To measure tribocharging of varying bidisperse mixtures of spherical, non-conducting grains under microgravity
To assess differences in manipulator performance with an absence of gravitational preloading.

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1 Mission Statement

1.1 STAR Mission Statement

The purpose of Project STAR was to observe tribocharging (the accumulation of charge due to contact interaction) of non-conducting spherical beads of varying sizes simulating regolith in vacuum and microgravity conditions. Tribocharging is difficult to study in terrestrial labs because atmospheric humidity significantly influences charging and charge dissipation, and terrestrial gravity and atmospheric drag complicate the measurement of the charge on grains. The RockSat-X platform was an ideal platform for these experiments, as it provided access to both vacuum and microgravity for a relatively low cost compared to traditional spaceflight.

An understanding of regolith behavior is important both for modeling the formation and evolution of small bodies in the solar system, as well as to aid in mission planning and exploration of these objects. The physics behind regolith interactions are currently not well understood, and additional data will allow validation and improvement of current computer simulation models for spacecraft-regolith interactions. Progress in this field of research has primarily been on the modeling side due to the difficulties in obtaining experimental data. Interest in the field is high due to the number of spacecraft missions to small bodies in the past decade and renewed interest by NASA and other entities to visit extraterrestrial bodies. Terrestrial experiments on tribocharging have two major weaknesses that limit their ability to simulate the processes that occur on planetary bodies: the duration of the experiment is limited because microgravity can only be achieved during free fall, and charging is influenced by the humidity in the atmosphere. Project STAR data can be compared to terrestrial experiments in order to assess the significance of humidity effects in terrestrial experiments.

The effects of tribocharging are difficult to measure directly in a bulk sample, so Project STAR utilized an indirect method of measuring the accumulated charge on the grains via video motion tracking under the application of an external electric field. Once the grains were electrically isolated (due to the lack of atmosphere to transport charge) and had been given an opportunity to build up charge (via collisions in a microgravity environment), high resolution video allowed motion tracking of the trajectories of individual particles. Since the particles were in an electric field, their charge can be deduced from their acceleration.

Current models of regolith interaction predict both the magnitude of the charge built up on the particles as well as the polarity. Based on models with multiple simulant sizes, the charge polarity was predicted to vary relative to the size of the simulant. In order to validate these findings, Project STAR samples contained a mixture of two grain sizes. Post flight analysis will determine whether one size will accumulate a net charge.

The primary objective for Project STAR was to take and record images of the regolith simulant throughout the flight with at least a 30 Hz frame rate. The images needed to be of a sufficient resolution to clearly distinguish particles of each of two regolith simulant sizes (0.1 mm and 0.5 mm diameter) in order to enable motion tracking. The 30 Hz requirement was derived from the predicted acceleration imparted on the grains based on the theorized
charge accumulation of the particles under the expected excitation conditions and limitations of the image processing pipeline, which required that the particles be accelerated to no more than one pixel per video frame. To account for environmental factors which affect the acceleration of the grains, the Project STAR payload was also required to record external accelerations on the samples throughout the duration of the flight. Since maneuvers from the rocket produced accelerations significantly greater than the expected accelerations of the particles due to electrostatic effects, this data was extremely important in separating tribocharging-induced acceleration from the gross acceleration of the rocket.

1.2 SCAMP Mission Statement

SCAMP’s mission objectives were to characterize manipulator performance in a microgravity environment with and without gravitational preloading, and to determine the effects of impeded motion on said characterizations. The only accurate micro-gravitational simulation available for studies such as this are parabolic flights, which has been used on SCAMP’s heritage design: DYMAFLEX. Therefore a Rocksat-X sounding rocket launch, with its access to the micro-gravitational environment and quick recovery of the payload, is a phenomenal choice for the data collection objectives that we have set.

DYMAFLEX is a 4-DOF arm attached to a platform called ExoSpheres, and was designed to study the dynamics of a small mass ratio between arm and body (1:7). ExoSpheres utilizes two CO2 pucks to disperse gaseous carbon-dioxide creating an air bearing when paired with our glass tabletop surface. This apparatus allows us to study the dynamics in two dimensions of these dynamics, but ultimately a third was desired for further verification and study. This led to DYMAFLEX and ExoSpheres to be transferred to Johnson Space Flight Center (Announce of Flight Opportunity 6 (AFO)) for parabolic flight testing over the course of 2 flights and a number of 40 parabolas each. The study of these dynamics is important for the progression of a new field of complex robotic actuators, allowing for smaller and lighter robotic platforms to be designed and utilized appropriately in areas such as satellite servicing and extra-vehicular maintenance.

SCAMP’s method of adapting the current DYMAFLEX model was to utilize one joint as a primary field of study, both satisfying our need for a robotic manipulator (now 1 DOF) and effective use of space in sharing the payload plate with Project STAR. Each of DYMAFLEX’s joints are composed of a motor and gearbox, more specifically a motor connected to a 100:1 ratio Harmonic Drive, and it was imperative that we maintain the same drive system to support an ultimate goal of flight certifying this robot. In terms of the impeded movement characteristics, a compliant and non-compliant surface were required to be designed for SCAMP’s end effector to interact with. It was ultimately decided that a rigid aluminum structure would be utilized for both to minimize potential bending in the contacts, but the compliant side utilizes rubber padding in its effort to provide non-linear compliant resistance.
2 Mission Requirements and Description

2.1 TERP Requirements

The TERP payload was split between Project STAR and SCAMP, which imposed project requirements in addition to the individual payload requirements described in §2.2 and §2.3. Volume was one of the largest constraints for TERP, with the STAR driving constraint being the distance between cameras and test tubes and the SCAMP driving constraint being the potential range of motion of the arm. Another main constraint for TERP was the power allocation between GSE and timer lines.

Project STAR sought to accommodate as many samples as possible, while still achieving 100 µm/pixel image resolution within volume constraints. To do this, the STAR team chose to use two parallel sample racks imaged from both sides, with the cameras at the minimal distance possible from the samples. These imaging requirements led to a fixed camera to test tube distance of 1.93" and two test tubes per camera occupying the entire camera field of view. This optimization resulted in less samples per camera, requiring more cameras than other configurations considered, but ultimately fitting the most samples. The two parallel racks were then condensed into two 2x2 sample holding mechanisms. With two 2x2 holdings, the sunshade enclosure around STAR would be 6.20"x8.25", allowing 4.44" for SCAMP’s actuator arm. This distance gave SCAMP a 30 degree range of motion (ROM), as seen in Figure 1.

![Figure 1: SCAMP ROM and Shaker Racks with Cameras](image)

The space underneath the actuator arm itself was to be used for both the STAR and
SCAMP electronics boxes, requiring that the height be no more than 3.75 in. The STAR electronics box was sealing against the RockSat-X payload plate, and required an additional 0.375 in of payload plate in order to seal itself. The datalogger was the only board going into the STAR electronics box, so the inside area need be only large enough to contain that board. SCAMP’s electronics box had to at minimum, contain the PocketBeagle flight computer and the Tweeter motor driver.

A secondary critical constraint for TERP was power. TERP was utilizing the GSE line and timer event lines one and two from the rocket, with the constraints as seen in Table 1. STAR required that the Raspberry Pis, datalogger, and STARduino be on the entire flight, using 450 mA. SCAMP and STAR’s motors were turning on with timer line one, such that timer line two could be used for the bias in a quiescent environment with all of the motors off.

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSE Input Voltage</td>
<td>28 V (± 6 V)</td>
</tr>
<tr>
<td>Timer Line 1 Input Voltage</td>
<td>28 V (± 6 V)</td>
</tr>
<tr>
<td>Timer Line 2 Input Voltage</td>
<td>28 V (± 6 V)</td>
</tr>
<tr>
<td>GSE Current Draw</td>
<td>≤ 1.85 A</td>
</tr>
<tr>
<td>Total Timer Line Current Draw</td>
<td>≤ 3.75 A</td>
</tr>
</tbody>
</table>

Table 1: Initial Design Requirements

The full mission timeline can be seen in Table 2. The motors were specifically turned on during the first part of microgravity such that SCAMP could get microgravity data, and the shaking of STAR samples could also occur during microgravity and vacuum. The motors are turned off early enough in the microgravity portion of the flight to allow the STAR voltage bias time in the quiescent environment to stratify the samples.

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-300s</td>
<td>Power up, start data collection and image capture</td>
</tr>
<tr>
<td>L+70s</td>
<td>Start sample excitation, start arm sweep</td>
</tr>
<tr>
<td>L+170s</td>
<td>Stop sample excitation, stop arm sweep, apply bias current</td>
</tr>
<tr>
<td>L+355s</td>
<td>Payload power down</td>
</tr>
</tbody>
</table>

Table 2: Initial Mission Timeline

2.2 STAR Requirements

In order to meet the science objectives described above, a number of additional engineering requirements were imposed on the STAR payload. These included designing a sealing system for the datalogger box of the payload, designing a shaking apparatus to induce collisions between the grains, developing custom electronics boards to allow for data collection, power distribution, generation of the 50 V bias, and containing the regolith simulant inside of a test tube while also exposing it to the vacuum of space. These requirements were driven by
the main payload mission objectives, as listed below.

1. Collect video of sufficient resolution and framerate to distinguish and track grains of regolith simulant
2. Mechanically excite (i.e. shake) samples to induce charging
3. Apply an electric field to samples to create accelerations
4. Collect environmental data to allow derivation of charge-induced accelerations on grains

The STAR payload was designed to observe eight samples of regolith simulant to determine the difference between simulant size distribution and polarity of accumulated charge, with the idea that the small or large simulant would charge either negatively, neutrally, or positively. All eight samples were imaged throughout the flight, with four cameras each capturing two samples. The small grains were 0.1 mm diameter, and the large grains were 0.5 mm diameter. The grain sizes were chosen in order to have a large number of grains in the small simulation space and have grains sizes that were visually distinct in the camera data. Additionally, these grain sizes mimic the sizes expected to be present on asteroids Tsuchiyama, Uesugi, Matsushima, et al. 2011. The acceleration imparted on the grains is proportional to the strength of the electric field, which is proportional to the voltage potential applied across the sample. Thus, a large voltage bias was desirable in order to produce a more detectable acceleration. A waiver was submitted and approved to have a voltage bias larger than 28 V on the payload. The NFPA 70E regulation (National Fire Protection Association) has recently changed the minimum DC voltage regarding shock hazards from 50 V to 100 V. Thus 50 V was chosen as it was below the minimum level for shock hazards, but would be effective in separating the charged simulant. This higher voltage also meant the electrical board responsible for generating said voltage must be conformal coated as per RockSat-X requirements.

The initial architecture for Project STAR called for mechanical excitation of the sample about the longitudinal axis of the rocket by shaking of the sample rack. This would induce collisions between the grains in order maximize tribocharging over the limited duration of microgravity. Excitation would begin shortly after de-spin of the vehicle and continue until just before apogee. Bias application was to continue until the rocket power turned off, maximizing the microgravity exposure of the samples under an electric field. Imaging of the sample was to be collected during excitation and the bias application, while engineering, environmental, and flight profile data was to be collected from system power-on, shortly after first-stage ignition, to system power-off. An initial mission operations timeline is presented in Table 2.

The initial design requirements for Project STAR, as described above, are summarized in Table 3.
### Table 3: Initial Design Requirements

<table>
<thead>
<tr>
<th>Item</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratification Bias</td>
<td>50 V</td>
</tr>
<tr>
<td>Image Capture Rate</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Image Resolution</td>
<td>100 µm/pixel</td>
</tr>
<tr>
<td>Simulant components size ratio</td>
<td>.2</td>
</tr>
<tr>
<td>Shaker Specifications</td>
<td>Determined by testing</td>
</tr>
</tbody>
</table>

The imaging requirements were derived from the need to discern individual particles as small as 100µm diameter in each image, and the need to image frequently enough to derive individual particle accelerations. The ratio of 0.2 for the simulant was a requirement from the PI, where these would provide a large enough disparity to theoretically see net charge accumulation.

### 2.3 SCAMP Requirements

As a means of fulfilling the objectives above, SCAMP’s design was augmented by the imposition of various engineering requirements such as a sealed manipulator housing, sealed electronics box, and the creation of aforementioned contact surfaces. All of these were critically important for both the preservation of all data and complex hardware protection from hazards such as seawater.

SCAMP utilized the same housing designs for the motor and harmonic drive as DYMAFLEX, however modified to include an o-ring seal and adapted for production on a CNC platform (compared to 3D printing as previously used in the robot.) A number of other pieces such as the inner drive plate (connecting the power output of the Harmonic Drive to the end effector) and outer bearing retainer (responsible for the retention and alignment of the bearings with the drive plate) had to be modified as well for sealing and vertical space requirements. The sealing aspect of these requirements were crucial for the verification process in terms of the components chosen (motor, specific drive, etc.) and their durability through launch, working conditions, reentry, and touchdown in saltwater; the most major reason for the sealing. Contrarily, items such as the end effector and contact points were designed from scratch as they are uniquely required for this experiment.

