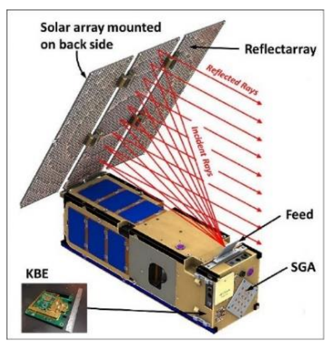
Deployable Metasurface Antennas for CubeSats

In this report I will summarize the work I have done during the 2020 FYSRF with Dr. Sean V. Hum on Deployable Metasurface Antennas. The goal of this project is to develop a mechanism which would stow and deploy flat, thin Metasurface panels that cover a large area from a small-volume nanosatellite. Novel prototypes, testing setups and measuring methods have been developed and built to validate the design in laboratory settings. This research, sponsored by Thales Alenia Space, will enable the demonstration of technological matureness for deployed meta-surface antenna systems for emerging 5G and IoT space communication applications.

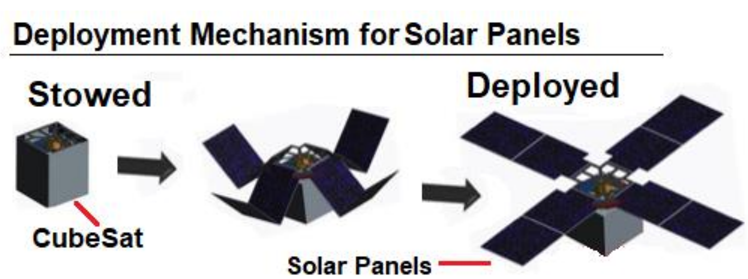
This report will present my contributions to the research project in chronological order, organized by month. At the end, I will reflect on key lessons I learned during the work term.

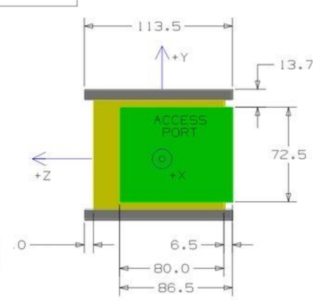
May – Understanding the Problem and Conceptual Design:

After being introduced to the research problem, I was encouraged to research deployable space structures in the research literature, which covers a wide range of topics from origami-deploying antennas to inflatable space station modules. Although we had limited input from the stakeholder, we anticipated that a CubeSat-sized satellite would be most appropriate for their mission requirements. Therefore, I focused on learning about CubeSats and deployable solar panel systems. This allowed me to explore functionally similar reference designs and understand the physical constraints on the desired solution.



Upper Left: *AstroMesh ® deployable reflector membrane, 12-meter diameter.*
Upper Right*: JPL's ISARA Mission Concept featuring reflectarray on a 3U CubeSat, 2017.*
Bottom Left: *Example of deployable solar panels, a similar but simpler design problem.*
Bottom Right: *Physical dimensions of CubeSat size, from CalPoly's CubeSat*

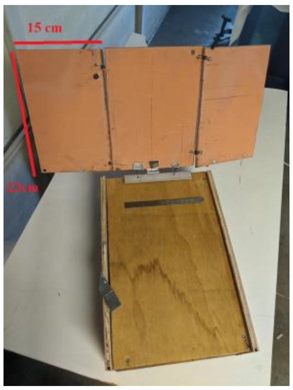


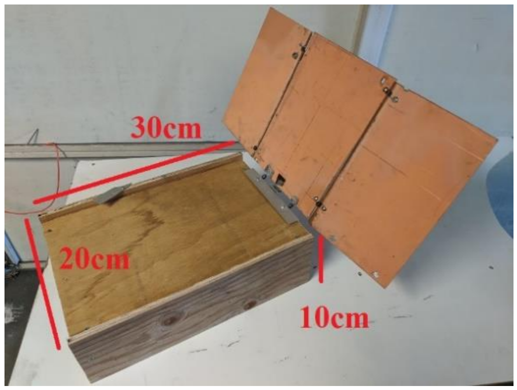


At this stage, I began to brainstorm various designs and mechanisms to accomplish the following objectives:

- Stow the deployable Metasurface panels within the space constraints of a 6U CubeSat.
- Reliably release the Metasurface panels upon command.
- Physically move panels into operational configuration, without failure and risk to the satellite.
- Accurately lock the panels in their final positions that provide the best gain and bandwidth.

