REENTRY EXPERIMENT SAT-X

UNIVERSITY of NORTHERN COLORADO

Aaron Adamson
Motoaki Honda
Jordan Kohnen
Casey Kuhns
Robert Shiely
Maurice Woods
Dr. Matthew Semak
Dr. Robert Walch
# TABLE OF CONTENTS

**Section 1;** Introduction .................................................................................................................. 3  
**Section 2;** Mission Overview ......................................................................................................... 3  
  2.1 Mission Statement and Project Background ............................................................................... 3  
  2.2 Success Criteria .......................................................................................................................... 4  
**Section 3;** Theory and Scientific Concepts .................................................................................... 4  
  3.1 Physics of Reentry ....................................................................................................................... 4  
  3.1.1 Forces ....................................................................................................................................... 4  
  3.1.2 Air Density ............................................................................................................................... 5  
  3.1.3 Acceleration & Velocity vs. Height ......................................................................................... 5  
  3.1.4 The "Atmospheric Wall" ......................................................................................................... 7  
  3.1.5 Mean Free Path Approximation ............................................................................................ 7  
  3.1.6 Work Done by Air Friction ..................................................................................................... 8  
  3.1.7 Kinetic Energy Distributed to the Air ..................................................................................... 8  
  3.1.8 Refining the Method ............................................................................................................... 8  
  3.2 Implications for Payload Design ............................................................................................... 8  
**Section 4;** System Overview ......................................................................................................... 9  
  4.1 Hardware ..................................................................................................................................... 9  
  4.1.1 Capsule Shell .......................................................................................................................... 9  
  4.1.2 Capsule Launcher .................................................................................................................... 10  
  4.1.3 Sensors and Electronics ......................................................................................................... 10  
  4.2 Software ..................................................................................................................................... 11  
  4.2.1 Data Collection ..................................................................................................................... 11  
  4.2.2 Telemetry and Power Connections ...................................................................................... 11  
**Section 5;** Conclusion .................................................................................................................. 12  
**Works Cited** .................................................................................................................................... 12  
**Section A;** Appendix ................................................................................................................... 13  
  A.1 Materials and Fabrication Methods .......................................................................................... 13  
  A.2 Systems Testing .......................................................................................................................... 14  
  A.3 Reentry Vehicle Mechanical Drawings and Electrical Schematics ........................................ 15
SECTION 1 - INTRODUCTION

The challenge of entering, or reentering, the Earth’s atmosphere is not new. For years, NASA has successfully designed vessels that have endured the harsh process of reentry. However, in most cases, this is made possible only through the act of over-engineering; designing to withstand conditions far beyond what is expect to be encountered and moving on to concentrate on other objectives.

Though this method proves to be effective, consider the benefit of knowing more precisely what to expect upon atmospheric reentry. The University of Northern Colorado Reentry Experiment SAT-X (ReX) project is designed to shed light on the reentry process, and provide test data that will help to remove our dependency on the default that is over-engineering.

Moreover, a secondary objective of the ReX mission will be to test the capability of the prototype capsule to serve as a platform for future reentry experiments. In an effort to document the methods used and the preparation involved throughout this project for future reentry Rocket SAT-X missions, this report shall cover both the theoretical physics and the engineering involved in building the Reentry Experiment SAT-X payload.

SECTION 2 - MISSION OVERVIEW

2.1 Mission Statement and Project Background

“To provide a method for institutions to utilize a deployable and recoverable payload for future Rocket SAT-X missions. With this, we can greatly increase the amount of data recovered by eliminating the need to transmit only restricted amounts of data to the ground.”

The Reentry Experiment SAT-X mission begins by designing a pair of small reentry capsules to be ejected from a Terrier-Orion sounding rocket at apogee. To accomplish this, the University of Northern Colorado department of Physics has become involved with a project called Rocket SAT-X, an outreach program funded by the Colorado Space Grant Consortium (COSGC) that presents university undergraduate students with an opportunity to become involved in aerospace engineering and the aerospace community at an advanced level. The Rocket SAT-X program challenges students to design and fabricate an experimental payload that will be launched on a Terrier-Orion sounding rocket, provided and launched by NASA’s Wallops Flight Facility in Virginia. The rocket flight will launch the payloads approximately 120km into space, where the rocket will then shed its fairing, exposing the student payloads to the space environment, as shown in Figure 2.1. Then the ReX SAT-X mission will continue with the exploration of the effects of atmospheric reentry on a vehicle that is returning to the Earth’s surface from space.