In terms of robotic operations, SCAMP’s performance would be assessed initially through an increasing-frequency sine wave sweep, and then utilize the remaining time in our allotted 100s between T+90 and T+190 to determine items such as contact stability and oscillatory motion against the non/compliant surfaces. The addition of load cells on the end effector structure will aid SCAMP in determining the precise moment it makes contact, as well as the amount of force being transferred into the surface. Additionally a camera allows for more easily time-synced data points, as well as provides additional data collection through visual analysis.

NASA approached the design team in January with an interest in studying the effects
of a moving mass along the arm to verify a conceptual method of mass estimation using centrifugal forces in an environment lacking gravitational preloading. The design evolved into a sliding platform of delrin attached to a spring reel mechanism, all released using a hot wire cutting mechanism, and allowed the shuttle (as we nicknamed it) to travel the entire 5 inch length of the end effector. The original design was to attach a molded lead mass of between 50 and 100 grams to the shuttle that allowed for uninterrupted movement, however nearing the end of the project it was realized that no material available to us in any configuration could give us more than 34 grams of moving mass in total. The additional mass was omitted from the flight design, but the shuttle system was presented to NSROC in a potentially fully functional state (the hot wire cutter was unpowered for flight due to no intention of having a moving shuttle without the mass attachment.)

3 Payload Design

3.1 TERP Design

TERP was the combined payload between STAR and SCAMP. The payload plate was partitioned into three main subsections: STAR sunshade, SCAMP actuator arm, and the electronics boxes underneath the actuator arm. A full CAD of the TERP payload can be seen in Figure 2, and a Functional Block Diagram (FBD) of Project STAR can be seen in Figure 3.
3.1.1 Payload Baseplate

Almost all of the components for TERP were bolted directly onto the RockSat-X-provided baseplate, as seen in Figure 4. The STAR electronics box bolted and sealed directly to the RockSat-X-provided baseplate, as well as all of the electronics boards save the datalogger. The SCAMP electronics box, manipulator, and endstops all bolted to the RockSat-X-provided baseplate.
Figure 4: RockSat-X Baseplate

The baseplate was also designed to maximize the payload area for both projects. The majority of Project STAR hardware is contained within the sunshade, which is the exact distance needed for two opposing cameras and two side-by-side shaker racks. The sunshade chamfers are to keep the entire structure within the keep-out zone of the payload plate. The rest of the space is occupied by the SCAMP actuator arm, with both electronics boxes kept underneath the SCAMP arm. While weight was a concern, preliminary mass budgets between Project STAR and SCAMP payloads had ample margin for the combined payload plate mass. The final mass budget can be found in Table 4.
Table 4: Final Mass Table

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (g)</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datalogger</td>
<td>241</td>
<td>0.53</td>
</tr>
<tr>
<td>STARduino</td>
<td>35</td>
<td>0.077</td>
</tr>
<tr>
<td>Image Capture</td>
<td>301.6</td>
<td>0.66</td>
</tr>
<tr>
<td>Shaker Rack</td>
<td>1705</td>
<td>3.76</td>
</tr>
<tr>
<td>Voltage Bias</td>
<td>10</td>
<td>0.022</td>
</tr>
<tr>
<td>SCAMP Motor Driver</td>
<td>27</td>
<td>0.06</td>
</tr>
<tr>
<td>SCAMP Beagleboard</td>
<td>40</td>
<td>0.088</td>
</tr>
<tr>
<td>SCAMP Camera</td>
<td>170</td>
<td>0.375</td>
</tr>
<tr>
<td>SCAMP Sensor Suite</td>
<td>600</td>
<td>1.32</td>
</tr>
<tr>
<td>SCAMP Actuator</td>
<td>1770</td>
<td>3.9</td>
</tr>
<tr>
<td>Fasteners</td>
<td>136</td>
<td>0.3</td>
</tr>
<tr>
<td>Payload Plate</td>
<td>1500</td>
<td>3.3</td>
</tr>
<tr>
<td>Ballast Mass</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6853.6</strong></td>
<td><strong>15.11</strong></td>
</tr>
</tbody>
</table>

Electronically, TERP was controlled by the timing lines on the rocket. The GSE rocket line controlled the power board, STARduino, datalogger, Raspberry Pis, and the SCAMP pocketbeagle and motor driver logic. Timer line one was used to control both STAR and SCAMP motors, and the second timer line was used to turn on the 50 V bias. Cabling was PTFE sheathed except for the Pi Camera ribbon cables (unavailable in a PTFE form factor), and the cabling coming from STAR’s commercial motors (also unavailable in PTFE). The full power budget can be seen in Table 5.

Table 5: TERP Power Budget

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Avg. Current Draw (mA)</th>
<th>Peak Current (mA)</th>
<th>Required Capacity (mAh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>STARduino</td>
<td>68</td>
<td>74</td>
<td>11</td>
<td>GSE</td>
</tr>
<tr>
<td>Datalogger</td>
<td>112</td>
<td>112</td>
<td>17</td>
<td>GSE</td>
</tr>
<tr>
<td>Image Capture</td>
<td>257</td>
<td>258</td>
<td>39</td>
<td>GSE</td>
</tr>
<tr>
<td>SCAMP Motor Driver</td>
<td>30</td>
<td>30</td>
<td>1</td>
<td>TE 1</td>
</tr>
<tr>
<td>SCAMP Beagleboard</td>
<td>54</td>
<td>71</td>
<td>2</td>
<td>TE 1</td>
</tr>
<tr>
<td>SCAMP Camera</td>
<td>45</td>
<td>45</td>
<td>1</td>
<td>TE 1</td>
</tr>
<tr>
<td>SCAMP Sensor Suite</td>
<td>28</td>
<td>28</td>
<td>1</td>
<td>TE 1</td>
</tr>
<tr>
<td>SCAMP Actuator</td>
<td>2150</td>
<td>2200</td>
<td>61</td>
<td>TE 1</td>
</tr>
<tr>
<td>Shaker Rack</td>
<td>283</td>
<td>283</td>
<td>8</td>
<td>TE 1</td>
</tr>
<tr>
<td>Motor Driver</td>
<td>283</td>
<td>343</td>
<td>10</td>
<td>TE 1</td>
</tr>
<tr>
<td>Voltage Bias</td>
<td>54</td>
<td>54</td>
<td>23</td>
<td>TE 2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3364</strong></td>
<td><strong>3498</strong></td>
<td><strong>174</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Margin</strong></td>
<td></td>
<td></td>
<td><strong>287%</strong></td>
<td></td>
</tr>
</tbody>
</table>

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3.2 STAR Design

The STAR payload consisted of eight test tubes of regolith simulant spread across two motor-driven shaker racks. Video of the samples was provided by a camera fastened to a sunshade, with the data stored in a separate watertight box to protect them from seawater upon splashdown. Each camera was able to image two samples, with four cameras in total. All other boards (STARduino, bias board, motor driver, power board) were kept exposed on the inside of the sun shade. Except for the cameras bolted to the sunshade, all components of the STAR payload were bolted directly to the RockSat-X payload plate. The fully assembled Project STAR payload can be seen in Figure 5.

![Figure 5: Project STAR Payload](image)

3.2.1 Mechanical Systems

The design of the mechanical systems was primarily driven by the size constraints of the payload footprint. The stringent volume requirements required complex and compact structures, and commercial off-the-shelf components (e.g. motor, test tubes) were either stringently constrained by the allowable volume or custom ordered to be within given tolerances. The resulting mechanical components consisted of four segments: the shaker rack, test tubes assembly, electronics box, and sun shield.

3.2.1.1 Shaker Rack

As the system that not only held together the simulant samples but also was to shake them, the shaker rack was a vital system that required extensive planning and design. It needed to be able to hold the test tubes, as well as provide an attachment point for the motor. While the shaker rack was supposed to move the test tubes axially, it was important that the test tubes did not move relative to the shaker rack. A two part clamping system was designed to mitigate the problem of test tube motion. Both the top and bottom test tube holders
consisted of two parts that clamped the tubes in between them. This kept the test tubes in place during flight. An initial trade was done to determine whether or not the eight test tubes should be held in two 1x4 or two 2x2 racks, with 2x2 turning out better for imaging once we had sufficiently minimized the test-tube to camera distances.

To dampen the vibrations from the test tube - shaker rack interface, and avoid possibly shattering the glass, a silicone cap was placed between the test tube and the shaker rack. These caps had the additional advantage of also keeping some moisture from the environment out of the regolith samples. Figure 6 shows an expanded view of the shaker holder. To prevent the test tubes themselves from axially moving, custom test tubes were ordered with 1/8 in lips. The clamping mechanism was below the top lip and above the bottom lip, such that any axial loading would only drive the lip into the shaker rack. Between the lip and the compressive forces from the shaker holder, the test tubes would not axially move throughout flight.

![Figure 6: Test Tube Rack](image)

In order to facilitate shaking the samples, the shaker rack was mounted onto slide rods. The main test tube holder contained linear PTFE bearings that rode along aluminum slide rods, allowing for smooth motion. A motor was to drive the shaker rack via a two bar piston linkage connecting the motor to the bottom of the shaker rack, as shown in Figure 7.
3.2.1.2 Test Tube Assembly

As described in Section 1.1, a system needed to be created for containing the regolith simulant, allowing a voltage to be applied, and exposing the simulant to vacuum. Wire mesh (McNichols No. 3888704810) was used to contain the samples. With holes less than 0.06 mm in diameter, it contained the regolith simulant (with the smaller simulant diameter being 0.1 mm), and, being made of metal, it was conductive, allowing application of the voltage bias across the test tubes.

3M 2216 Structural Flexible Epoxy was used to attach the mesh to the test tubes, as it is rated for the high shock and vibrational loads of a sounding rocket flight. The mesh cutout pattern is shown in Figure 8. One cutout was epoxied onto the test tube, regolith simulant was placed into the tube, and then the second cutout was epoxied on. When the mesh was epoxied on, a red oxide silicone cap was also placed over the mesh to hold it in place while the epoxy cured. A slit was cut into the edge of the cap to allow the electrode lead from the mesh to pass out the top of the assembled test tube. The slit was also epoxied over. All eight test tubes consisted of different ratios between 0.1 mm and 0.5 mm regolith simulant, with the goal of investigating the differences in their tribocharging as shown in Table 6. The samples contained between 1.8 and 2.4 grams of regolith simulant.
Table 6: Regolith Simulant Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass Ratio</th>
<th>.5mm Mass</th>
<th>.1mm Mass</th>
<th>Total Sample Mass (grams)</th>
<th>Expected Outcome (0.5 mm simulant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>1:5</td>
<td>0.4</td>
<td>2.0</td>
<td>2.4</td>
<td>Positive</td>
</tr>
<tr>
<td>Sample 2</td>
<td>1:2</td>
<td>0.8</td>
<td>1.6</td>
<td>2.4</td>
<td>Positive</td>
</tr>
<tr>
<td>Sample 3</td>
<td>1:1</td>
<td>1.2</td>
<td>1.2</td>
<td>2.4</td>
<td>Positive</td>
</tr>
<tr>
<td>Sample 4</td>
<td>3:1</td>
<td>1.8</td>
<td>0.6</td>
<td>2.4</td>
<td>Positive</td>
</tr>
<tr>
<td>Sample 5</td>
<td>5:1</td>
<td>2.0</td>
<td>0.4</td>
<td>2.4</td>
<td>Neutral</td>
</tr>
<tr>
<td>Sample 6</td>
<td>6:1</td>
<td>1.8</td>
<td>0.3</td>
<td>2.1</td>
<td>Negative</td>
</tr>
<tr>
<td>Sample 7</td>
<td>8:1</td>
<td>1.6</td>
<td>0.2</td>
<td>1.8</td>
<td>Negative</td>
</tr>
<tr>
<td>Sample 8</td>
<td>10:1</td>
<td>2.0</td>
<td>0.2</td>
<td>2.2</td>
<td>Negative</td>
</tr>
</tbody>
</table>

To prevent moisture intrusion into the test tube samples, the tubes had red oxide silicone caps epoxied onto both ends, as explained above. In order to ensure they would be exposed to vacuum conditions during the flight, a small (approximately 3mm by 3mm) "x" was cut into the top silicone cap of each tube to act as a flapper valve. Once the epoxy had been cured, all test tube samples where placed in a vacuum chamber and then backfilled with CO₂. The heavier than air gas would slow diffusion of moist air from the "x" flapper valve into the test samples.

3.2.1.3 Electronics Box

Another critical component for the payload engineering goals was the electronics box, shown in Figure 9. As no telemetry was downlinked during flight for STAR, the datalogger box was critical to maintaining the integrity of the data when the rocket landed in the ocean.
The datalogger box was machined out of a solid block of aluminum and was sealed against the baseplate with a viton O-ring.

