SSC21-S1-08

Validating Deployment Dynamics of the Canisterized Satellite Dispenser (CSD)

Stephen K. Tullino
Air Force Institute of Technology
2950 Hobson Way, Wright-Patterson AFB, OH 45433

Eric D. Swenson
L3Harris Technologies Inc.
1025 W. NASA Boulevard, Melbourne, FL, 32919

Jessica L. Marshall Tullino
The University of Alabama in Huntsville
301 Sparkman Drive, Huntsville, AL, 35899

ABSTRACT

Planetary Systems Corporation (PSC) designed the CSD to be a more secure, predictable, and consistent CubeSat deployment system. Though the CSD has proven its safety and reliability on orbit and in other air- and ground-based tests, there was still not enough data needed to develop analytical profiles describing CSD deployment angular and linear velocities and accelerations. The goal of this research effort is to first tune a dynamics model using experimental data collected from three sources: (1) PSC's microgravity deployment tests onboard a C-9 aircraft in 2014; (2) AFIT led lab bench experiments in 2016; and (3) AFRL-AFIT led tests at NASA Glenn Research Center's (GRC's) microgravity drop tower in 2017. The second part of this presented research is to evaluate the model prediction performance against various configurations followed by an evaluation of which experimental data sources yields the best tuned dynamics model.

NOMENCLATURE

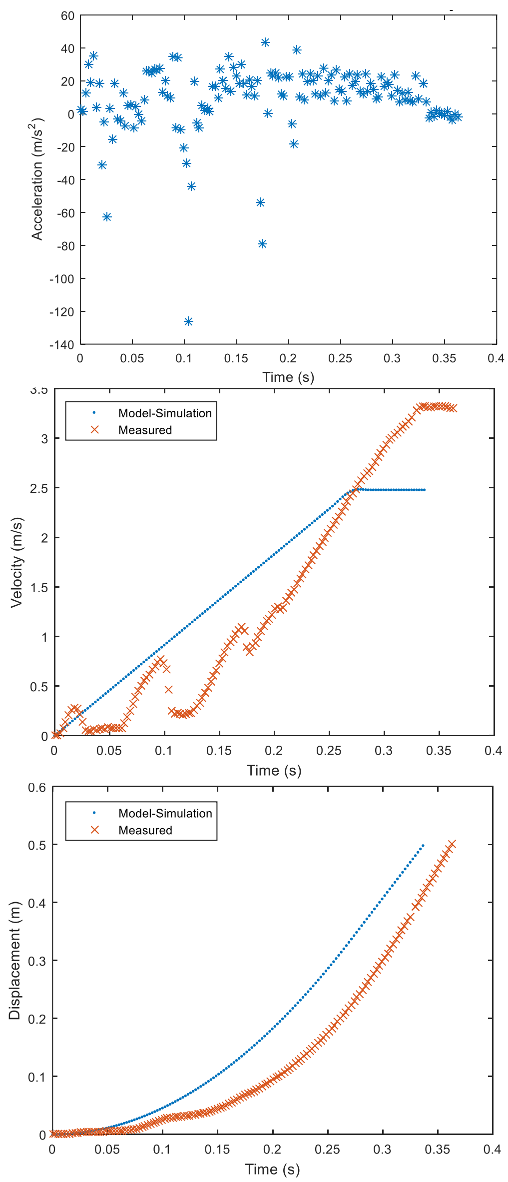
I_b	=	MOI Tensor
M	=	External torque applied to a body (b) or # axis (#)
$\underline{q}$ *or* $\boldsymbol{q}$	=	Quaternions 1-3
q_4	=	Quaternion 4
$\bar{q}$	=	Quaternions 1-4
$\bar{x}$	=	State Vector
$[\,]^{\times}$	=	Skew symmetric (cross-product) matrix

INTRODUCTION

CubeSat canisterization provides small satellite developers well-defined and predictable, in terms of launch interfaces, access to space by containing and subsequently releasing their CubeSat payloads. The original container designs, P-POD/ISIPOD, use a combination of a high tolerance (<0.1 mm) fit on eight lateral edges of a CubeSat using guide rails combined with a spring-loaded pressure plate pushing the CubeSat against the release door. PSC created the CSD to combat uneven deployment and cumbersome guide rails seen in P-POD/ISIPOD type dispensers. PCS's CSD addresses uneven forces via one (or more) constant-force springs, which provide a uniform and predictable force; whereas P-POD and ISIPOD use conventional springs that provide displacement dependent forces as described by Hooke's Law (1).