Figure 2.1
Concept of Flight Operations
1. Launch, 2. Ascent; Onboard electronics initialize, 3. Apogee; Fairing deployment, ReX capsules ejected, 4. Decent; ReX Capsules collect data, data transferred via XBee radio to rocket then to ground via Wallops telemetry connection, 5. Splashdown

By collecting extensive inertial and thermal data as it enters the Earth’s atmosphere, ReX will provide a great amount of information concerning the complicated reentry process for a particular type of vehicle. After reviewing the flight data and comparing it to the mathematical model outlined in Section 3, the design of the capsule will be characterized and documented, focusing specifically on the ReX SAT-X reentry capsule’s reentry experience. This analysis will be conducted...
so that any future Rocket SAT-X team using the capsule platform will be able to predict, with reasonable accuracy, how the payload will behave, what temperatures will be experienced during flight, and what the capabilities of the capsule platform will be available at any time during a mission.

In addition to collecting data to be used for future extravehicular missions, the ReX team aims to create a comprehensive mathematical model that will be used to predict the capsules behavior during reentry. Not only will this model allow the team to compare actual data to a theoretical model, but it will also aid designing the capsule to no-more-than-necessary specifications. This goal stems from the idea that some Wallops missions tend to over-engineer mission hardware; designing components such as heat shields to standards that are well beyond what is necessary, so as to have more time to focus on more important issues. By optimizing the payload design, fewer resources may be used in payload fabrication, saving money and time.

### 2.2 Success Criteria

In order to achieve full “mission success”, the ReX payload must collect enough usable data at a high enough resolution to create a reliable flight characterization profile for the ReX reentry vehicle. Additionally, in following our objectives, this must be done while optimizing the vehicle’s mass, size and technological complexity (a secondary objective to the ReX mission is to minimize the use of “over-engineering techniques”, mentioned in Section 2.1). The resolution needed to create such a profile lies in the ability of the onboard sensors to detect both large and small variations in the vehicles flight path, such as oscillations, high-G accelerations, and turbulence. Also, since the threat of overheating is a characteristic of the reentry process, the sensors must be able to accurately describe how and where heat builds on the vehicle surface, as well as how it effects the system during flight. Finally, since the amount of collected data is also important, the payload must be designed to survive long enough to allow complete data collection until impact (splashdown).

### SECTION 3: THEORY AND SCIENTIFIC CONCEPTS

#### 3.1 Physics of Reentry

##### 3.1.1 Forces

To model the process of atmospheric reentry, it is important to know what forces are being exerted on the reentry vehicle. Taking a purely Newtonian approach, the most prominent force associated with the reentry process is simply air resistance. This is given by:

\[
F_{\text{air drag}} = \frac{1}{2} \rho \cdot v^2 \cdot A \cdot C_d
\]  

(3.1)

where \( \rho \) is the air density, \( V \) is the air speed velocity, \( A \) is the cross sectional area, \( C_d \) is the drag coefficient associated with the probe, and \( m \) represents the mass of the probe.

With this, and assuming a purely vertical descent, the resultant acceleration due to air drag and gravity is calculated via Newton’s Second Law, resulting in the following equation:

\[
a_{\text{resultant}} = g(h) - \frac{\rho(h) \cdot v^2 \cdot A \cdot C_d}{2 \cdot m},
\]  

(3.2)

Notice, this equation is dependent on the altitude above the surface of the Earth, \( h \). Next,

\[
g(h) = \frac{G \cdot M_{\text{earth}}}{(R_{\text{earth}} + h)^2}
\]  

(3.3)

\( m \) represents the mass of the capsule, \( G \) is the universal gravitational constant, \( M_{\text{earth}} \) is the mass of the earth, \( R_{\text{earth}} \) is the radius of the earth, and \( h \) is the height above the earth’s surface.
3.1.2 Air Density
The atmosphere of the Earth is not easily describable, as there are a great number of variables that effect, in particular, the atmosphere’s density. As a result, there is no general relation for how the density of air varies with altitude. However, as shown in Figure 3.1, there is information available that describes the density of the atmosphere in small vertical increments, which can be plotted to illustrate the apparent trend in the variation of air density with altitude (U.S. Standard Atmosphere).