The design of a deployable space system is challenging because a wealth of precautions against must be taken to ensure the design will not fail in space. The concerns over cold-welding, thermal cycling, vacuum out-gassing, and solar radiation are reflected in deliberate design and material choices that differentiate the solution from, say, a kitchen cabinet. To simplify the design, we decided to create a design that can be mounted externally to a 6U CubeSat. While this significantly limits design freedom, we thought it was strategically better to demonstrate Metasurface on a simple, failproof deployment system before testing complex designs.





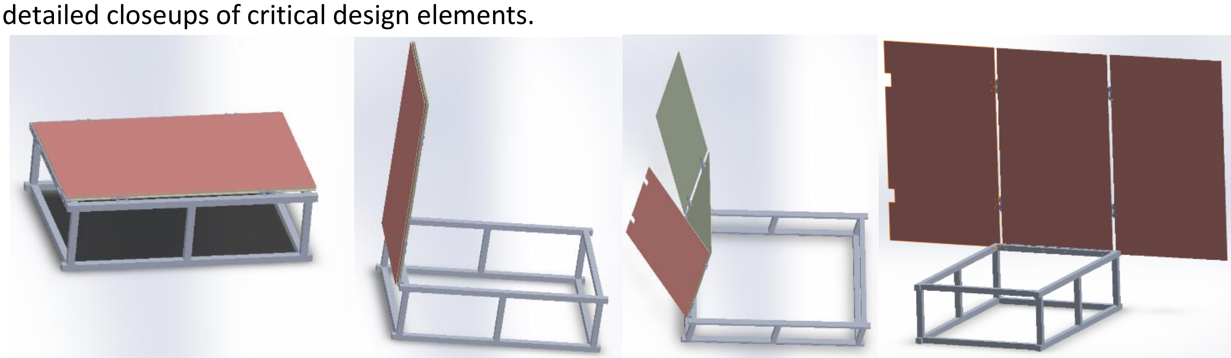
Conceptual Prototype: *3 panels (folded together) rotate away from the larger face of the 6U CubeSat. Then, two side panels rotate 180 degrees from the middle panel, powered by torsional springs. Alternatives to torsional springs were investigated in June.*

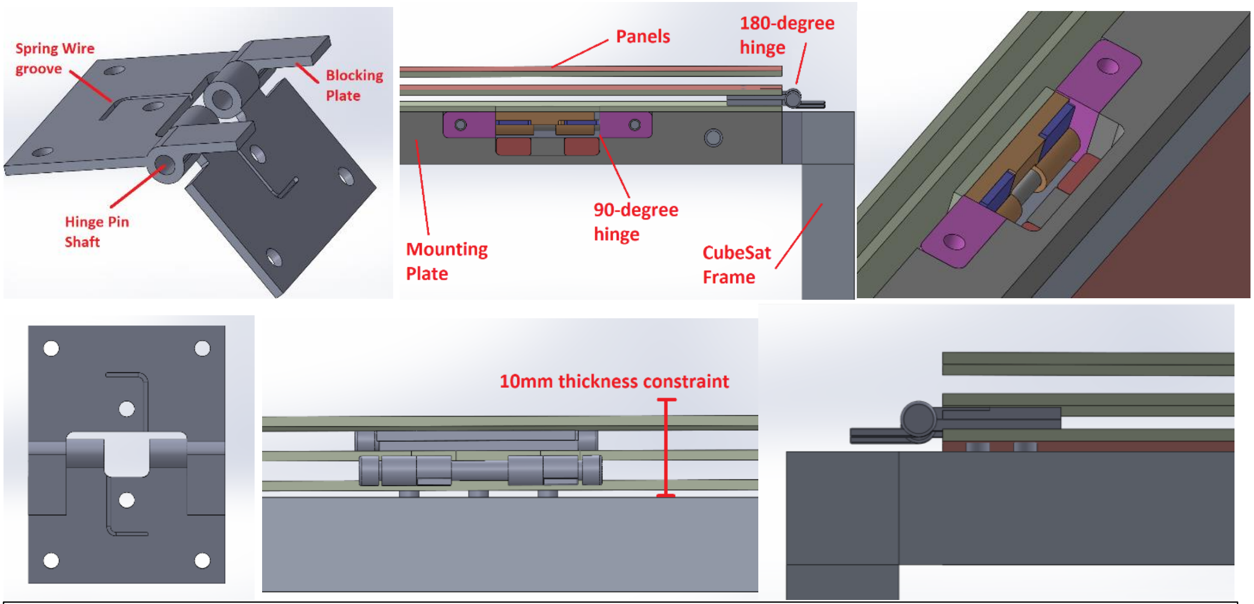
June – Initial Prototyping:

After making a conceptual model (pictured above) of the deployment system, I investigated alternatives to individual elements and built basic physical prototypes for each. Options like micro-motors, flexure and SMA joints were eliminated due to higher design complexity; A combination of magnetic clips and blocking plate was chosen for their simplicity; and the Nichrome wire- fishing line solution was chosen for its success in previous space missions.

Hold and Release	Guided Deployment	Final Blocking
Mechanical Latch/ Hook Solenoid and/or electromagnet Nichrome Burn Wire and Fishing Line	Torsional Springs & Hinges Flexure joints Shape Memory Alloy joints Micro-Motors	Spring-loaded Latch Simple block-plate Magnetic Clip Tensioning Cables

Having finalized the conceptual design, I modeled the system in SolidWorks and designed mechanical parts that comprise the system. Custom-built hinges that conform to space constraints and house the torsional springs were designed, along with their mechanical interface with a standard 6U CubeSat frame. The four picture below show the deployment sequence, while the 6 pictures below show detailed closeups of critical design elements.





Top Left: *3D View of 180-degree hinge. Note that blocking plate prevents hinge from opening more than 180°*. Bottom Left: *top view of 180-degree hinge.*

Top Middle: *Side view panels mounting onto CubeSat frame*. Top Right: *3D view of 90-degree hinge*.

Bottom Middle: *Thickness view of panels, 8mm out of 10 utilized*. Bottom Right: *side view of 180-degree hinge fitting in between panels.*

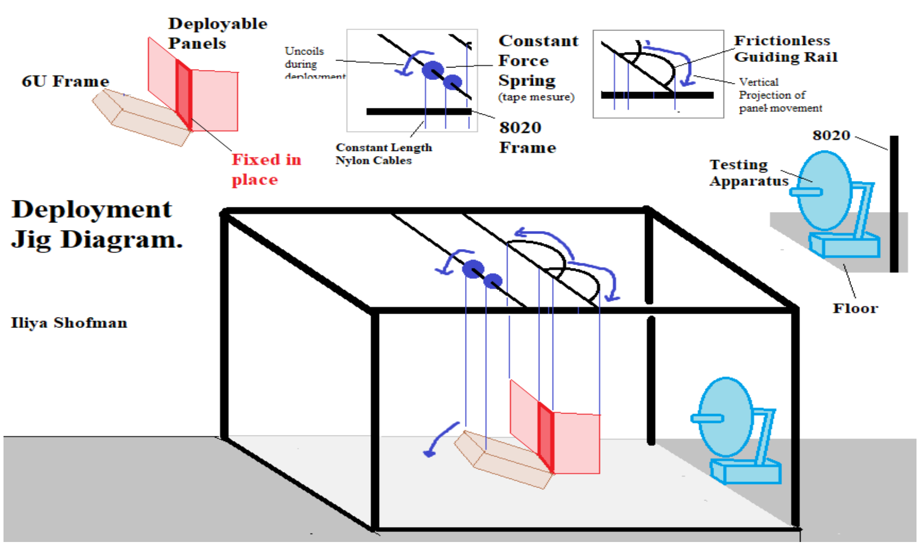
At this level of design, the primary concerns consisted of dimensions and tolerances for each feature such as a hole, material thickness, length, etc. After ensuring that the parts were realistically sized with an additional safety margin, I contacted several CNC fabrication shops for quotations on part manufacturing costs.

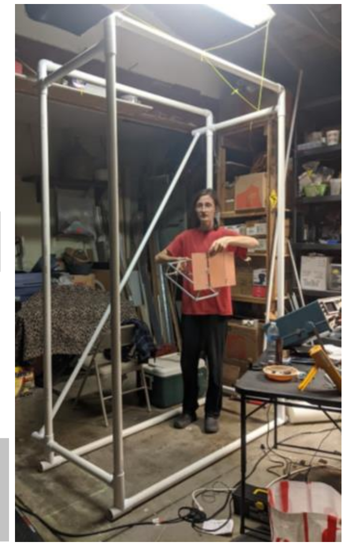
June - Design of Testing Setup:

Meanwhile, thought was given on how to test the deployment mechanism in a laboratory before launching it into space. It is critical to know if and how the panels may fail to unfold, which may include friction in the joints, manufacturing defects, and material failures. As an extension, the electromagnetic characteristics of the Metasurface may be measured for consistency and accuracy to ensure the antenna will function as expected in space.