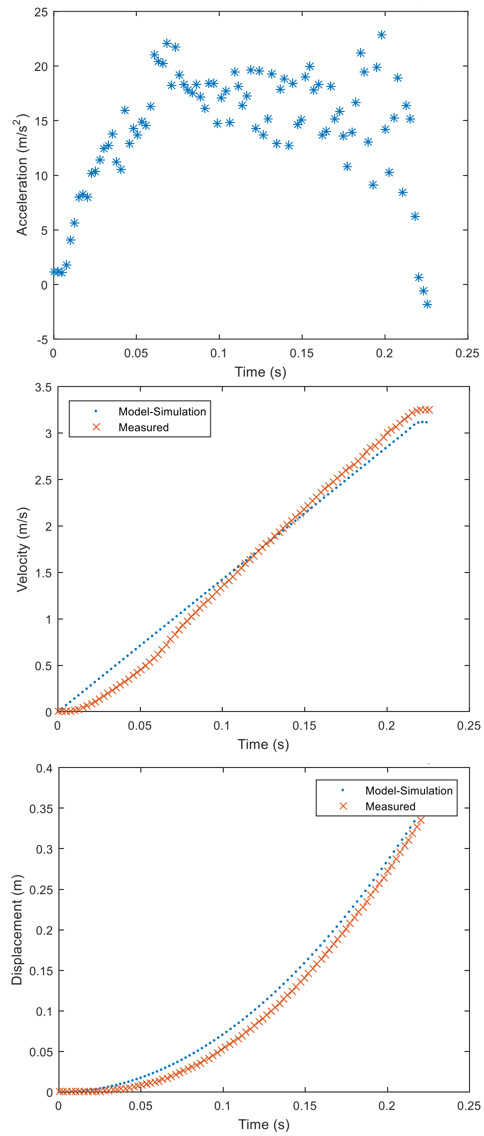
In 2014, PSC conducted CSD qualification deployment tests in a simulated microgravity environment on a NASA C-9 aircraft to measure linear and angular rates of ejected 3U/6U payloads. Significant error sources were identified: aircraft induced angular rates (~6 deg/s), accelerometer drift, and the frame used to secure the CSD was not stiff enough. Due to high testing costs (>$400k per flight set), PSC could only conduct one test campaign which did not yield enough reliable test data (2). PSC found the CSD dispenses payloads at low rotation rates (~10°/s) which is lower than other dispensers.

Given the need to better understand deployment dynamics, AFIT researchers conducted laboratory bench top deployment experiments followed by analyses to characterize deployment dynamics seen during payload ejection (3). Using physical CSD characteristics and data from these experiments, analytical computer models were developed, and their predictions were compared with respect to C-9 flight and lab experimental deployments. Identified errors were analyzed to improve the models to better understand deployment dynamics and the performance-affecting variables. Since CubeSat dispensers are designed to work in space, the researchers found that deploying CubeSats from CSDs in a benchtop lab environment is very difficult due to effects of gravity, so the researchers moved experiments to a microgravity test environment which is described next. Below are measurements taken in 2017.



Figures 1, 2, 3. IMU Linear Acceleration, Linear Velocity Model Prediction vs Measured, Linear Displacement Model Prediction vs. Measured (top to bottom) (3)

Figure 2. shows a root-mean-square error between the measured and modelled data of 0.4831m/s, and Fig. 3. shows an RMS error of 0.0428m. It was seen that there were perturbations in motion and was initially suspected that the door interfered after reviewing high-speed camera footage. This was seen when the door was isolated – the motion data seen on Figs. 4-6 were much cleaner, and the RMS errors were 0.1535m/s and 0.0139m, 68.2261% and 67.5234% improvements in model error, respectively. (3)



Figures 4, 5, 6. IMU Linear Acceleration, Linear Velocity Model Prediction vs Measured, Linear Displacement Model Prediction vs. Measured (top to bottom) (3)

To simulate moments induced by contact point distribution between the CSD and CubeSat, the model allows the user to define the contact feet positioning, degree of contact, and the CubeSat COM in three dimensions. The model also applies tab loads through the end of travel within the CSD. Angular moments were more difficult to assess, as gravity influenced rotation, primarily how the spacecraft was going to immediately pitch downwards upon ejection – which skews motion on the other axes (since angular motion is coupled) (Fig. 7). (3) (4)