Figure 3.1
U.S. Standard Atmosphere, 1976
A plot of 200 experimental data points giving the Earth’s air density at certain altitudes. However, this plot is for a limited set of height values, making it only partially useful in extrapolating data to be used in Equations 3.1 and 3.2.

Finding an analytical expression for this entire air density profile is rather difficult. However, by examining the plot over small intervals and assuming that each interval follows an exponential decay, the density profile can be described by “stitching together” multiple exponential functions, as shown in Figure 3.2.

3.1.3 Acceleration & Velocity vs. Height
Using equations 3.3 and the information in Figure 3.2, the acceleration and velocity of the reentry vehicle can be numerically calculated. These values are plotted in Figure 3.3 and assume
- Mass=1kg
- \(C_d=0.5\) (spherical)
- Cross-Sectional Area=0.007m²

Figure 3.2
“Stitched” Plot of Air Density using Small Intervals of Exponential Decay Curves
The set of expressions in the top right corner of this plot are examples of how each interval is described using an exponential curve. The final “stitching” of the intervals will allow the team to evaluate equations 3.1 and 3.2 more completely.

Figure 3.3
Velocity during Descent for “Ball Model”
Velocity variation with height of a ball-shaped object dropped from 120km
(For future reference, we will refer to this scenario as the “Ball Model”, since a spherical object can be used to convey the concepts described below more easily than using the actual ReX reentry vehicle)
An appreciation of this curve can be facilitated by comparing it to the variation in height of the terminal and free fall velocities of the same object falling from the same height. This will be done with the use of some graphs. First, however, we need an expression for the terminal velocity, which can be found by using equations 3.2 and 3.3 (setting the acceleration equal to zero).

\[ v_{\text{terminal}} = \sqrt{\frac{2 \cdot m \cdot g(h)}{\rho(h) \cdot A \cdot C_d}} \]  

(3.4)

Also, the velocity profile of a freely falling object from differing heights can be calculated using the following equation:

\[ v_{\text{free fall}} = \sqrt{2 \cdot g \cdot (h_{\text{max}} - h)} \]  

(3.5)

In Figure 3.4a-c, Equation 3.2 is plotted along with equations 3.4 and 3.5 to provide a context with which to better understand and describe the object’s behavior during descent.

Again, the “Ball Model” is used:

Figure 3.4a  
Ball shaped object dropped from 30km

Figure 3.4b  
Ball shaped object dropped from 60km

Figure 3.4c  
Ball shaped object dropped from 120km

In the plots above, the blue curve describes the object’s velocity as it descends. Notice that the red line that describes the object’s terminal velocity creates an asymptote around 40km above the surface. Below this altitude, the capsule actually falls faster than its terminal velocity for a short period.
3.1.4 The “Atmospheric Wall”

As seen in Figure 3.4a-c, at the point where the terminal velocity and free fall velocity curves cross the capsule experiences a significant change in velocity. Because this acceleration happens over a very short time, we compare this phenomenon to an object hitting a “wall of atmosphere”. As the object is dropped from increasingly larger heights, the impact from hitting this “wall” becomes greater, as shown in Figure 3.5a-c.

3.1.5 Mean Free Path Approximation

It is important to step back and acknowledge that Equation 3.1 and the equations derived from it rely on the assumption that the air making up the Earth’s atmosphere is a continuous form. It is beneficial to confirm that this is a valid assumption.