To test the deployment mechanism, it is necessary to emulate the space environment – especially microgravity. When the panels deploy on earth, the springs must be made strong enough to fight against gravity forces during the unfolding process. In space, however, these springs will be too strong and could fling the panels too rapidly, which will make the satellite tumble out of control. Thus, a setup that allows for closer-to-realistic mechanical performance testing of the prototype is necessary.

A large cage out of PVC tubing and connectors was devised. Constant force springs and nylon fishing line cables will be used to suspend the CubeSat frame and the deployable panels, thereby bearing the gravitational forces on the prototype. As the panel deploys, low-friction rails will guide the movement of the suspension cables to avoid extraneous tension forces on the prototype. Clearances in the frame can be made to allow electromagnetic measurements to be made without scattering.





Left: *Diagram showing the deployment testing process. Originally, the frame was planned to be built from 8020 Aluminum*.
Right: *Assembled PVC frame of the testing setup, with author holding CubeSat model for scale.*

July – Presenting Early Concepts:

In the first half of this month, I prepared for a presentation of the conceptual design to the project sponsor, Thales Alenia Space. Their representatives were interested in increasing bandwidth and suggested having the side panels angled towards the feed. This requirement added another element of complexity and uniqueness that differentiates this design from deployable solar panels.

Later in the month, I worked on writing an abstract summarizing my work for the Undergraduate Engineering Research (UnERD) Day Conference at U of T.

July – Designing Measurement Methods:

While planning a testing procedure in the “cancelled gravity” platform, we concluded that it was necessary to somehow measure the position of the Metasurface panels to quantify the effect of positional inaccuracies of the panels on electromagnetic performance. For example, suppose the panels are supposed to lie in one plane, but end up being angled due to an incomplete deployment or distorted due to thermal gradients in orbit. We would like to know if, the antenna gain, bandwidth, focal position, and scattering pattern will change significantly as a result.

Several methods to measure the position of the panels were developed and prototyped. Since physically touching the panels could disturb their position, we had to consider contactless photogrammetric methods. The table below summarizes and compares these methods, which include a Commercial 3D scanner, a home-made Structured Light Scanner, the Camera Picture Method and the Mirror Method. For the near future, we decided to proceed with the Mirror method since it is the simplest and most impactful measurement on positional inaccuracy.

<table>
<tr><td>1. Commercial 3D Scanner</td><td>High cost, but integrated, easy to use solution. Requires more advanced data processing.</td><td>2. Structured Light Scanning</td><td>A homemade 3D Scanner alternative using similar operational principles to commercial version.</td></tr>
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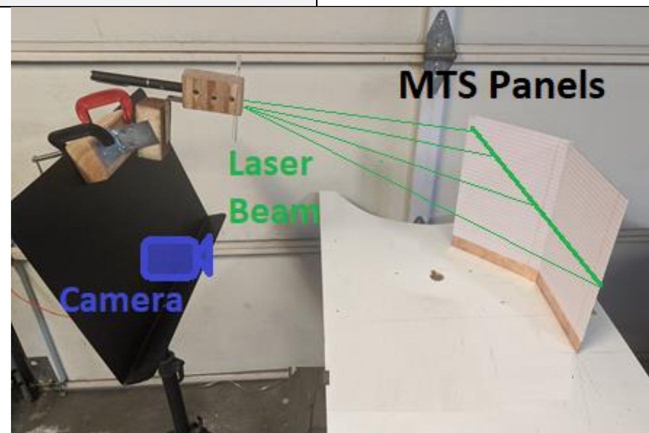
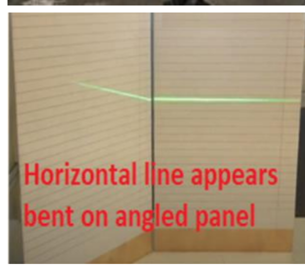
Price ranges from $500 to $30000, with difference in price attributed to portability, speed, and accuracy of the 3D scanner.