As well as sealing the datalogger from ambient conditions, the electronics box contained a J30J-25ZKS connector that allowed for electrical connectivity between STARduino, the Raspberry Pi’s, and the datalogger. These connectors were chosen since they were the smallest size connectors found rated for the thermal conditions of reentry. While they did not seal against the box on their own, MG Chemicals 832TC Epoxy Potting Compound was used to pot the connectors from the inside of the electronics box to keep the electronics box sealed.

### 3.2.1.4 Sun Shield

The Sun Shield was designed to perform multiple mission critical functions. This part not only provided our cameras with a controlled lighting environment but also served as a stable structure for the mounting of our cameras, Raspberry Pi’s and LED lighting.

The footprint of the Sun Shade was dictated by four main factors: the focal distance of the cameras, length of the two shaker racks, available payload section constraints, and the position of SCAMP. The width was 6.2 inches in order to provide an optimal distance for mounting the Pi cameras. With this width, the cameras were a distance of 1.93 in away from the test tubes, which allowed for the clearest imaging of the test tubes. The length of the Sun shade was 8.25 in, which was the length of the two shaker racks (8 in) with margin. This length put a rectangular 6.25 x 8.25 in² sun shade into the exclusion zone when put as
far to one side of the payload plate as possible to maximize space allowed for both payloads. In order to allow maximum allowable space for both STAR and SCAMP, the two sun shade corners in the exclusion zone were angled in order to avoid the exclusion zone.

In addition to the constraints on the horizontal footprint of the sun shade, the height was also constrained by the height allowed by the half-height designation of the payload plate. This designation meant that the TERP payload could be no taller than 5.13 in. The sun shade was designed to be 5 in to allow some margin of clearance between the two payload plates, while at the same time allowing for minimal light to come in through the side of the payload. With the height clearance as small as it was, the payload above TERP was essentially acting as a lid for the sun shade, allowing the mounted LEDs to provide an independent and controlled lighting source for the cameras.

The sun shade was mounted to the baseplate via bolts attached through a 0.5 in flange around most of the sides of the sun shade. This width of flange allowed for enough clearance of the bolt head to not shear from the flange, but also be small enough to not encroach upon the SCAMP space. One end of the sun shade was left open from manufacturing, which was closed with an L bracket and 10-32 bolts.

3.2.2 Electronics Systems

The design of the electronics system was driven by the science requirements to collect images of the sample tubes, environmental data, as well as the need to preserve data onboard. The images collected by Project STAR were far too large to be telemetered using the RockSat-X system, so both the images and the environmental data were logged using the datalogger board. The resulting electronics architecture consisted of seven parts: the cameras, the Raspberry Pi Zeros, the STARduino flight computer, the power board, the bias board, the datalogger board, and the motor driver board. The datalogger board was the only component mounted inside the datalogger box, and all other electronics were mounted inside the sun shield.

3.2.2.1 Camera Systems

STAR consisted of four cameras, each individually controlled by a Raspberry Pi Zero. All four cameras and Raspberry Pi’s were mounted directly to the sun shield. The camera was mounted such that the field of view included the entirety of the two samples regardless of the rest position of the rack after shaking and other electronics were mounted below the edge of this field of view. The cameras were mounted in portrait orientation (shaker axis parallel to the larger dimension of the camera field of view) to accommodate the travel of the shaker rack. The small available volume necessitated that the entire width (smaller dimension) of the field of view be utilized. This, combined with the requirement to distinguish individual particles as small as 0.1 mm diameter, resulted in a chosen camera resolution of 1640 x 1232 pixels based on the Pi Camera’s available resolution modes. At this resolution, the Pi Camera v2 can record up to 40 Hz video, meeting the minimum 30 Hz requirement.
Preliminary testing of a Pi camera proved successful, with the ability to take clear images of the 0.1 mm regolith simulant a set distance away. As these cameras were meant to interface with a Raspberry Pi, the Raspberry Pi Zero was chosen to be the camera processor, as four units could be fit inside the sun shield. While other small cameras exist, the Pi Camera was found to be the best option in Project STAR’s cost range.

To communicate with the camera, Project STAR used the Raspberry Pi Zero standard ribbon cable. From the 2017 payload experience, STAR knew that these cables would almost certainly burn up in reentry, but despite their flimsiness, they could survive the flight. The Raspberry Pi Zeros then compressed and relayed the video data to the datalogger.

The Raspberry Pi Zeros were programmed to run a video capture script on startup that saved the images as video files of 15 seconds each in order to minimize the likelihood of data loss in the event of a power failure, since the data buffer is closed only after the end of a video. A video format was chosen for image compression purposes, as the data rate required proved unattainable with lossless still images. The Raspberry Pi Zero has hardware support for H264 and Motion JPEG video compression at the required resolution and framerate. Testing confirmed both options were tenable, but H264 was generally better quality, and was used for flight.

Each Raspberry Pi Zero was then connected to a dedicated USB flash drive on the datalogger board. The Pi has support for both SPI and USB communication, allowing multiple data storage methods. However, the SPI bus on the GPIO pins is limited to 1 MB/s, well below the STAR bandwidth requirements. The STAR team considered booting the Pi Zeros from a remote SD card, raising this limit to 10 MB/s, but was still concerned this could be too slow. This also posed a substantial risk for breaking the Pi Zero’s. The USB protocol allows for a far higher data transfer rate than was needed, and required minimal modification of the Pi Zero’s, so it was ultimately chosen. The main complication with using USB was the need for precision differential pair wiring.

### 3.2.2.2 STARduino Flight Computer

The STARduino flight computer controlled all onboard data collection except for image capture. It was a custom-designed printed circuit board shield that interfaced with an Arduino M0+. Selecting a processor already developed by the Arduino community greatly simplified flight software development by abstracting away many of the lower level processor configuration tasks. The Arduino M0+ was selected because it utilizes the ATSAMD21G18A processor. This processor is significantly more powerful than the Atmel ATMega processors used in most Arduinos and Arduino derivatives. As further described in §5.1.2, the initial design of STARduino was not as a shield for the Arduino M0+, but as its own board with an ATSAMD21G18A processor.

STARduino was designed to accomplish its data collection tasks with a combination of onboard sensors. In order to satisfy the science goal of collecting gyroscope and accelerometer
data, STARduino contained a high-G 3-axis accelerometer (the Analog Devices ADXL375) and a low-G 9-axis IMU (the Bosch BMX055). STARduino also contained a Maxim 31725M temperature sensor, a Maxim DS3231MZ+ real-time clock (RTC), and additional pressure and temperature sensors (SSCMNN015PA2A3 and MAX31725MTA+, respectively). Data from the sensors were logged to the microSD card on the datalogger, which was supported through the processor’s SPI bus.

STARduino’s external interfaces were with metal-shell J30J-type connectors and molex connectors. STARduino contained one 9-pin J30J-9ZKN connector, with wires branching off to the power board and the datalogger. An additional 2x3 thru-hole header was added to interface with the motor driver and the bias board, with wires directly soldered to the board terminating in two 1x3 Molex connectors.

A high frequency optoisolator was used on STARduino to allow it to send a pulse to the Motor Driver, commanding the driver to step at a fixed frequency. The isolator was necessary due to the different power sources and the need to avoid ground loops, which substantially degraded performance of other systems during testing. There were also concerns about the exact value of the voltage bias, so STARduino read a reduced voltage from an isolated amplifier on the bias board.

3.2.2.3 Power Board
As noted in §5.1.2.1, the power regulator was removed from STARduino and moved to its own power board. As opposed to STARduino, in which the regulator was only regulating the 28 V input to 5 V and 3.3V lines for STARduino use, the power board additionally regulated the TE 1 line from 28 V to 12 for the motor driver. This was done due to an additional switch from using a custom motor driver to a commercial, off-the-shelf (COTS) one. The COTS motor driver did not have power regulation, so this had to be done externally, and it was added to the requirements for the power board.

The power board was designed around the TI LMR16020 switching regulator. The LMR16020 is able to handle an input voltage up to 60 V, and had a continuous current output of 2 A. The design utilized a switching frequency of 1000 kHz, assumed a 5% transient response, and a 40% high-side estimate for the inductor current ripples. There were three LMR16020 switching regulators on the power board, one for each power line: 5 V, 3.3 V, and 12 V. The 5 V and 3.3 V outputs came from the GSE line, and the 12 V output from the TE 1 line. The current draw was estimated at 0.25 A, 1.75 A, and 0.75 A for the 3.3 V, 5 V, and 12 V lines respectively.

At integration, a similar LMR16020 power regulator board with 10 V and 5 V lines was utilized, since the STARduino power regulator was shorted too close to integration to be repaired. The 5 V line was used during integration to power the datalogger and the Raspberry Pis, but the 10 V line was left without a load. During integration itself, it was brought to the team’s attention that the payload was blasting noise back down the rocket’s lines. One of the current theories is that the unloaded switching regulator was adding to that noise.
going back on the line, but that has never been investigated.

Due to this, the power board design that went out included noise suppression. It utilized a DFT7160-105B common-mode choke to prevent high-frequency noise from coming onto the payload and from leaving it. The DFT7160-105B was one of the smallest form factors found that could handle the 0.5 A current draw at 30 V, and would attenuate nearly 20 dB at the frequency of the switching regulators. There are two of these on the power board, one for the GSE line and another for TE 1.

In addition to the common mode choke, each line had a LC low-pass filter on the input before getting to the LMR16020 and on the output of the board to prevent noise heading back onto the rocket and out to the rest of the payload. These were optimized to allow just below the switching frequency of the regulators to pass through, and utilized a 68 nH inductor and a 0.4 $\mu$F capacitor.

### 3.2.2.4 Bias Board

The bias board was designed to boost the 28 V from the TE 2 line up to 50 V for biasing the ends of the test tube. It utilized the LT8330 to bring up the voltage. As per the requirements set by Wallops, the output current could be no more than 10 mA. With the LT8330, the output current was 3 mA.

As noted in §3.2.2.3, noise suppression was a large concern after integration. The power board utilized a DFT7160-475BLB common mode choke to filter out the high frequency noise, and a LC low pass filter to deter any of the 2 MHz noise from the LT8330 switching regulator noise from coming back onto the rocket or on the output lines of the board.

In addition, there was concern that there was not going to be a constant 50 V output onto the test tubes. This prompted the requirement that there be a way to measure and record the actual voltage going out onto the test tubes. To do this, the AMC1311 isolated amplifier was added to the bias board to allow STARduino to safely read the current bias voltage.

### 3.2.2.5 Datalogger Board

To reduce the size of the sealed electronics box on the payload, all of the electronics were exposed to the environment, and a singular datalogging board was left in the electronics box. The datalogging board, therefore, had to store all the video for all four Raspberry Pi Zeros and the environmental data from STARduino. The video from the Raspberry Pis needed to be stored on individual USB flash drives, and the environmental data needed to be stored on a microSD card.

The datalogger utilized 1175-1018-ND dual-USB female hubs to store the flash drives, due to their compact size. Because the datalogger was being mounted to the top face of the electronics box, horizontal USB hubs were used instead of vertical ones due to concerns.
with the soldered pins being able to hold up to the launch loads. Similarly, the HR1940CT-ND hinged microSD drive holder was utilized to mechanically constrain the microSD card. Previous payloads flown with the Balloon Payload Program have been corrupted due to the microSD card being internally cracked upon impacting the ground in a spring-loaded microSD card holder. By using a mechanically hinged microSD drive holder, the chance of a mechanical failure was lower.

3.2.2.6 Motor Driver Board

The motor driver was a COTS Sparkfun motor driver current limited driver, model ROB-12859. This motor driver was designed to drive one motor, but through testing, the STAR team found that it could easily drive two motors in phase simultaneously, well within the current limits. The main challenge in using this driver was the need to replace a large electrolytic capacitor with a ceramic capacitor due to vacuum. The driver also supports microstepping, but this limits its maximum speed and was unnecessary for STAR. All driver inputs were fixed either high or low, and the driver received a step pulse train from STARduino via an optoisolator.

3.2.2.7 Connectors and Wiring

Project STAR utilized J30 and J30J type connectors to mount to electronics boards and the sealed electronics box. While these were not sealing, prompting the use of sealing epoxy on the electronics box, these were the smallest size connectors that could be found with the number of pins needed. The largest sized connector used, 25 pins, would have been 53 mm long with a MDM connector, standard in the United States. The J30 series connectors was 30 mm long for the same 25 pin connector. This additional saved space with the J30 series connectors allowed for the boards - and therefore the electronics box - to be smaller, allowing more space for other components on the payload.