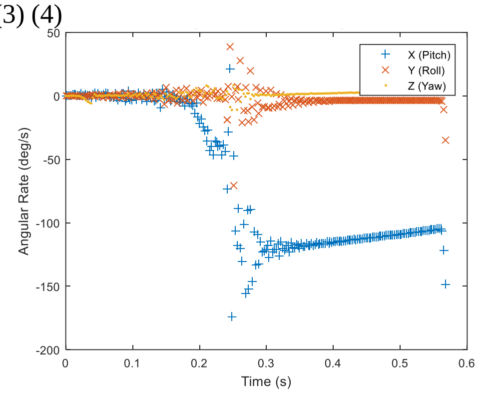


Figure 7. IMU Angular Rates (3) *Note Pitching Motion*

In attempt to overcome this, the CSD was orientated where it would eject the spacecraft upwards. This unfortunately yielded noisy motion and large deviation on measured data, a large and inconclusive error between measured and modelled angular motion. It was this issue that drove researchers to conclude testing in a microgravity environment is the best way to get reliable data.

In 2017, an AFRL-AFIT team conducted freefall tests in NASA GRC's 2.2 s drop tower. The CSD was installed onto frame within a drag shield and the CSD successfully ejected a representative payload downwards into a catcher bag at the bottom of the frame during freefall. The drag shield (which protects against air drag) and inner frame were rigidly mounted together to ensure minimal disturbances (see Figs. 8-11).

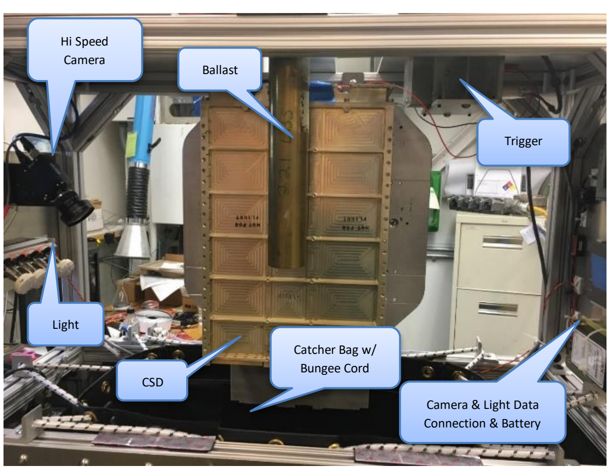


Figure 8: Experimental Rig Setup for NASA GRC's 2.2 s drop tower *(5)*

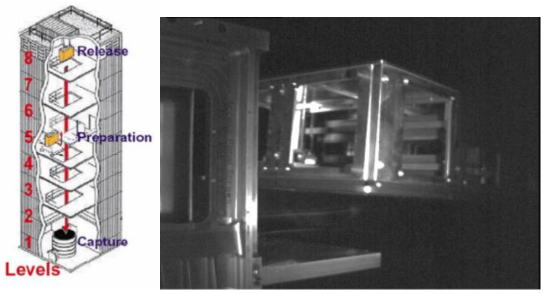
Figures 9, 10, 11: Hoisting Experiment Chassis (left), Encapsulating Experiment Chassis in Drag Shield (Center), Hoisting of Full Rig (right) *(5)*

58 drops were accomplished in one week, where CubeSat payload center of mass (COM), total mass, push plate contact forces, and the use of Moog isolators (typically used to reduce launch environments) were varied to characterize how these affect deployment (5). The following controlled regressors were used to provide performance baselines, as well as extreme case configurations (to be used as realistic boundary conditions):

- The variation of push-plate contact points, specifically:
    - Four contact feet fully engaging the CSD push-plate, enveloping the COM per CSD spec. (Resembling the Pumpkin SUPERNOVA foot contact pattern, a common 6U satellite bus used in past CSD research.) (3) (4)
    - No contact feet used, where only the spacecraft tabs were contacting the CSD push-plate. This was the original NASA SLS EM-1 configuration, and though no longer recommended, it is still worth researching for missions still considering it.
    - Three contact feet only, to evaluate potential effects of failing to successfully envelope the spacecraft COM.
- Varying CubeSat COM to evaluate the effects of spacecraft mass properties on deployment dynamics. Two configurations were used: nominal/centered COM within the prescribed CSD COM envelope, and a top-heavy COM not within specs (67mm above geometric center).
    - Centered: mass = 5.57 kg, I_{xx} = 37,897 kg-mm^2, I_{yy} =56,089 kg-mm^2, I_{zz} = 30,017 kg-mm^2

- Top heavy: mass = 5.88 kg, I_{xx} = 38,387 kg-mm^2, I_{yy} =58,970 kg-mm^2, I_{zz} = 31,454 kg-mm^2

- Moog isolators were connected to the CSD to evaluate the isolator's effects on CubeSat linear acceleration and angular tip-off rates.