The mean free path is the average distance between molecules in a certain volume of air of specific temperature and pressure. Compared to the size of the reentry object, if the separation distance between air molecules is small enough, then the air can be treated as a continuous object. The mean free path can be found using

\[
\text{Mean free path} = \frac{1}{\sqrt{2\pi d^2 n'}} , \quad (3.7)
\]

where \(d\) is the average diameter of the air molecules and \(n'\) is the number of molecules per unit volume. \(n'\) is defined,

\[
n' = \frac{P}{KT} , \quad (3.8)
\]

where \(P\) is atmospheric pressure, \(K\) is the Boltzmann constant, and \(T\) is the temperature of the atmosphere. Notice, \(T\) and \(P\) are both height dependant.

Again, using the “Ball Model”, we have the following plots.

![Figure 3.5a](image)

**Figure 3.5a**

Ball shaped object dropped from 30km

![Figure 3.5b](image)

**Figure 3.5b**

Ball shaped object dropped from 60km

![Figure 3.5c](image)

**Figure 3.5c**

Ball shaped object dropped from 120km

This sudden deceleration from the “wall” can induce a large amount of G-shock and heat buildup experienced by the reentry object, due to loss of kinetic energy by air friction. This will become a topic for concern in the design of the payload, as both effects could prove hazardous to the functionality of the capsule.
Safely assuming that an air molecule has a diameter of \(2 \times 10^{-10}\) m, Figure 3.6 shows the mean free path with respect to altitude:

![Figure 3.6 Mean Free Path](image)

**Figure 3.6 Mean Free Path**

At a height of 100 km or more, the mean free path is large. In such a case, we are unable to treat the atmosphere as a continuous fluid. However, the ReX reentry capsule’s expected reentry height (the height at which the capsule experiences the effects of the “atmospheric wall”) is 35 km, and the mean free path at that height is \(3.2 \times 10^{-5}\) m, a value that is small enough to allow us to treat the atmosphere as a continuous fluid. With this, we can confirm that our approximation is acceptable.

### 3.1.6 Work Done by Air Friction

To estimate thermal energy during reentry process, total work done by friction must be calculated. To find total work done by friction, simply use:

\[
W_{\text{air friction}} = \int F_{\text{air friction}} \cdot ds \tag{3.9}
\]

### 3.1.7 Kinetic Energy Distributed to the Air

In Figure 3.7, the initial assumption is that all of the kinetic energy lost when the object hits the “atmosphere wall” is converted into heat energy that is transferred into the objects surface material. However, this is not entirely true, as some of the kinetic energy loss is used to move the air of the atmosphere around the object. Appealing to the law of conservation of momentum, the amount of converted energy devoted this task can be roughly approximated.

Again, using the “Ball Model”:

![Figure 3.7 Heat Energy of Reentry](image)

The area beneath the curve corresponds to the total work done by air friction, which will be transferred into heating up the surface of the reentry object.

### 3.1.8 Refining the Method

Thus far, we have discussed only the fully developed portions of the reentry model. However, the team is currently working on two more considerations to further our understanding of the reentry process. First, a careful thermodynamical treatment of the absorption and radiation of energy by the capsule is desired in order to optimize our selection of building materials for the capsule shell. Second, we would like to understand how the exchange of energy between the capsule and the air affects the capsule’s trajectory. This will require a fluid-mechanical analysis.

### 3.2 Implications for Payload Design

In using this mathematical model, it becomes evident that there are two aspects of the reentry process that will govern the design of the reentry vehicle: impact velocity and thermal loading. By reducing the drag profile of the capsule, the thermal loading on the skin of the vehicle can be significantly reduced. However, by doing this, the resistance to moving through the air is significantly reduced, causing the terminal velocity of the capsule to increase to a level that may cause capsule implosion upon landing. On the other hand, increasing the drag profile of the capsule reduces the terminal velocity of the falling reentry vehicle, but could cause it to overheat and meltdown due to friction with the atmosphere. Therefore, as with any scientific experiment, a careful decision must be made to determine an appropriate balance between the two hazards.
To make this decision, the ReX team created several prototypes that would be used to test the various aspects of flight. While the mathematical model could be used to determine a theoretical value for the terminal velocity and thermal loading for each prototype, additional short range drop tests were also necessary to determine which capsule design was best at orientating itself into a proper, straight-down trajectory (ideally, the capsule will fall nose first, without tumbling or high-speed spinning, which could cause damage to the internal electronics). Figure 3.8 outlines the four payload design prototypes.