With all of the independent electronics systems trying to interact with one another, wiring required much planning to enable all systems to be properly wired an not interfere with any other systems. As seen in Figure 10, STARduino needed to interact with the motor driver, electronics box, and the bias board. The electronics box needed to, in addition to STARduino, be connected to all four of the Raspberry Pis.
Each Raspberry Pi had five wires for USB protocol that were being routed from the Raspberry Pi through the electronics box, and terminating at the datalogger. All of this wire needed to be shielded in order to prevent excessive noise from interfering with the data signals. This was done with metal braided heat shrink that was put on the wires after they had been soldered. On the Raspberry Pi end, wires were soldered to a Raspberry Pi Stem breakout board that utilized the USB pads underneath the Raspberry Pi. These terminated in a five pin Molex connector, which broke out the interface to allow for easy debugging of systems. The second half of this connection was soldered to the mating J30J-25TJS connector of the electronics box. The other half contained the soldered link between the datalogger and the J30J-25ZKS connector mounted to the electronics box.

The wiring interface on the power board consisted of a J30J-25ZKN 25 pin connector. This branched out to different locations, and terminated in multiple Molex connectors. There were four 2x1 Molex connectors carrying + 5 V and GND to each Raspberry Pi, one 2x1 Molex carrying + 3V3 and GND to STARduino, and one 2x1 Molex carrying + 28 V and GND from the rocket.

STARduino contained a nine pin J30J-9ZKN connector, and a 2x3 thru-hole array for additional connections. The nine pin connector was used for carrying input power from the
power board to STARduino, output power and SPI lines from STARduino to the datalogger. All of these connections terminated in Molex connectors, attached with their complementary Molex connectors originating from the power boards and the mating J30J-25TJS electronics box connector, respectively. The additional 2x3 thru-hole array was used for the interfaces between STARduino and either the motor driver or the voltage bias.

The voltage bias board contained a single nine pin J30J-9ZKN connector. It had input voltage and ground from the second timer event line via a 2x1 Molex connector. Two output pins were used for the 50 V line being passed to the bottom of the wire mesh caps on the test tubes. Each of these were split to a 4x1 Molex connector so each line provided power to a single shaker rack of test tubes. The same was done with two output pins for the ground wires going to the top of each test tube rack. The three remaining pins on the connector contained +5V, ground, and the output of the 5 V voltage divider, all of which were being fed to STARduino via a 3x1 Molex connector to store the magnitude of the electric field applied across the test tubes.

As described in §3.2.3.2, the final version of the bias board consisted of wires directly soldered from the power and ground lines of the second timer line. Both of the rocket lines were split into two lines, and then each of those two lines was split into four, totaling eight wires off of both timer line power and ground. Each set of four wires was put into a mating 4x1 Molex connector to the ones on the test tube mesh, replacing the 50 V and ground lines that were supposed to be coming from the bias board.

The COTS motor driver was powered with a 2x1 12 V and Ground Molex connector mating from the power board. There were two sets of I/O pins on the motor driver used for driving stepper motors, and each I/O pin set contained the same one of four wires from each motor. The three remaining pins on the connector contained +3V3, ground, and the analog PWM pin from the STARduino mating 3x1 Molex connector that stepped the motor driver. These three wires fed into the isolating analog converter to allow STARduino to control the motor controller without compromising payload isolation.

3.2.3 Descopes

3.2.3.1 Shaker

The center piece of the shaker rack holder was machined with holes for four PTFE linear slide bearings. Due to manufacturing defects, only two bearings could be inserted into the shaker rack holder for the shaker rack to still slide, as the top and bottom set of bearing holes were misaligned. With all four linear bearings inserted, there was a torque on the slide rods to align to the misalignment, which elevated the friction on the system such that the motors could not overcome it. The top two bearings were put onto the shaker rack for flight as they were more easily replaced if need be.

Even with the reduced number of linear bearings, when the entire shaker rack assembly as shown in Figure 7, there was too much friction for the motor to overcome, and the motors
were unable to move the shaker rack. When the motors were turned on, they stalled, but were still able to vibrate the entire payload plate. Because the motors were constant current, there was no issue with power consumption due to stalling the motors. For flight, the entire shaker rack was locked into place by overtightening the linear bearing screws such that they were pressed against the slide rod as opposed to next to it, keeping the shaker rack in place. When timer line one was triggered on, the payload plate vibrated as a whole, with vibrations concentrated on the shaker rack. While this produced less simulant mixing than intended, it induced sufficient rubbing to expect charging within the science requirements.

3.2.3.2 Bias board

During the final assembly of the payload prior to flight, the bias board was overtorqued onto the standoffs and snapped, rendering it useless. The test board was then crimped and readied to be used in flight. During final check in for the payload, when the second timer event line that was powering the bias was turned on, the board failed, smelled of smoke, and was deemed unfit for flight. The reason for this failure is still not known. In order to fly with any bias, the 28 V from the timer line itself was used as the bias instead of the 50 V supplied from the bias board. This is how the payload flew, with a 28 V bias as opposed to a 50 V one.

3.3 SCAMP Design

3.3.1 Mechanical Systems

SCAMP’s actuation mechanism was relatively simple, utilizing an Allied Motion High Torque Brushless Motor (HT02000-A00) to generate power, then transferred through an aluminum drive shaft into an oldham coupling and finally into the CSG-14-100-2A-R Harmonic Drive and then through into the end effector. This configuration exactly matches that of DYMAFLEX in an attempt to accurately replicate the dynamic capabilities within a joint.

Sealing mechanisms needed to be added to DYMAFLEX’s design to preserve data, as well as the encoders and costly harmonic drive but with a severe emphasis on maintaining a close-fit package (the space allotted for our manipulator bordered the Keep Out Zone closely.) The eventual solution was to design a seal for a 3/32 in o-ring, requiring a 1/8 in wide groove, ultimately leaving a .004 in outer wall. This solution allowed SCAMP to maintain its full range of motion (30 degrees) and stay out of the keep out zone.

The addition of a sealing D-sub connector was necessary for motor power transmission as well as encoder data, so an adapter section was necessary to add to the central motor housing. The connectors chosen had a face seal on the external connector side, so a two part sealing mechanism was chosen to be most appropriate.
3.3.1.1 Electronics Housing

Maintaining a sealed electronics box was of the utmost importance during recovery for the preservation of data as well as the recovery of items such as the Elmo Tweeter motor driver. A clamshell design was ultimately used due to its convenience in both electronics mounting and reliable sealing characteristics (not relying on the baseplate surface to seal upon.) Sealing was provided entirely by silicone O-rings, one mounted in one side on the clamshell and the others on the connectors. The electronics were mounted the inside of the box by machined aluminum standoffs, which were part of the single-piece clamshell side. While the integrated standoffs greatly increased the difficulty of machining, the added leak path of a though hole standoff leaking was deemed an unacceptable risk.

3.3.1.2 End Effector

SCAMP’s end effector had a 5 in reach and was responsible for contacting both the compliant and non-compliant surfaces. Fastened to the robot housing through a dovetail joint for a superior connection (effectively eliminating possible movement in roll and yaw, as well as side to side and forward/back translation, with a cotter pin inserted as a retention mechanism (thus preventing all other forms of movement.) Attached to the end effector was planned to be a series of load-cells to aid in determining forces against each contact as a function of time, as well as an accelerometer. Running down the entire length of the end effector was a mass shuttle (a 0.25x0.5x0.65 in³ piece of machined Polyoxymethylene [Delrin]) was planned to be responsible for carrying a mass of 100 g between the far and close end, however due to space constraints no material available to us could provide greater than 32.2 g of mass without compromising other design aspects (a concept discovered just a few weeks before integration.) Additionally, the hot wire cutting system was proved to be functional however was omitted for the final iteration due to a lack of possibility of the mass addition, and a redesign for RockSat-X 2019 is already underway to satisfy this requirement.

3.3.1.3 Payload Plate

SCAMP was allocated a small section of the payload plate that provided the most space efficient layout for both teams, while maintaining a 30 degree field of movement. SCAMP’s electronics box was specially designed to prevent sealing against the payload plate so that it could be easily assembled and tested in our electronics laboratory while STAR assembled their payload. The electronics box design had a face seal perpendicular to the payload plate, and to prevent compromising the integrity of such sealing mechanism slots had to be machined into the plate to compensate for factors such as thermal expansion and machining errors. This idea worked very well, and maintained a sealed electronics box throughout the entirety of flight.
3.3.2 Electronics

SCAMP electronics were designed to fit in the highly constrained electronics box, and mount the COTS boards we had to work with. For this reason, the system was split into 3 different parts: the PocketBeagle flight computer, the Tweeter motor driver and the power supplies for the system. To allow the system to start before launch to accommodate a long boot time, the Tweeter logic and the PocketBeagle power were driven by a GSE line. The Tweeter motor power was provided by a timer line.

![SCAMP electronics clamshell, exploded view](image)

Figure 11: SCAMP electronics clamshell, exploded view

3.3.2.1 Motor and encoders

The motor and encoder used for the project were identical to those used on DYMAFLEX, to ensure that the test results of this fight are directly applicable to the DYMAFLEX project. The Motor is an HT02000-A00 8 pole brushless motor with integrated hall effect sensors. The encoder is a USDigital EM1 optical encoder with a 2000 disk and 2X interpolation. Both the hall sensors and encoder are powered by 5V.
3.3.2.2 Flight Computer and breakout board

The main flight computer was a COTS PocketBeagle SoC. The PocketBeagle is a true system on chip, featuring a 1 GHz Arm processor, 512MB of RAM, 2 programmable real-time units and on-board power management. The PocketBeagle was chosen over other commonly-used microprocessors and SoC’s due to it’s size and performance. Other common SOC systems (such as the Raspberry Pi) are not available in a small form factor. Systems such as an Arduino do not have the processing power to perform the mission. Another deciding factor was that the PocketBeagle has an on-board CAN Interface. This interface is critical in communicating with the motor controller.

The carrier board for the PocketBeagle is designed to provide a mechanical mounting interface, and electrical breakout and interconnect. The board also carries the analog-to-digital converter, isolation ICs, a CAN transceiver, and level shifting hardware for rocket communication. The board

The main communication IC is the MCP2562 CAN interface IC. While the PocketBeagle features a CANbus controller, the onboard hardware does not have the capability to drive the CANbus. For this reason the MCP chip is used. This chip takes in a the CANbus differential line, and decodes it to the RX pin. Likewise it accepts asynchronous data from the TX pin, an does the appropriate diving of the bus. This particular chip features a selectable logic output, which allows a 3.3V output to be used, negating the need for a level shifter IC.

The Rocket RS-232 communication is handled by an SP3232EBCY RS-232 driver and an ISO7720FQDRQ1 isolation IC. The SP3232 chip is an integrated charge-pump RS-232 driver, capable of creating Rs-232 voltages from just a single-ended 5V power supply. However, because the RS-232 rocket connection contains a ground, an isolation IC is required to prevent ground loops. ISO7720FQDRQ1 IC handles this task very well. The dedicated Isolation IC was used because is provided a guaranteed 1MHz bandwidth, and did not invert the signal as a common optoisolator does. A second isolation IC was included to be used with the GPIO pins to drive the hot wire cutter, but was left unused due to descopes.

The load cell reading was accomplished using an ADS1247 ADC with a built-in Programmable Gain Amplifier(PGA). This particular ADC was chosen for its 2000 sample/sec data rate, 24 bit accuracy, and most importantly the built-in PGA. Due to the low output of a load cell, an amplifier must be used before feeding the signal to the ADC. By selecting an ADC with a built-in ADC, the design can be simplified as an amplification circuit does not have to be designed.

3.3.2.3 Tweeter Motor Driver and Carrier Board

The Tweeter Motor controller is a COTS, 3-phase brushless motor driver that communicates over CANBus. This motor controller was the one used in DYMAFLEX, and as such was an immutable design parameter. From the manufacturer, the driver comes pre-installed with
51 male header pins, serving as the interface for the many functions of the controller. The purpose of the carrier board was to receive these pins, and break them out to the connectors, and provide some I/O logic support. Specifically, board provided CANBus termination, encoder signal conversion, an RS-232 programming connector, current sensors, and electrical connections for the tweeter and ADC sled to the main Harwin M80 connectors.

One of the main functions of the Tweeter carrier was to convert the single-ended encoder signals into differential signals to the Tweeter. This was accomplished using an AM26C31IPWR line driver IC. This IC takes in a single ended signal and outputs a differential one. No additional power supplies were needed, as the chip is powered from the Tweeter’s own auxiliary 5V output. Note that this chip is a 4-channel chip, and the unused channel was tied to the +5V line. If the unused input pin was left floating, it would drift between high and low, and cause the output to rapidly oscillate. These oscillations would feed noise into the rest of the system, and increase the overall current consumption of the chip (the current consumption is roughly proportional to the switching frequency.) The Hall effect sensor inputs are not differential, so no such conversion IC is needed.