Source: www.3dnatives.com</td><td colspan="2">




Requires a complicated, finicky hardware setup and development of program to automate calculations.</td></tr>
<tr><td>3. Camera Picture Method</td><td>Assuming panels remain flat within their plane, measure the angles between planes through pixel measurements of pictures.</td><td>4. Mirror Method</td><td>Assuming panels remain flat, measure the angle between the middle and side panels using the law of reflection.</td></tr>
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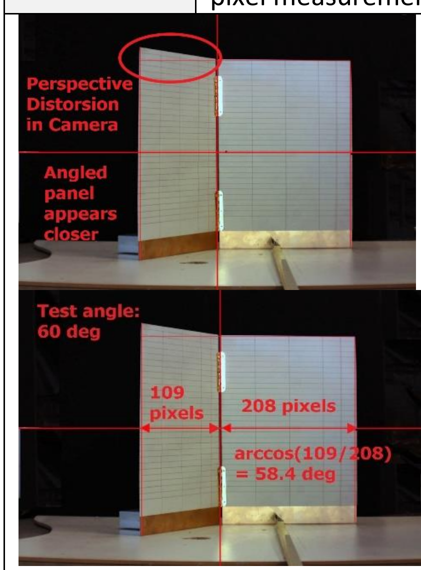
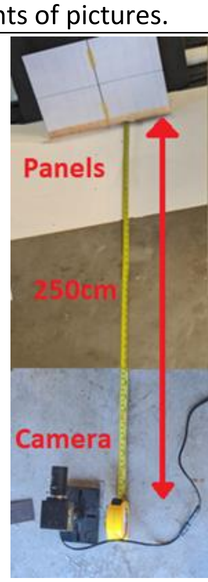
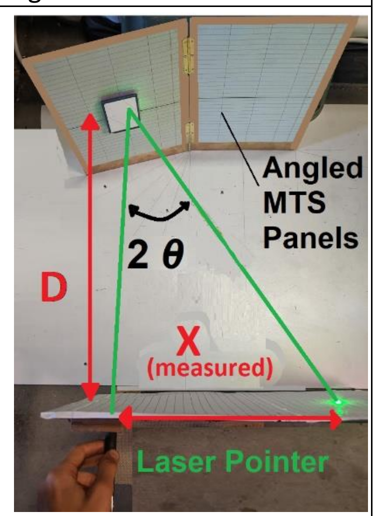




Prone to distortion errors and requires exact positioning of camera. Poor accuracy for angles near 0-degrees and 90-degrees.</td><td colspan="2">
Tape a thin mirror onto side panel and shine a laser beam onto it. Measuring the distance between the source and the reflected beam and applying trigonometry, we can determine the angle of incidence and thus the angle between panels (θ).



This measurement is very stable, as relatively large errors in X result in small uncertainties in θ near target angle.</td></tr>
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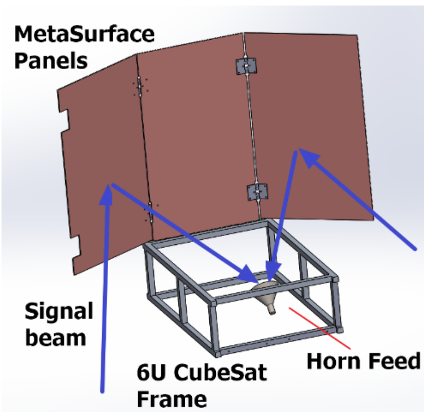
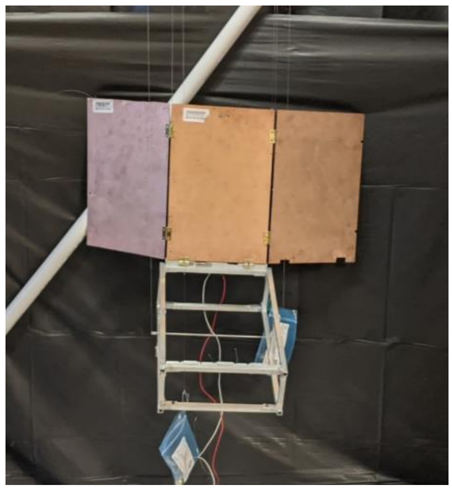
August – Upgrading the Prototype and Improving the Testing Setup:

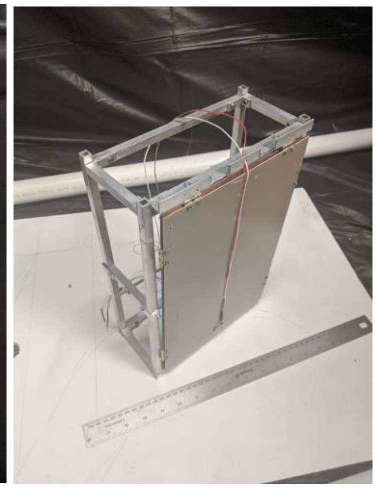
As requested by Thales, I devised a means to have the panels deploy to an angled position, so that the final angle between panels may be adjusted. This design features a fine-threaded set screw with a spherical tip that can achieve angle positioning with up to 0.2-degree precision. Simplified calculations were made that the ideal angle is about 15°, and that an error of 0.25 degrees will shift the signal focus by 1mm. Since a deviation of up to 1 wavelength (1cm) is tolerable, this translates into a 2.5-degree panel angle accuracy.

A higher fidelity prototype was built to include new design features. It includes a 1:1 scale aluminum frame resembling commercially available models. Small arts-and-crafts hinges were modified to house a torsion spring, thus resembling the custom-designed hinges. A nichrome wire hold-and-release mechanism was designed and successfully implemented.



Angled MTS Panels Focus Signal into Horn Feed





Left: *Metasurface acts as a flat reflector that manipulates EM radiation to focus and amplify signal.*

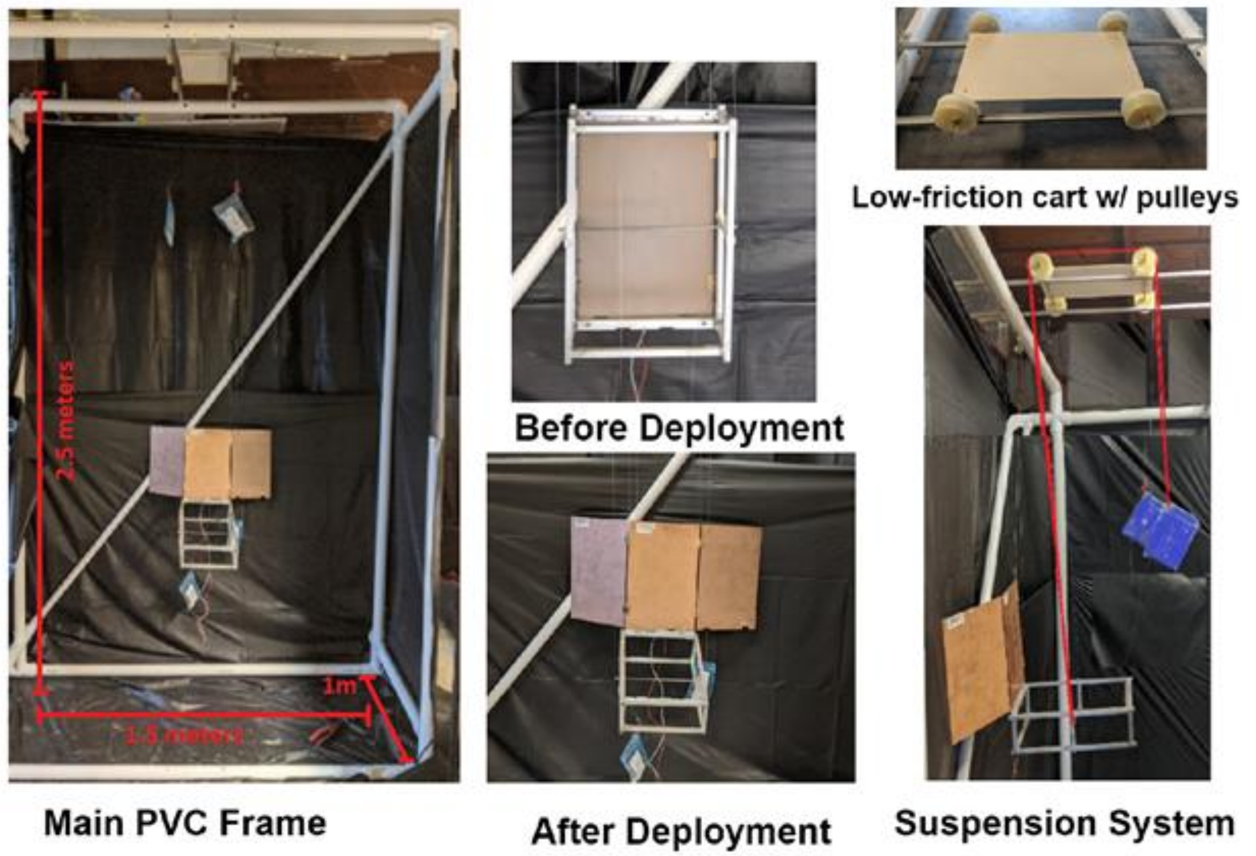
Middle: *Higher fidelity prototype, deployed configuration.*