Figure 3.8
Prototype Designs
A description of the benefits and risks of using a variety of capsule shapes. The final payload design was a hybrid of the stream-lined and Apollo capsule shapes.

After performing several drop tests, the stream-line shaped capsule was deemed to be the most suitable candidate for the final payload design. Not only did the design orient itself flawlessly during each drop test, but the mathematical model seemed to support the possibility of such a shape surviving the longest of the four designs. With this, the team then focused on creating a heat shield for the nose of the capsule to reduce the possibility of overheating and meltdown due to air friction. Due to the intense vibrations and accelerations of launch, ceramics and the more traditionally rigid types of heat shields were deemed inadequate. Instead, the team tested several combinations of carbon fiber and graphite based epoxies to protect the capsule from the intense heat (see Section A2). As shown in Figure A6, a layer of carbon fiber weave, glued on with an epoxy infused with graphite powder was the most effective means of protecting the capsule and was then integrated into the final payload design.

SECTION 4: SYSTEM OVERVIEW

4.1 Hardware

The Reentry Experiment SAT-X payload consists of two ejectionable reentry vehicles that will house an assortment of sensors used to gather inertial and thermal data during reentry. In addition to the reentry vehicles, the payload will be outfitted with a pair of reentry capsule launchers, used to jettison the capsules from the rocket body after fairing deployment at apogee.

4.1.1 Capsule Shell

The exterior housing of the reentry vehicle is designed as a mixture of two “ideal” reentry shapes. Because of its large drag profile and low center of gravity, the reentry vehicle was originally modeled after NASA’s Apollo reentry capsule. The Apollo capsule’s shape provides a great deal of interior space for housing electronics, presents a large, forward-facing surface for heat dissipation, and a low center of gravity that aids in stabilizing the capsule during flight. Additionally, the smooth, conical shape is easily machinable, allowing the team to fabricate multiple versions of the same payload for prototyping and testing. However, the Apollo-shape alone is not sufficient, as it failed to properly orient itself in a downward-facing “flight trajectory” during testing. To correct for this, the design was modified to incorporate a profile that was more streamlined. With the addition of tail fins to an elongated aft section, the hybrid streamlined-Apollo capsule (Figure 4.1) exhibits exceptional self-orienting characteristics that will allow the capsule to travel through the Earth’s atmosphere with minimal tumbling and heating.
4.1.2 Capsule Launcher

In order to prepare the capsule for a reentry flight, it must be released from the sounding rocket body after the fairing of the rocket has been deployed (refer to Figure 2.1). To ensure that the capsule is clear of the rocket as it is released, a set of small springs will push the capsule from the rocket at approximately 1m/s. These springs will be placed at the tail of the capsule, providing a constant, outward force throughout the duration of the flight. However, to ensure that this does not happen prematurely, a locking mechanism must also be incorporated into the capsule launcher harness. As shown in Figure 4.2a-c, a cylindrical locking cam is designed to lock the capsule in place during launch using positive pressure, ensuring that the lock is still engaged regardless of power supply or control systems status. When apogee is reached, a motor will rotate the cam, causing the locks to disengage, releasing the capsule.

4.1.3 Sensors and Electronics

The payload will be equipped with multiple microcontrollers, each responsible for collecting data and controlling certain events that must be initiated during the flight. There are two main microcontroller systems: one housed in the base station and the other in the reentry vehicle. Both are built off of the ATmega2560 microcontroller. The base station and probe both incorporate an array of sensors to completely characterize threedimensional motion of the individual components throughout the flight. The sensor equipment includes an HMC5843 triple-axis magnetometer, two ADXL345 triple-axis accelerometers, an ITG3200 triple-axis gyro, and an LPR530AL dual-axis and LY530AL single-axis gyro. Additionally, each probe will carry several temperature sensors to collect data concerning the thermal loads and thermal gradient experienced on the skin of the capsule at different points during the reentry process. The base station and probes will communicate via 900MHz radio transceivers. Additionally, each capsule will carry several temperature sensors to collect data concerning the thermal loads and thermal gradient experienced on
the skin of the capsule at different points during the reentry process. The base station and capsules will communicate via 900MHz radio transceivers.