The board also featured breakouts for the two communication interfaces of the Tweeter. The RS-232 programming interface was broke out onto a separate connector, allowing the board to be programmed regardless if the motors were connected. This configuration also allowed the connector to be left off in the flight version, allowing the board to fit in smaller space. The CAN interface was also broken out to a separate power/data connector, which allowed for the board to be tested with the rest of the electronics, even if the motor was disconnected. The CAN traces were routed as length-matched differential pairs, pairs, and terminated with a 120 Ohm resistor, as mandated by the CAN standard.

Because the need for higher-accuracy sensing was determined so late in the design, the ADCs intended to be used were moved to a separate daughter board, called the ADC sled. The Tweeter carrier provided power and analog data for the ADC sled. To aid the ADC sled in data collection, the initial shut resistors placed on the 3 motor phases were replaced ACS70331EESATR giant magnetoresistive contactless sensors. These sensors feature a single-ended output, and 1GHz bandwidth, which makes them superior choices to a standard 4-terminal current measurement. Unfortunately, due to a stackup height issue, the ADC sled could not be mounted, so the ACS7033’s went unused.

3.3.2.4 Power supplies

Based on the internal wiring of COTS components, it was determined that three galvanically isolated power supplies were needed. One power supply was to provide 5V power to the PocketBeagle, and associated components, one to provide 5V power the RS-232 level shifter, and the last had to provide a low-ripple 5V supply to the ADC and load cell. The connectors for this board were 2X2, right-angle Harwin M80 connectors, chosen to be compatible with the remainder of the connectors used in the internals of the electronics box.
Initial design efforts focused on building custom power supplies for each output, as a custom power supply will have much less mass and footprint than a COTS solution. Given the intense space constraints, this was an attractive goal. However, it was quickly found that a custom power supply typically required a custom transformer, something that the program could not afford to acquire due to both time and cost. The solution was to use COTS power supply modules. This solution reduces the number of board revisions (we don’t have to debug a power supply - a very complicated design) and thus reduces development time and cost. While the COTS power modules cost more, the reduced number of board revisions actually makes them the cheaper option in the long run.

The final configuration used a S24SE05004 isolating step-down converter for the 5V PocketBeagle supply. The converter is rated to output 5V at 4A, which is sufficient to power the PocketBeagle and associated electronics. However, it is important to note that the power dissipation of the S24 exceeds 2 Watts at output currents of 600mA (near the typical operating point of the PocketBeagle), and as such, requires a heatsink. During normal operation on Earth, this heatsink is not needed due to natural convection and airflow. However, due to the cramped conditions and lack of circulation, the module had to be heatsunk during the mission. This was accomplished by mounting it in such a way that the thermal interface side was pressed up against the side wall of the electronics box. The thermal interface was further improved by sandwiching a thermally-conductive insulating pad between the wall and the module.

To reduce the amount of ripple and noise coming from the supply, LC filters were installed on both the input and output side. Each filter consisted of two 22uF electrolytic capacitors and a 1uH inductor. This forms a low pass filter with a cutoff frequency of 24kHz. Given that the switch frequency is 550kHz, this results in a 50 dB attenuation of the switch frequency. The arrangement of filters on both the input and output side ensures that the output is free of high-frequency noise, and that the input side is not transmitting noise to other systems. The noise suppression of the system is further enhanced by having a common-mode choke on the input, shared by the three power supplies. The common mode choke, as its name implies, suppresses common-mode noise coming in through the input. This reduces noise and transients transmitted through the chassis of the electronics box, and any other conductors that may provide a parasitic capacitive path for high frequency currents. In addition to filtering, the PCB features unpopulated footprints for enable/disable resistors, and footprints for trim resistors on the output. Both of these features were added as an additional factor of safety against design mistakes and supply difficulties. For example, if the module was mistakenly ordered in the pull-high-to-enable configuration, one of the enable resistor pads could be populated, restoring functionality. Likewise, if the output needed to have its voltage adjusted, the trim resistors could be easily added in, without having to resort to making a new board, or bodge fix. Because this power supply would always be loaded at over 10% load, a dummy minimum load was not implemented. Additional features such as high-voltage, low-value bypass capacitors across the isolation were not added, as they were not part of the manufacturer’s suggested implementation. Other nice-to-have features such as a power-on LED and test points were omitted due to board space constraints.
The power supply used for the rocket side of the RS-232 downlink was an ITW2405SA isolating, step-down module capable of supplying 200mA of current at 5V(1W). The module outputs 5V to supply the charge pump RS-232 level shifter and the distal side of the digital isolator. Like the larger S24 supply, this supply also features LC filters on both the input and output. Per manufacturer suggestion, the input is filtered by a 4.7uF capacitor, and a 4.7uH inductor. They form a low pass filter with a cutoff frequency of 34kHz, leading to a 45dB reduction in switching noise reflected on the input. While the manufacturer did not provide a recommended EMI suppression scheme for the output, the same filter was applied to stop the 550kHz switch noise from propagating to the RS-232 line. This regulator shares a common mode choke with the other power supplies. Due to the simplicity of this module, no other supporting components were needed other than dummy load resistors. Load calculations showed that the current draw of the rocket side of the RS-232 communication drew less than 5mA, which was less than the rule-of-thumb minimum current for a switching supply (this supply would need to be loaded with 20mA, to meet the 10% minimum load). To counter this, a pair of 1/2 Watt resistors were inserted to load the power supply. While rated for 0.5W, the resistors only dissipate 0.05W each, and the large case and over-rating allow for safe power dissipation in the confined quarters of the electronics box. As with the S24, niceties such as test points and power-ok LEDs were dropped due to board spacing and layout constraints.

The 5V analog supply for the ADC was provided by an ITW2412SA isolating step-down module and a MIC5225-5.0YM5-TR low dropout regulator (LDO). The ITW-12 was used in the same configuration as the ITW-05, including the same LC filtering setup. To reduce the thermal load on the LDO, the dummy load resistors were placed immediately after the ITW-12, but before the LDO. This way, the 0.1W of heat would be dissipated by the two (relatively) large resistors, and not the LDO, which is limited to 300mW of power dissipation in free-air on Earth. In this configuration the LDO only as to dissipate a few mW, as the current draw of the analog system is in the range of 3-4 mA. The configuration of a switching regulator and an LDO was chosen to reduce the noise from the switching regulator as much as possible. Had a ‘bare’ switching regulator been used, some switching noise would have been injected into the analog system, alongside the natural ripple of regulator. By placing an LDO immediately after, the ripple can be suppressed, and the substantially smaller ripple of the LDO is seen on the output. Immediately following the LDO, 3 capacitors of 10uF, 1uF, and, 0.1uF are placed to further remove any high-frequency components before the power is sent to the analog subsystem.

The large range of input voltage, alongside the relatively high value of the voltage itself, presented interesting challenges in component selection. Devices that expect 24V input would often find the maximum voltage of 34V (immediately after transition to rocket power) intolerable. Devices rated for the next higher voltage class of 48V, would find themselves operating below their minimum voltage if the input voltage fell below 24V, something that was permissible per the power ICD provided by Wallops. The power supplies selected were capable with dealing with the voltage range, but only barely. All three power supplies have a maximum allowable voltage of 36V, just two volts over the maximum supplied by Wallops. In an ideal world, transient suppression devices, and polyfuses would have been used to protect
the board, however due to time and board space constraints, they were not implemented. The relatively high input voltage also affected the selection of capacitors, particular on the input side. Capacitors with high voltage ratings tend to have smaller capacitances, and larger case sizes. This trend forced us to split the input filter capacitor for the S24 from a single 47uF device, to two 22uF devices. This slight drop in capacitance did not affect the filtering properties, but allowed for a smaller case to be used, so that we could meet height constraints.

The final board design was routed entirely on the top side of the PCB, with the bottom layer being a large ground plane. While this routing setup complicates component placement, it offers the best noise suppression performance. Special care was taken to make sure that each trace on the top side was routed over its corresponding ground plane, and that it never crossed over another ground plane. The only place where this was violated was in the placement of the common-mode choke, which had to be placed over the post-filter ground plane due to the sheer size of the device. The effects of this violation were not characterized due to lack of resources and appropriate instrumentation.

3.3.2.5 Connectors and Wiring

The external connectors for SCAMP were selected to be airtight and waterproof without additional modification, and utilize a common interface standard. The MDBR series of IP68-rated sealed D-sub connectors from Amphenol met these criteria. While the IP68 rating is suspect (the datasheets disagree on the exact rating - some claim IP67) the connector series was the only one that could be sourced in a reasonable time for a reasonable cost. One important feature of the connector was the fact that it was seal-rated even when unmated, which allowed the mating external connector to be a standard D-sub (rather than an expensive sealing one). Additionally, the standardized form factor allowed us to use an inexpensive d-sub for testing and integration while the electronics were mounted in the electronics box. However, a sealing D-sub carries a rather large footprint penalty, as the sealing O-ring requires a relatively large amount of space. This severely constrained connector placement, and forced us to use high-density connectors. The end result was two 26-pin, MDBRA26PMAN0 connectors on the electronics box, and a single MDBRE15PMAN0 connector on the motor housing. Note that these connectors are actually male connectors, and not female, as dictated by convention. Normally, the fixed side of a connection is the harder to damage female side, as replacing a connector on the fixed side (mounted to cabinet, or panel pass-through) is much more difficult than replacing the cable.

The internal connectors were all Harwin L-Tek M80 connectors. These connectors are small-size (2mm pitch spacing) and feature acceleration resistance of up to 50G, and vibration resistance of 10G. While there are many types of connectors that operate in this regime, the Harwins were chosen because the lab had the appropriate tooling for them. Acquiring the appropriate tooling for such connectors is often cost-prohibitive, as the a single crimp tool can cost over 300$, not including alignment tools, and insert/remove tools. As the lab had used these connectors in the past, past experience with using them could be leveraged to prevent assembly issue, and the existing stock could be used to quickly assess the viability.
In order to simplify assembly, and testing, the electrical lines running to the rocket had connectors installed mid-way. Had they not been installed, the system would have had to be permanently soldered to the rocket connector. Because the other end of the soldered connection is a D-sub 26 connector, you would not be able remove rocket power and telemetry, without also unplugging sensors and other devices sharing the D-sub. However, placing the AMPMODU MTE connectors mid-way solves these issues. The 5 rocket lines going to SCAMP were partitioned into two sections: Power and telemetry. Both were handled by a 3-position AMPMODU MTE connector.

The external wiring was chosen to be PTFE-sheathed, rather than other sheathing materials due to outgassing concerns. 24 AWG wire was selected as the 3.5 Amp rating far exceeds our expected current draw, and the gauge is large enough to work with easily. The internal wiring was 24 AWG PVC-sheathed wire. This decision was primarily driven by the availability of the wire. Outgassing concerns were not expressed in this choice, as the wire was in the pressurized electronics box.

The distribution of wires among the the external connectors, as well as the specific pinouts of the on-board connectors was the subject of major design work. The main driving factor in the assignment of signals to pins was the desire to keep high-frequency noise away from sensitive, low-level signals. For example, on the PocketBeagle carrier, the CAN bus and the load cell analog system shared a connector, due to board placement. To prevent the coupling of 1MHz noise from the CAN bus to the load cells, the two signals were positioned at opposite ends of the connector. To further increase noise rejection, a set of ground pins were placed between the analog side of the connector and the digital side. This configuration will provide shielding from radiated EM noise from the digital side, as the pin will act as Faraday cage, and shunt any received noise, rather than allowing it to continue to propagate until it hits the analog side. Similar logic was applied to the other boards, and were possible, sensitive signals were kept far from high-frequency ones.

### 3.3.3 Descopes

Throughout the design reviews, SCAMP’s developed descopes included: utilizing only one of the two contacts for impeded motion testing, eliminating varying moment of inertia testing, and down-sampling the camera feed in the event of peaking processing power.

### 4 Student Involvement

- Juliette Abbonizio *Aerospace Engineering Undergraduate Student*
  
  - Juliette was a part of the STAR CAD team, and was responsible for designing the payload structures. She also assisted in converting the design of the STAR Sunshade to a sheet metal part. Juliette was responsible for adding fasteners to multiple components in the main assembly.
• Joseph Breeden Aerospace Engineering, Mathematics Undergraduate Student
  
  – Joseph was responsible for the STAR Camera Systems, and its interface with the datalogger board. Joseph also assembled most of the payload wiring and connectors, and helped fix the motor board, bias board, power board, and STARduino shield. Joseph also wrote all flight software used on STAR within STARduino and the four Raspberry Pi Zeros.

• Daniil Gribok Aerospace Engineering Graduate Student
  
  – Dan designed the electronics for SCAMP, with design assistance from Nicholas Limparis. He was also responsible for the SCAMP software. In addition to those duties, he designed the electronics box, and seal. He also performed the wiring and electronics assembly for SCAMP and assisted with connector design for STAR.

