH error stackup</td>
</tr>
<tr>
<td>3500</td>
<td>Target for parachute deployment</td>
<td>Factor of safety for deceleration and deployments</td>
</tr>
<tr>
<td>3050</td>
<td>Lower Bound for parachute deployment</td>
<td>Not enough time for deceleration or deployments</td>
</tr>
</tbody>
</table>
Key Altitudes

**REPTAR Flight Profile**

- **Upper Bound**
- **Lower Bound**
- **Parachute Deployment**
Descent Stage Design

- Without Deceleration: 91 m/s & 840 Gs
- Selected Parachute
  - 48” Diameter
  - Cd = 2.2
- With Deceleration: 5.7 m/s & 53 Gs

Terminal Velocity of REPTAR

Parachute Deployment
Descent Subsystem Design

- Parachute
- Thermal Wadding
- Ejection Canister
- Bottom Plate
- Fiberglass Housing
- U-Bolt

Descent

CU AES Senior Projects 2016-2017: REPTAR SFR
Chute Exit Velocity Model Development

\( e \) = specific energy of black powder \([3\text{MJ/kg}]\)
\( L \) = energy losses for pressure, thermal, friction, etc
\( m_{BP} \) = mass of black powder
\( m_c \) = mass of parachute = 0.122kg
\( V_c \) = velocity of parachute
\( E = e \cdot m_{BP} \) Total Energy in Control System

\[
\frac{e \cdot m_{BP} - L}{2} = \frac{1}{2} m_c V_c^2 \quad V_c = \sqrt{\frac{2(e \cdot m_{BP} - L)}{m_c}}
\]

From the regression:
\( V_c = 7831m_{BP} - 1.7218 \)

Setting the velocity equations equal to each other and solving for \( L \)
\[
L = e \cdot m_{BP} - \frac{m_c}{2} [7831m_{BP} - 1.7218]^2
\]
Landing Legs Design

- 4 Legs designed to absorb remaining energy of vertical velocity
- Made of highly compressible aluminum foam
- Deploy and lock using torsional spring system utilizing Kanthal coil

Deployed System

- 1.45 cm
- 1.65 cm
- 6.5 cm
- 7.8 cm

Leg Design
Side Panel Design

- Needed to absorb energy due to horizontal velocity on impact due to wind during descent
- Designed to compress aluminum foam stored internally
- Deploy via torsional spring system utilizing Kanthal coil
Landing Stage Design

• Landing subsystem is meant to keep system under 40 G upon impact
• Nominal landing speed of 5.7 m/s from descent subsystem
  • Need to account for high wind speed as well
• Crushable leg structure designed to limit G-Loading during impact
  • Done in both horizontal and vertical directions
Landing Testing

- Both deployments underwent static deployments without Kanthal coils in no-wind and 6 m/s wind scenarios.
- Aluminum foam performed as expected, but initial design was susceptible to buckling causing a tapered redesign.

![Aluminum Foam Stress Strain Graph](image-url)
Aluminum Foam Material Testing

- Test Energy Absorbing Properties of Aluminum Foam
  - Tested in ITLL Instron Materials Testing Laboratory
- DR 3.1
  - Survive 40 G
- Purpose
  - Validate compression strength of foam
  - Validate possible compression of foam
- Model
  - $W = F \cdot d$
  - $\sigma_{\text{crush},f} = 0.58T S_s \rho^{3/2}$
Test Results

- **Load Cell**
  - Range from 496-49800 N
  - Maximum Error of 0.16 %, 79.97 N
- **Tested to 64% Compression**
  - Deviates from model at 46% compression
  - Design assumed with 60% compression
Torsion Spring Calculations

- Torque required to deploy the base legs and the side panels is calculated using the Drag Force from the descent through the atmosphere.

- Force of Drag, \( F_d = \frac{1}{2} \rho V^2 AC_d \)

- Moment, \( M = F_d \times l \) where \( l \) is the length dimension of the legs (7.3 cm)

- \( c_d = 2.02 \), used as a worst case scenario for a flat plat straight into the wind.

- \( A_{Base\ Leg} = 7.8 \text{ cm} \times 1.65 \text{ cm} \times 2 \) legs for undeployed legs into direct velocity.

- \( \rho = 0.8191, 0.8543, 1.0065, 1.112 \text{ kg/m}^3 \) for altitudes of 4000, 3600, 2000, and 1000 m, respectively.

- \( V = 100, 90, 6 \) (with chute) m/s for various terminal velocities at altitudes as well as expected landing speeds reached following chute deployment.
• From Drag Force calculations:

  • Moment required for base legs to deploy:
    
    • $M(4000 \text{ m}) = 1.661 \text{ N m} = 14.70 \text{ in lbs}$
    
    • $M(3600 \text{ m}) = 1.403 \text{ N m} = 12.42 \text{ in lbs}$
    
    • $M(2000 \text{ m})_{\text{wg chute}} = 1.653 \text{ N m} = 14.63 \text{ in lbs}$
    
    • $M(2000 \text{ m})_{w/\text{chute}} = 0.0073 \text{ N m} = 0.065 \text{ in lbs}$
Avionics Deployment Considerations

- **Critical Element:**
  - Avionics Interface

- **Requirements:**
  - REPTAR shall survive an instantaneous G-Loading of 40 G
  - REPTAR shall communicate its location over a radius greater than or equal to 45 miles

- **Concerns:**
  - Physical Interface and Sensors
  - Power Budget
  - Avionics Thermal Budget
• FET Controlled Burn Wire Interface Connector to AWG 14 Wire (29 Amp. Max)

• Power Monitor capable of “snapshotting” 1 second periods and determining power transfer.
Battery and Regulator Performance

Regulator and Battery Performance over Flight

<table>
<thead>
<tr>
<th>Regulator</th>
<th>Max Rated Current Draw [mA]</th>
<th>Max Modelled Current Draw [mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3V3 Avionics</td>
<td>1,200</td>
<td>920</td>
</tr>
<tr>
<td>3V3 Burn Wire</td>
<td>8,000</td>
<td>5,560</td>
</tr>
<tr>
<td>12V Black Powder</td>
<td>10,000</td>
<td>4,670</td>
</tr>
</tbody>
</table>
Antenna Considerations

• **Critical Element:**
  • Antenna Performance

• **Requirements:**
  • REPTAR shall communicate its location over a radius greater than or equal to 45 miles

• **Concerns:**
  • Antenna Pattern inside REPTAR Structure
  • Location of Iridium Communication Satellites relative to REPTAR
Descent Iridium Antenna Pattern Performance

<table>
<thead>
<tr>
<th>Iridium Parameter</th>
<th>Power [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitted Power</td>
<td>32.0</td>
</tr>
<tr>
<td>Minimum Receive Sensitivity</td>
<td>-127.6</td>
</tr>
</tbody>
</table>
Landed Iridium Antenna Pattern Performance

**Iridium Parameter** | **Power [dBm]**
---|---
Transmitted Power | 32.0
Minimum Receive Sensitivity | -127.6

**Ground**

- **E-Plane**
  - -90°
  - +90°

- **H-Plane**
  - -90°
  - +90°

**Boresight**

- +90°
- -90°
Iridium Orbit Path

STK Descent Model (1km Elevation) Iridium Orbit:
- 100 Hour Orbital Period
- 86 Active Satellites
- 100% Earth Antenna Coverage

STK Model in Descent:
- 100% Coverage

STK Model after Landing:
- Worst Case: 75% Coverage (90/120 minutes)