The base station will have several unique functions to perform. The base station will be responsible for receiving and interpreting several timing events from the rocket telemetry. That information will be used to activate the subsystems aboard the payload, including three shock resistant, high definition video cameras, the reentry vehicle electronics, and the launching/capsule release mechanism. The base station will also be transmitting real-time data and status updates to the launch facility via a telemetry link to the ground, provided by Wallops.

![Figure 4.3](https://example.com/image.png)

**Figure 4.3**

**Functional Block Diagram**

Simplified diagram of how data is collected and moved throughout the payload’s electronics

### 4.2 Software

#### 4.2.1 Data Collection

The base station and capsules are outfitted with an array of sensors to characterize the motion and forces experienced during launch and reentry of the vehicles. Since the flight includes a wide range of accelerations and roll rates, but also requires the most low-noise, detailed information possible, the gyros and accelerometers operate at different ranges in order to provide the most appropriate information for a given situation. If the high detail, limited range sensors saturate at any point of data collection, the software will revert to the high range sensors, so that neither range nor accuracy will have to be sacrificed. All of the data generated by the sensors will be stored locally on non-volatile flash memory cards. The reentry vehicle computers will send an abbreviated, lower resolution copy of the flight data to the base station via 900MHz XBee radios at 115200 baud. For real-time monitoring (and in case of an unrecoverable payload) the maximum amount of data allowed through the 900MHz connection will be sent using the rocket’s telemetry link to the launch facility.

#### 4.2.2 Telemetry and Power Connections

The base station will utilize a series of telemetry and power connections controlled by Wallops Flight Facility to receive timing events from, and transmit data to, the launch facility. The first timing event will occur at T-3 minutes, during which time the base station will power on and run through the self-diagnostics procedure. The second timing event will occur at launch, which will initiate full resolution recording of accelerations and roll rates for the duration of the mission. The last timing event will occur when the fairing is removed from the rocket, indicating readiness for capsules ejection.

To transmit data, there will be ten parallel lines, each of which will be used to indicate the payload’s status during the flight, including “Successful Power On”, “Completion of Self-Diagnostics Routine”, “Attempted Capsule Ejection”, and “Successful Capsule Launch”. There will also be four analog lines utilized by the base station to measure the signal strength of the capsule radio connection. Finally, a single serial connection running at 19200 baud will provide summarized segments of the inertial data transmitted by the capsules throughout the flight.
SECTION 5: CONCLUSION

The Reentry Experiment SAT-X sounding rocket payload is scheduled to launch on the 19th of July, 2011 at Wallops Flight Facility, VA. Upon arrival, the University of Northern Colorado team, in accordance with Wallops pre-flight procedures, will submit the payload for final inspection, as it is put through a series of environmental tests (including vibration, spin, and voltage tests). After the mission, the team hopes to characterize the payload and modify any flaws in its design before it is presented as a standardized ejectable platform for future Rocket SAT-X customers.

WORKS CITED


SECTION A; APPENDIX

A.1 Materials and Fabrication Methods

The capsule will be fabricated using 6061 Aluminum (Figure A1), which will be machined using an automated CNC mill (Figure A2) located at Road Narrows Robotics in Loveland, CO. Road Narrows Robotics also provided the use of a Rapid Prototyper plastic printing machine, which was used to create a plastic prototype model (Figure A3) of the capsule for preliminary testing.
A.2 Systems Testing

To prepare the ReX payload for flight, a series of tests must be conducted to ensure that all of the mechanical and electronic subsystems are fully functional, both as individual subsystems and as a fully integrated assembly. Some of the tests include: Gyro test (Figure A4), IMU test (Figure A5), heat shield test (Figure A6 and A7), and a Drop Test conducted at the NOAA 1000ft weather observation tower in Erie, CO (Figure A8).
A.3 Reentry Vehicle Mechanical Drawings and Electrical Schematics

1. Capsule Nose Cone
2. Electronics Deck Plate
3. Electronics Deck Stand-Offs
4. Electronics Deck Fasteners
5. Junction Gasket
6. Set Screws
7. Capsule Tail