• Charlie Hanner Aerospace Engineering Undergraduate Student
  
  – Charlie was responsible for SCAMP’s mechanical design including the adaptation between DYMAFLEX and its current design, integration of o-ring seals, and the original design for the end effector system and the contacts. Additionally Charlie completed most of the machining for the robot and electronics box with the support of Nicholas Limparis.

• Nicholas Limparis Aerospace Engineering Graduate Student
  
  – Nick served as the primary electronics and hardware performance advisor for both SCAMP and STAR. He helped verify electronics designs prior to ordering, and provided invaluable advice to the software and electronics team (particularity with regards to EMI suppression). In addition to that, he reviewed parts and assisted in manufacturing difficult parts for both STAR and SCAMP

• Michael Owca Aerospace Engineering Undergraduate Student
  
  – Michael was a part of the STAR CAD team, responsible for designing the payload structures. In particular, Michael worked on designing the shaker rack system, which involved finding an appropriate motor, designing the piston linkage system, and the shaker rack itself.

• Aravind Ramakrishnan Physics, Computer Science Undergraduate Student
  
  – Aravind was a part of the STAR electronics team, and was responsible for designing the initial electronics versions of the motor driver, STARduino, and the voltage bias.

• Michael Schwab Aerospace Engineering Undergraduate Student
  
  – Michael was a part of the STAR CAD team and was responsible for the design of the STAR Sunshade and the Electronics Box. Additionally Michael kept the CAD model up to date and managed the main assembly. He also coordinated with Charlie Hanner to ensure successful integration of the two payloads.
Blaire Weinberg Aerospace Engineering Undergraduate Student

- Blaire was responsible for the main electronics designs for the datalogger, power board, and STARduino, and led the redesign of the motor board, bias board, power board, and STARduino shield with the help of Joseph Breeden and Nicholas Limparis. Blaire also designed the o-ring seal on the electronics box, machined the STAR payload, and helped with the payload wiring and connectors.

5 Testing Results

5.1 STAR Testing Results

5.1.1 Motor Driver

The chosen motor driver is designed for only one stepper motor, but has peripherals for two motors to allow for variability in connectors. Once we got one motor running smoothly, we attached a second motor to the extra peripheral. Once the current limit was sufficiently raised, both motors operated smoothly together, so we concluded that a single motor driver could operate both motors.

As explained in the descopes section, the desired sinusoidal motion of the shaker rack became impossible due to bearing defects. However, in discovering this and trying to align the bearing properly, we also noticed that the vibration induced by the motor still sufficiently shook the particles. During initial design, we had considered using voice coils as an alternative shaker design and discarded it because of complexity and cost. The bead behavior under this vibration was more similar to what we had expected under voice coils, so we decided to keep this behavior and locked the bearings permanently. We then had to re-tune the motor driver current limits to this new configuration, which had the added bonus of drawing very little power (90mA instead of 300 mA).

Testing also showed that the motors operated differently when run on an interrupt based step method (as used later) than on a delay based step method (as used initially), indicating that the Arduino library overhead or other electronics/software considerations may have impacted early characterization of the motor speed range. This became inconsequential after the motor descope, but should be considered in future motor controller design.

5.1.2 STARduino

Three versions of the STARduino flight computer were developed for this payload.

5.1.2.1 Power Regulated, Microcontroller-based

The first version of STARduino contained nearly the exact same components as the one flown for RockSat-X 2017. It included a power regulator to convert the 28 V from the rocket
to +5 V and +3V3 to power the rest of the payload. The +5 V line powered the Raspberry Pi Zeros and the USB drives on the datalogger, and the +3V3 line powered the rest of the STARduino sensor suite and the SD card on the datalogger.

During the final assembly for integration, there was a short between the payload and the regulator, which destroyed the chip, and the power going to the rest of the payload. For integration, a power board from another project that converted +30 V to +5 V and +10 V was swapped in to ensure that the imaging and datalogging could be tested during integration. Due to this error, the power converting was moved to a separate power board (See §3.2.2.3), which allowed independent testing of the microcontroller and power circuits and easier error identification later on.

5.1.2.2 Externally Powered Microcontroller-based

The second version of STARduino eliminated the power regulation from the board, and only contained the microcontroller and sensor suite. The ATSAMD21G18A microcontroller is the same as that on the Arduino M0+, so the board was flashed with the bootloader for the M0+ and programmed from the Arduino IDE. For testing purposes, a simple “turn a pin high” program was flashed to check that the microcontroller was able to execute programs properly. When flashed to the Arduino M0+, the pin was turned high, but when flashed successfully (according to the Atmel ICE bootloader) to STARduino, the pin would only float. Due to the time remaining until flight, instead of debugging and finding the issue with the microcontroller, a shield for the Arduino M0+ would be developed with all of the sensors that were needed, as described in §5.1.2.3.

The current working theory as to why the microcontroller on STARduino was unable to execute the programs flashed to it are either that there is an issue with the external clock, or an issue with the internal microcontroller fuses. In either scenario, an error would cause the program to fail to execute, even with a loaded bootloader and the ability to flash code to the memory. No testing has yet been done to diagnose whether or not either of these are the reason for the STARduino failure, although there may be future interest in doing so.

5.1.2.3 Arduino M0 Shield

With the microcontroller-based STARduino not executing code soon before flight, the switch was made to use a pre-fabbed Arduino M0+ and a custom STARduino shield. The shield contained all of the same sensors as on the previous STARduino boards, but received power and transmitted data to the pins of the Arduino M0+. This was the unit flown on the flight, with the data being stored on the SD card on the datalogger. All of the sensors were able to communicate with the Arduino M0+ except the magnetometer on the BMX055, which was never solved.
5.1.3 50 V Bias

5.1.3.1 Rev One

The initial 50 V bias included the lt8300 isolating buck regulator to take the 28 V input down to 20 V. From there, there was a boost stage that took the 20 V up to 50 V. During the testing for this board design, the buck stage worked, bringing the voltage down to 20 V. The boost stage was working, but not as expected, only bringing up the voltage to just below 35 V. A missing ground trace was discovered within the regulator’s resistor ladder, although it did not effect the overall performance of the board when fixed.

Due to this, a isolated boost stage board was ordered, with an input of 20 V to try and precisely see what was the issue with the boost stage. No results ever came of this, as the board continued to output just below 35 V but nothing could be found in the schematic to determine why that was occurring.

5.1.3.2 Rev Two

After integration, a board reorganization called for a smaller footprint, and as the LT8330 boost stage chip was able to handle an input of 28 V without a buck stage to 20 V, the buck stage of the Rev One board was dropped. In addition to a resistor network, a potentiometer was added to more finely tune which resistors to use if the board worked. When tested with the potentiometer populated instead of the resistor network, the board was able to output 50 V after some fine tuning of the potentiometer. Aside from a slight resistor miscalculation which should have produced 48V, the actual issue with the Rev One board was never found. Dividing the potentiometer value into the resistor network left the two values at 1 MΩ and 32 kΩ for the flight board, which also output 50 V.

5.1.4 Datalogger Board

The initial version of the datalogger board contained two 1175-1018-ND dual-USB female hubs to store the four flash drives for the Raspberry Pis, as well the HT1940CT-ND hinged microSD card holder for the STARduino data. To fulfill STARduino redundancy requirements, there was also the MT25QL01GBBB8ESF-0AAT onboard flash chip to store the same STARduino data. The MT25QL01GBBB8ESF-0AAT flash chip was out of stock and backordered for at least four months, so the second version of the datalogger utilized the W25N01GVZEIG TR flash chip instead.

Both the flash chip and the microSD card were not working on the second version of the datalogger, which was then traced to a short or mis-wiring on the flash chip. When the flash chip was removed, the microSD card was able to properly store data. At this point, the flash chip was descoped from the project to focus on more pressing issues.

The third version of the datalogger did not have any flash chips, and just contained the two female USB hubs and the hinged microSD card. One of the USB traces were routed underneath a power trace, and the resulting noise interfered enough that data could not be
stored. Rev 3.1 fixed this routing, and was the board used at integration.

After integration, the issue of noise suppression came to light, and the datalogger was also susceptible. The data trace width had previously been too small, and some of the data signal was being reflected off of the termination point and run back onto the line. In addition to fixing the data trace width, filtering capacitors were added to the power traces on the datalogger to handle noise in the power lines. After integration, it also came to light that each USB line should have their own power and ground connection from the Raspberry Pi as opposed to a connection from the rocket to alleviate ground loops and increase the likelihood of proper data storage. This resulted in the creation of five isolated power and ground planes on the datalogger for each USB hub and the microSD card holder to replace the singular power and ground plane previous to all of the other datalogger revisions. All of this addition required no size change to the datalogger, and this board was the one used in flight.

5.1.5 Camera Systems

Camera systems testing focused on verifying the camera field of view, verifying the software, integrating with the datalogger, and focusing the camera. We created a cardboard mockup holding a test tube the specified distance away from the camera lens, and thereby confirmed our calculations for the 1.93” separation. We then added an LED board to this mockup and surrounded it in a dark box to test the LED brightness. Even though the LEDs were uncomfortably bright to human eyes, they were not overly bright to the camera, which automatically adjusted and produced high contrast video of the beads. Thus, we decided not to dim the LED boards with an extra resistor as had been initially suggested. This test also showed that our LED placement would most avoid producing glare spots as had been present in 2017.

The software consisted of short python and bash scripts that recorded video indefinitely to a new folder upon startup. Testing this showed that the software worked as expected, including using the USB drive, and required minimal modification. The working software was saved as a system image, which could be flashed onto a new Pi in under 30 minutes. Tests were done on both wifi enabled Pi Zeros, which were far more convenient for testing, and flight representative Pi Zeros, which performed similarly. Due to a power short near flight, one of these test Pi Zeros was swapped in for flight.

The most extensive phase of testing was recording to the datalogger. To do this, the datalogger was attached to one or more Pi Zeros at a time, and the Pi Zeros ran their flight software. Due to the expense of the cameras, most of these tests were done without cameras until we were confident in the system. Through these tests, we identified that a power trace passing over a USB differential pair was supplying sufficient noise to render one Pi Zero useless. However, even once this was fixed, noise between the data lines generally prevented all four Pi Zeros from working simultaneously. To fix this, we isolated the Pi Zero power supplies to prevent ground loops and covered each wire set in metal-braided heat shrink. With this, all four Pi Zero’s would operate simultaneously in 15 out of 16 consecutive tests.
Finally, the cameras needed to be focused to be able to discern the beads from such close range. This could not be done until the final assembly, because at such close range, a small variation in range caused a large variation in the camera focus. Thus, with the sunshade and shaker racks on the baseplate, we attached a monitor to each camera, with a Pi Zero acting as a direct feed-through. We then rotated the camera lens until the beads could be individually distinguished.

5.1.6 Dunk Test

To ensure that the electronics box would seal, a full dunk test was done in the Neutral Buoyancy Research Facility at the University of Maryland. Once the connector on the electronics box had been potted and let set to dry, the empty electronics box was sealed with the O-ring and placed onto the baseplate as it would be in flight, and left to sit approximately 4 ft deep in water for nearly six hours. During assembly of the test, paper towels were placed inside of the electronics box to determine if the seal had broken during the test. Upon retrieving the box from the water, the paper towels were dry, and the seal passed the dunk test, qualifying the box for flight, increasing confidence that any data stored during the flight would not get lost upon landing in the ocean.

5.2 SCAMP Testing Results

As with STAR, SCAMP planned testing items such as thermal and vacuum testing with the University of Maryland Resources, however due to tight time requirements and the sheer duration of CNC operations to build a functional robot these were not completed. However, testing during integration week became massively helpful to us as a team in terms of both electronics and hardware improvements before flight. The most obvious of which was a separation between the ring gear and flex spline assembly due to a lack of an inner bearing retainer. Launch forces simulated on the vibration table had caused the end effector to act as a lever and the vibrational forces allowed for the teeth of the gears to slide more easily. This was easily remedied through research into the development of DYMAFLEX in finding that this problem had already been encountered and an inner bearing mount that prevented this from occurring. A 12 gram piece and twelve 2-56 bolts addition to the inside of the housing solved this problem for flight.

5.2.1 Mechanical Testing

The majority of our mechanical testing for SCAMP consisted of dunk-testing our sealed electronics box for a three hour period, as well as motor functionality. The actuator aspect took the form of bench testing, and ensured perfect alignment between the motor shaft and harmonic drive gearbox, as well as the ability for the robot to remain sealed after actuation.
5.2.2 PocketBeagle and Carrier Board

5.2.2.1 PB carrier V1.0

Rev 1.0 of the PocketBeagle carrier was intended primarily to verify the accuracy of the PB pinout, and the functionality of some of the support IC’s. It was designed from the ground-up to be an inexpensive development board. The board carried a SP3232EBCY RS-232 charge pump RS-232 level shifter, a MCP2562 CAN interface IC, and an ADS1246 ADC with an MCP1501T-20E/CHY voltage reference. In lieu of the Harwin M80 connectors, the board featured right-angle 2.54mm spaced header pins to break out the board I/O. By using this standardized pitch, common jumper wires can be used, obviating the need to expend expensive flight-grade connectors for testing. The PocketBeagle was attached to the board using 2.54mm header pins and sockets.