Right: *Stowed configuration fits within 6U CubeSat volume constraints.*

After preliminary trial runs, several improvements to the testing setup were made. The initial idea of using constant-force springs was scrapped because they had limited travel range and could coil out of control if stretched too far. When the panels were simply suspended from nylon cables and deployed, the satellite jittered and oscillated for several minutes on the suspension system. The designed was changed to suspend all elements using pulleys and counterweights.

After additional tests, it was determined that the sliding rails had some friction, which skewed the deployment of the prototype. It was necessary to make a higher-quality low friction sliding rail that would move smoothly.

After further testing, it was noticed that the side panels bump into suspension cables used to hold the CubeSat frame. Since the CubeSat is suspended by a rod passing through its center of mass, a heavy steel bar was temporarily screwed to the other end to shift the suspension point away from the panels. In the future, the centroid rod must be made sufficiently wide to avoid collision with deploying members.

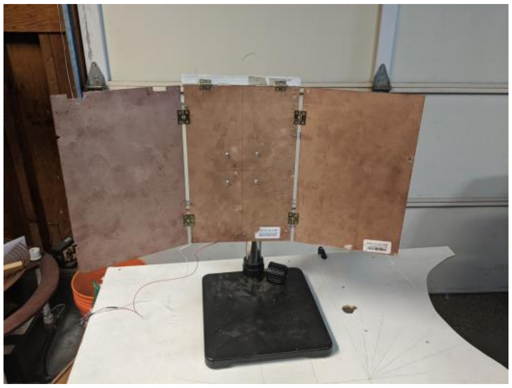


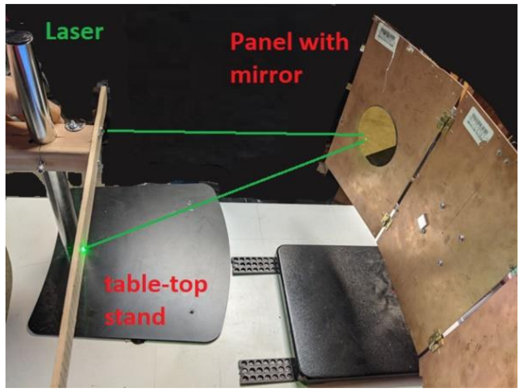
The picture above shows several views of the testing setup. The table below contains embedded videos of the various failed test runs discussed on the previous page.

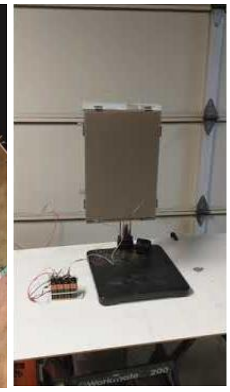
Failed Run #1: Pendulum Swinging	Failed Run #2: Heavy Counterbalances + Friction Jamming
CubeSat body started swinging like a pendulum because it was simply attached via suspension cable. 	 Heavy counterbalances and panels jammed against CubeSat frame prevented deployment. Counterweight mass will be adjusted, bigger clearance will be made for rotating parts, and stronger springs will be chosen to overcompensate for deployment failures.

Since laboratories at U of T remained closed throughout most of the summer, all prototyping work was done in home settings. This prevented a fully functioning testing bed from being assembled and made ready to use at the end of the summer. However, to keep the research moving, a simplified testing setup has been devised which will allow for electromagnetic measurements on the deployed assembly without the CubeSat frame.

The pictures below show this simplified setup. The three unfolding panels are mounted onto a stand which holds the middle panel fixed and vertical. A round mirror is attached to the center of a side panel. Another stand holds the laser pointer for the Mirror Method measurement. Both stands need to be aligned and positioned with respect to each other before measurements.







Left: *Deployed panels on stand mount*. Middle: *Simplified testing setup diagram.*

Right: *Video of simplified deployment test* ***(successful!).***