Preliminary tests showed that the board performance was mixed. While the CAN network differential pairs were ok, the TX and RX lines leading to the transceiver were reversed, leading to an inability to use the CAN interface when the PocketBeagle was plugged directly into the board. RS232 communication, however, worked without a hitch, save for a voltage level issue at the output of the chip. The issue stemmed from a difference in voltage levels used by the PocketBeagle and SP3232 IC. The PocketBeagle is a 3.3V device, but the SP3232 is a 5V IC. The 5V input allows it to easily boost the voltage to the levels mandated by the RS-232 standard, but as a result forces its output RX pin to output up to 5V. Should 5V be applied to the PocketBeagle, the pin receiving that signal will be destroyed, and the IC as a whole may be rendered inoperable. Fortunately, during the first test, the IC was connected to the PocketBeagle using jumper wires, and the RX pin was left disconnected. The error was realized during that test, and the RX pin on the carrier board was removed to prevent damage when the PocketBeagle was plugged in later. Despite the shortcomings of the board, it proved useful in developing when developing the first version of the command software.

5.2.2.2 PB Carrier V2.0

By the time the Rev. 2 design was completed, the electrical interfaces had settled, and available board area was known. The board featured a new PocketBeagle footprint, isolation IC’s for GPIO and the flight version of the ADC chip. Flight-quality connectors were installed on this board, as it was intended to be used during integration and flight. Preliminary testing showed that the ADC was reading wildly inaccurate values, with a lot of noise superimposed. The issue was traced down to the lack of a connection between the analog ground and digital ground. Because this board was manufactured as a ‘bare’ board with no soldermask, it was very straightforward to make a solder bridge between the two grounds. Additionally, a trace had been damaged during transport, which lead to the loss of the RX channel on the CAN IC. This issue was rectified using a jumper wire across the damaged trace. One major issue was that the CAN IC was powered off the external 5V line, while the remainder of the IC’s were powered from the 5V line post-PocketBeagle. This meant that when the PocketBeagle was powered from the USB port, the post-PocketBeagle IC’s would function, but the CAN IC would not (USB power was not back-fed into the external 5V power line). This caused
issues when attempting to debug the PocketBeagle in isolation, where the power supply PCB was not connected. While the issues with the board caused some inconvenience, the board preformed well during integration, and the design was deemed good for flight.

5.2.2.3 PB Carrier V3.0

The last revision of the PocketBeagle carrier resolved a few issues identified during assembly for integration, but otherwise remained unchanged. The biggest change was a passive increase in board area to accommodate board standoffs, so that the board could be mounted to the electronics box. Other than adding an electrical connection between the analog and digital grounds, no other changes were made. During assembly, the board had trouble fitting into the allocated space in the electronics housing. This was caused by an error in the board perimeter dimensions, where no tolerance was left to account for fabrication errors. This problem was quickly remedied by filing down the sides of the board.

5.2.3 Tweeter and Carrier Board

5.2.3.1 Tweeter Carrier V1.0

Version 1.0 of the tweeter carrier was designed to be as bare-bones as possible. The board featured only the line driver IC, three current shunt resistors, an indicator LED and I/O connectors. The board worked during the integration test as expected, with no issues. There was a minor concern with the fact that the connectors were positioned vertically, and that the wires would impact the neighboring power board. It was found that this did not pose a substantial problem, as the wires were routed slightly higher than interned to avoid the obstruction. Due to time constraints, the current shunt output was not tested, but it was found that they did not impede operation, so they were left populated.

5.2.3.2 Tweeter Carrier V2.0

Version 2 of the board was originally going to be a flight-quality copy of the V1.0 board, with only minor changes. However, with the addition of the ADC sled, the design radically changed. To aid in current sensing, the shunt resistors were replaced with ACS70331EESATR giant magnetoresistive effect sensors. The addition of these sensors, as well as the ADC sled forced the routing of the board to change. Unfortunately, due to a stackup height issue, the ADC sled could not be attached for flight. However, the Tweeter carrier was designed to function without the ADC sled attached, so functionality was not affected.

5.2.4 Power Supply Board

5.2.4.1 Power Board rev.1

The first design of the power board was functional, albeit with reduced performance. This revision of the board used the same power supply modules as the flight revision, but lacked filtering in many places. The S24 had no filters implemented, and the ITW supplies had
only filtering on the input side. To compound the noise issues, there was no minimum load on the ITW supplies and the whole board lacked a common-mode choke. Additionally, due to a component selection error, the filtering capacitors intended for the S24 module were tantalum capacitors, with a voltage rating of only 36V. This voltage rating was deemed to be close to the maximum of 32V on the input, and the capacitors were left off to reduce the risk of them catching fire in event of a voltage spike on the input line. A few capacitors on the output side were also judged to be operating too close to their ratings, and were left off. Despite aforementioned omissions, the board performed its function well during integration, aside from injecting large amounts of noise into the rocket power lines. This was brought to our attention by the technicians at Wallops, and rev 2 was made to solve those issues.

5.2.4.2 Power Board rev.2

Power board revision 2 fixed the noise issues noticed with rev.1. Testing showed that the new board had substantially improved noise figures.

<table>
<thead>
<tr>
<th>Board rev.</th>
<th>Output</th>
<th>max Pk.-Pk. noise (mV)</th>
<th>RMS noise (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>5V analog</td>
<td>17</td>
<td>5.1</td>
</tr>
<tr>
<td>2.0</td>
<td>5V analog</td>
<td>7</td>
<td>2.4</td>
</tr>
<tr>
<td>N/A</td>
<td>ambient noise</td>
<td>4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 7: Output noise of power supply boards

Note that the ‘ambient noise’ row indicates the reading of the oscilloscope with the leads disconnected from the power board, and shorted together. The readings were performed in AC coupled mode. As evident from table 7, the rev 2 board reduced the noise on the output by over 50%. Unfortunately probing of the input side revealed no discernible change in the noise. It is suspected that the measurement technique is flawed, but we have no way of confirming this with the equipment we have available to us. Additional testing, such as overvoltage and transient input/load response was not tested due to lack of proper test equipment and time.

5.2.5 ADC sled

The ADC sled was fully assembled and populated, the electrical functionality was untested due to time constraints. Additionally, a stackup height error with the Tweeter carrier caused the Tweeter itself to fail to properly mate to the Tweeter carrier with the ADC sled sandwiched between them. Due to these reasons, the board was left off the flight stackup.

5.2.6 Wiring and connectors

5.2.6.1 Wiring

The was not explicitly tested for functionality, rather it was continuously tested as the system was assembled and put through its paces. The internal wiring was sufficient, but it was noted that the bend radius was a little too large to comfortably fit in the provided
spaces. This did not impact functionality, and merely made assembly a little cumbersome. The external wiring however, was discovered to have a major issue. The insulation of the PTFE wire did not properly bond to the conductor strands, and thus would slip off. Despite proper application of heatshrink tubing, more than 50% of the wires used in the integration wiring harness showed significant slippage. The flight wiring harness suffered from the same issues, however they were mitigated by more careful assembly, and additional tie-ups to the payload itself.

5.2.6.2 Connectors

Much like the wiring, the connectors where not explicitly tested, other than a continuity test to verify the accuracy of the pinouts after assembly. There was a single incident involving a flight harness, in which the power pins suddenly shorted during a test. The issue was traced back to assembly procedures; after everything had been soldered, the connector was washed and cleaned with isopropyl alcohol. Apparently, some water had leaked into the 2-part connector housing during the wash, and was not fully removed by the isopropyl wash. This water eventually wicked into the space between the power and ground pins, and shorted the two. That particular flight harness was removed from service, and a new one was made. Other than that, all connectors performed as expected during testing, and no anomalies or problems arose.

6 Mission Results

6.1 STAR Mission Results

6.1.1 Camera Systems

During flight, three of four Pi cameras captured video. Camera one captured 255 seconds of video and cameras two and three captured 435 seconds of video. These videos were enough to satisfy the first of the mission requirements, imaging a total of six of eight regolith samples. The videos clearly show the particle motion due to attitude control maneuvers, although these have not been correlated with IMU data. One frame of a video from camera two is shown in Figure 12.
While this has not been correlated to data taken on STARduino, the regolith simulant is interacting more after launch, indicating that the shaker mechanism was indeed working. From until the video stills, it can be seen that the larger particles are moving towards the right end of the test tube, or what is "towards the top" conventionally. This is believed to be due to the introduction of the 28 V voltage bias, which was actually able to separate the regolith due to charge, as seen in Figure 13. If this were the case, this would fulfill the second and third main payload objectives for Project STAR.
One curious thing about the videos that were taken on all three cameras is that after 300 s, the video was still being taken, although the image itself is still. The reason for this is still unknown. It is unlikely to be due to a lack of power, as there are still images being taken and stored at this time, the image is just not changing.

The third camera took data, although the samples themselves were not of the ideal quality. Between the natural humidity of the Wallops Island area, and a storm that occurred a few days prior to launch, there was some moisture that had gotten into the two test samples, and the regolith simulant had merged together, as seen in Figure 14. The white material in between the grains in Figure 14 may be due to water boiling off between the grains. This data is probably not scientifically useful.
The reason the last camera was unable to take video cannot be conclusively determined, since the camera and attaching ribbon cable were melted and burned upon rocket reentry. However, the current best theory is that during final launch check-in at the Refuge Inn prior to launch rocket integration, the 50 V bias board shorted, and an ad-hoc wiring straight from the 28 V provided from the second timer line was created to ensure some sort of bias across the test tubes. Theoretically, the movement and shuffling of things inside of the sun shield during this rewiring could have jostled the camera connector out of place in some way, preventing any video from being stored.

6.1.2 STARduino Sensors

The sensors on board STARduino were meant to provide data about the motion of the vehicle, aiding analysis of the images. However during flight, the data stored was all of the same value, indicating that there was likely an issue with either the I2C bus trying to retrieve and send data to the SD card, or with the sensors themselves. This is unable to be tested further, as the STARduino shield has lost all of the sensors during reentry.

Due to this, Project STAR was only able to succeed in three of the four original payload objectives. The images, shaking, and applied bias are enough to qualify this for overall payload success due to the additional, non-critical nature of the sensor data from STARduino.
6.2 SCAMP Mission Results

Unfortunately, SCAMP was unable to obtain usable data from the flight. For unknown reasons the load cell registered a higher-than-normal load during the initial homing sequence, and the robot failed to move. It is suspected either the load cell came loose during launch, or the exposure to vacuum changed the properties of load cell, causing erroneous readings. Because the robot lacked an absolute encoder, the system relied on driving the robot in torque mode until the load cell reading increased. This would indicate that the robot has moved up against a hardstop, and the position of the arm can be calculated. If the load cell registers contact too soon, the position of the robot will be offset, possibly causing the robot to collide with a hardstop during free motion. What happened during flight seems to be the worst-case scenario - the load cell registered contact immediately, causing the robot to think it was located in the counter-clockwise-most position of its motion, when in fact it was located at the other end. This caused the robot to try to move past hardstop it was resting on. As the desired position diverged from the actual one, the system safed itself, and stopped trying to move. However, we are not able to confirm this theory, as the camera failed to record any video. Work is ongoing to try to retrieve data from the camera, however, no progress has been made in determining the cause of the failure or locating any data.

7 Conclusions

7.1 General Conclusions

Both teams had the opportunity to work on a project that ultimately flew in space, and learned via the team design process. The teams were successful in trading off space allocation with design goals such that two very large and complex payloads were able to share the same payload plate. This goal of accomplishing as much as possible within allocated constraints is representative of actual space industry constraints that team members will encounter in internships and upon graduation. The teams mostly succeeded in communication, and despite many setbacks to both payloads, both teams delivered operational payloads that effectively shared the allocated baseplate and both collected useful data.

7.2 STAR Conclusions

Project STAR was both successful and unsuccessful. There was mostly scientific success, with images being taken and recorded per the specifications, but with a loss of one camera and a partial loss of later data. All changes made in response to the 2017 flight were successful, but some newer systems struggled. The shaker and bias boards were partially descoped, but relevant data was still obtained. Most prominently, the team drastically underestimated the amount of testing and number of revisions that would be required to ensure system functionality.

Project STAR’s primary scientific objective was to collect high-frame rate, high-resolution video of eight samples of regolith simulant. The project succeeded at recording video of six samples. In the process, the team learned much about how Raspberry Pis and Pi Cameras
work, and practiced scaling a project from a prior year to a more substantial project this year. In designing the many custom circuit boards outline above, the team gained extensive electronics experience. The whole team got to work as a team towards a challenging goal and gained design experience.

Going through the systems, the custom flight computer STARduino was heavily descoped to the point of being a shield for an existing processor. Looking back, this would have been a far more tenable design from the start, requiring less design of complicated custom boards that simply replicate existing hardware. However, the final STARduino system succeeded at all requirements except acquiring magnetometer data. It also met additional goals imposed later on by other systems. The bias board was unsuccessful, but was good in teaching us about the limits of our equipment for assembling some of the smallest electrical components. The power board was never a part of the initial design, but was ultimately successful in providing power to all systems while eliminating the noise sent back through the system.

The shaker system was also descoped heavily, but ultimately met its goal of inducing substantial particle interaction. We have not yet processed our science data thoroughly enough to know if it succeeded at inducing charges, but visually, it appears to have succeeded in shaking. The electronics box succeeded in protecting the datalogger and surviving splashdown. The datalogger mostly operated, though we cannot determine if the failure of the fourth camera was due to the camera, the Pi Zero, or the datalogger.

### 7.3 SCAMP Conclusions

SCAMP had multiple aspects of its experiment that can be considered more successful than other areas. Technically, as of our current state of data analysis, SCAMP’s minimum success criteria hasn’t been met to full satisfaction, with items such as flight images and contact stability being compromised as touched on earlier.

The manipulator and electronics box maintained a full seal throughout launch, reentry, and splashdown thus verifying our o-ring seal designs. Additionally, all mechanical components (e.g. Macon motor, Harmonic Drive, and bearings) maintained full alignment and functionality even after recovery. The launched manipulator will be used as a testing platform for software development for RockSat-X 2019 as well as a bench-top study for robotics-related learning opportunities.

Additionally, aside from the load cell anomaly, the electronics performed very well. None of the components were damaged, and the system remained functional all the way until the GSE lines cut out. This electronics design will be used in the Rocksat-X 2019 program to lower development costs and allow for more time to be devoted to software.
8 Potential Follow-on Work

8.1 STAR Potential Follow-on Work

Future versions of Project STAR could continue to develop tribocharging efforts in a variety of ways. As always, there could be more samples flown. These samples could either have more large and small regolith ratios, or could contain multiple of the same regolith ratio. Additionally, more environmental data could be taken. During the 2017 Project STAR flight, STARduino logged data from all sensors except for the real time, as well as temperature, pressure, and humidity outside of the electronics box. The same year, all of the flight video that was taken was washed out, and unable to be used for analysis. The opposite happened during the 2018 Project STAR flight, where none of the sensors logged useful data, but the two of the cameras recorded useful images that can be analyzed. Getting both of these to work at the same time would be useful. Nonetheless, we still plan to analyze the two useful grain videos returned from this flight.

Additionally, getting a reading on the voltage bias while that is on would be useful for later post-processing of the data. There was a voltage divider on the bias board that would have piped an analog voltage to STARduino to record the measured output of the voltage bias while it was on. However, as noted in §3.2.3.2, the bias board did not work at the last moment, and a stand-in 28 V bias from the timer line had to be used. A natural follow on to the 2018 payload would be to actually have a larger bias, with the values recorded with the rest of the data.

Project STAR will not be attempting to fly on the RockSat-X 2019 flight. If this were to be done again, the 2019 year would be taken to develop some of these aforementioned goals, and a proposal may go out for the a seat on the 2020 flight.

8.2 SCAMP Potential Follow-on Work

The future of SCAMP and its inordinate importance to DYMAFLEX (and the future of space robotics for the Space Systems Lab) has a planned future through the next few years, with an eventual goal of flight certifying this drivetrain. The SCAMP program has already been accepted for the RockSat-X 2019 flight, and we are currently continuing the refinement of our actuator design in anticipation for this opportunity.

Over the last year all of the PI’s and some of the students who worked on the project sat down and created a realistic timeline and had a conversation about how we could potentially better prepare ourselves (or other student projects) for a similar flight. At the end of the meeting it was concluded that a two year development process for teams would be much more prepared and with more testing to increase our chances of a fully functional and successful flight. This, is exactly the opportunity SCAMP has, but with one bonus: the robot has already flown and we have an even better starting platform for next year. Our hardware has been proven in flight to remain sealed through launch, re-entry, and splashdown with full alignment maintained within the motor and harmonic drive assembly. Our largest im-
provement for next year is software development time which will now have hundreds more hours to ensure full capabilities are maintained.

Additionally, we plan on utilizing all of this data to help in our software configurations for other Satellite Servicing Robotics in our laboratory such as RANGER. The positive effects of this experiment can help an inordinate amount in areas such as failed captures and impeded motion (especially within a confined area such as the Neutral Buoyancy Research Facility.)

9 Benefits to the Scientific Community

9.1 Benefits from STAR

The primary image data obtained on this flight has the potential to further current understanding of tribocharging. Preliminary results from the data obtained on this flight will guide the team’s changes for another proposed flight with RockSat-X.

Images from flight can also aid current computer simulations for modeling tribocharging in regolith. As not much is known about the charging effects, any quantifiable and modelable notions of tribocharging will greatly improve current computer simulations. Additionally, complementary experiments are planned in a 1G lab. Thus, the STAR results will be compared to lab results, which may indicate the effect of humidity on charging.

Throughout the process of developing Project STAR, other smaller developments were made that could be of use to the scientific community, including the method of packaging regolith simulant. One of the difficulties with testing tribocharging is the need to contain the sample while applying an electrical bias to it and exposing it to vacuum and microgravity. The mesh-based containment system pioneered by Project STAR may be of interest to future researchers in the field.

9.2 Benefits from SCAMP

SCAMP has two primary benefit areas: 1) The space-ready robotic manipulator community, and 2) robotic development within UMD’s Space Systems Lab. SCAMP’s data, if proven to be meaningful, can help determine the dynamic capabilities of an actuator in a micro-gravitational environment and can help reduce the oscillatory motion of a manipulator under impeded movement. This is considered a large problem and an understudied characteristic of space robotics, and our single DOF study of this field can provide great benefit to professionals in the field, as well as professors and their students throughout studies in university. The SCAMP team also intends to utilize the experience gained from this project to help better prepare our payload for the RockSat-X 2019 flight in a substantial effort to collect a greater amount of data for processing and control.
10 Lessons Learned

Most of the problems that arose and later turned into lessons learned concerned the electronics and software of the payload. As a critical component of the payload, there was much to be learned about designing custom boards and interfaces. The electronics and testing timelines were highly underestimated, but are now better understood. The complexities of designing a space constrained payload was also something learned throughout this process. There were many components that had both physical and manufacturing challenges associated with them, and others that had assembly challenges to overcome.

One of the lessons learned from participating in RockSat-X 2017 was that interfaces with COTS hardware should be thought out from the beginning of the payload design, as opposed to assuming that COTS components would work exactly as anticipated out of the box. Due to this issue, the Raspberry Pi’s were one of the most challenging components to use. However, Project STAR 2018 built on the knowledge from last year to start the interface of the Raspberry Pi’s with the datalogger early, which still turned into a challenging and time heavy endeavor. One of the main issues with testing the Raspberry Pi - Datalogger setup was that early on, tests done to qualify various interfaces were failing, and there was no way to tell if it was due to components not working, or the test apparatus wasn’t working. Creating high quality test setups and rigorous tests that would provide answers about what was working was a critical skill learned through the course of working with the hardware this year.

While working with the Raspberry Pi’s especially, the virtue of engineering things properly became a huge help to the success of the payload. There were many tests that were inconclusive as to why the data was not being stored to the datalogger. It could have been due to the datalogger itself, the Raspberry Pis not sending data properly, or any number of issues with the interface between the two boards. By creating more robust testing procedures, the issue was able to be determined. The initial design for the wiring for the Raspberry Pi included soldering wires to the back of the Pi to tap into the USB interface of the board. This was unreliable due to a number of reasons, including the quality of soldering job, the quality of the joints, and whether or not multiple wires had been shorted together or not. A better solution entirely was used during flight, which was the use of the Raspberry Pi stems. These had to be soldered on only once to the Raspberry Pi, and allowed for a more rigorous set of tests to be conducted with one less likely source of failure when a test did not produce expected results. Additionally, twisting the two USB data lines together, matching trace impedance, and utilizing metal braided heat shrink decreased the cross-talk between the two lines, provided a better data signal to be stored. While the interface may have been working without these changes, it could never be ruled out conclusively when tests were failing.

Another critical lesson learned with the flight electronics was with respect to noise suppression. The initial revision of flight boards for both STAR and SCAMP had little to no noise suppression, which was brought to the attention of the integration team, since the WFF techs were unable to measure any current draw and there was noise tracing back up the rocket line. This brought out the importance of noise suppression to those developing...
electronics, which had previously not been considered. After integration, a new revision of flight electronics that included noise suppression were designed in order to mitigate the issues WFF was previously seeing with TERP. Research was done to learn more about noise suppression, which was a much larger issue than those designing the electronics realized, and chokes and LC filters were added to the boards, in addition to isolation for preventing ground loops. All of these methods were things that weren’t known prior to designing the electronics for TERP, and changed how boards are now designed.

The software aspect of SCAMP was substantially more complicated than initially envisioned. Due to the fact that the system had many hardware interfaces, software development was very-low level, and consumed large amounts of time. The biggest issue was the CAN interface library. The chosen implementation of CAN for Linux was CANOpen Node. While the library worked fine for integration, it was found that there were issues in using the library for the tasks the SCAMP desired. CANOpen Node is designed to be used in a microcontroller application, which responds to commands and executes them in a loop, rather than the sequential series of tests desired by SCAMP. This mis-application of CANOpen Node lead to many difficulties, as implementing a state machine to handle the sequential command consumed more time than expected. To further the difficulties, the configuration tool for CANOpen Node relies on features that were deprecated in Firefox 14 and beyond. In order to use the tool, one must install and configure a version of Firefox from 2012 or earlier. The combination of very low-level programming, along with time-consuming configuration lead to insufficient time to properly develop the software. For future designs, software should be started immediately, especially for components that are known to be fixed (such as the Tweeter, which uses CAN communication).

Throughout the design phase of the project, CAD proved to be a valuable tool in working out payload interfaces, identifying interference problems, and aiding in manufacturing. In manufacturing, it was discovered that many of the holes specified in the CAD were not the right size or tolerance for the screw that they were designed to accommodate. In addition, fasteners were not initially modeled in the CAD for simplicity, but when the screws, nuts, and washers were added to the CAD, a number of mechanical interferences were identified between washers and the payload structure. Most of these washers had to either be discarded or cut to accommodate other mechanical elements. Moreover, many of these additions occurred after parts needed to be ordered, which made creating a bill of materials to order very difficult regarding fasteners.

Additionally, most major design tolerances need to be considered during the initial design phase. Before the piston linkage system of the shaker rack was manufactured, it was discovered that the shaft of the motor extended well beyond the base of the shaker rack, making it impossible for a linkage system to rotate in a full circle around the shaft of the motor. At the same time, it was also noticed that the CAD shaker disk was sitting halfway through the RockSat-X baseplate. The entire linkage had to be redesigned, and the motor shaft had to be reduced by 2/3 of the original length in order for any sort of linkage to actually work. Had the tolerances been looked at when doing the initial design work, a different motor could have been chosen that would have not needed to be disassembled and cut in order to work.
Wire handling was also something that was not thought about until it became an apparent issue. Many electronics had either no connectors or very expensive connectors between them. To test any two systems together ultimately called for the entire system to be assembled. We later nearly doubled the number of connectors we were using to alleviate this challenge, but then were at a loss for space to tie down these connectors during final assembly. Usability concerns must be accounted for in the design process in order to facilitate assembly and usage. Making sure that all connectors and fasteners are in the CAD will also help determine where wires can and should be routed such that there is ample space to reach everything.

TERP also learned of the importance of maintaining a redundant team, consisting of members at different points in their studies. The core electronics team consisted of three members, and after the loss of one member, the remaining team was overwhelmed and had difficulty training new members. Likewise, the CAD and Structures team was entirely juniors, so if one student needed to catch up on academics, generally all three members did, which stifled productively for short periods. That said, overall the team and the payload were successful in producing the intended product and collecting what appears to be useful data.
A Schematics

A.1 STARduino Shield

Figure 15: STARduino Schematic
A.2 STAR Bias Board

Figure 16: Bias Board Schematic
A.3 STAR LED Board

Figure 17: LED Board Schematic
A.4 STAR Power Board

Figure 18: Power Schematic
Figure 19: SCAMP PocketBeagle Carrier Board
A.6 SCAMP PocketBeagle Carrier Board ADC

Figure 20: SCAMP PocketBeagle Carrier Board ADC
A.7 SCAMP Tweeter Carrier Board

Figure 21: SCAMP Tweeter Carrier Board
A.8 SCAMP Power Supply Board

Figure 22: SCAMP Power Board schematic
References