Figures 12, 13: Drop Tower Rendition *(6)* **(left), and Video Capture of Deployment as CubeSat exited the CSD (right)** *(5)*

Data from these microgravity tests clearly identified linear and angular motion (Figs. 7 and 8) and were able to successfully bridge PSC's data gaps. The measured deployment linear acceleration values for all 58 runs had an average value of 2.155 m/s^2 with a 95% confidence interval (CI) of 0.976 to 3.333 m/s^2, and promptly went to zero when the spacecraft cleared the CSD. The consistent average linear deployment acceleration for each run was expected due to the constant force nature of the CSD spring system. The large variability of the measured accelerations is caused by "door bounce" where the CSD's clamping mechanism is engaged and disengaged multiple times at the beginning of each deployment. The final ejection velocity was 1.261 m/s, with a CI of 1.202 m/s2, to 1.321 m/s2, and closely agreed with PSC's predictions for a ~5.5-~5.8 kg payload (per Fig. 16) of ~1.25 m/s final ejection velocity. These results for a mid-level mass payload (mid-level because 6U two-spring CSD's have a max payload mass of 12kg), coupled from data from previous research for a light 0.7 kg payload (average of 3.3 m/s) increase confidence in PSC's originally C-9-derived CSD linear velocity profile.

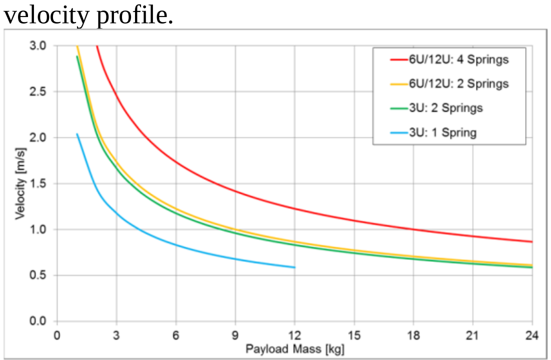
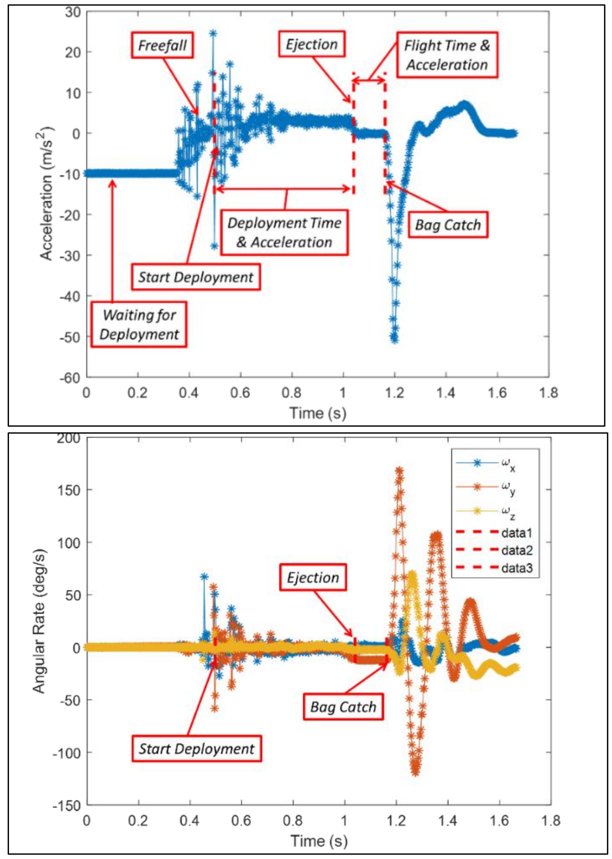


Figure 14. PSC Payload Ejection Velocity (7)



Figures 15 and 16. Changes in Linear Motion (top) and Angular Rate Data with Changes in Motion (bottom). *Note 0 m/s^2 linear motion in Fig. 7 indicates freefall. Figures 7 and 8 are synchronized with the same timescale.*

Angular rates were on average lower than PSC's measured rates of <10°/s (see Table 1) for nominal case, and measured velocities closely agreed with PSC's linear velocity curves. Also demonstrated were the effects of COM and contact points had on rates. Moreover, the Moog Isolators have negligible impact on deployment dynamics (5).

Table 1. Microgravity Test Angular Rates (5)

Configuration	**Angular Rate**
Nominal: 4 Feet – Centered COM	Up to -4°/s +/- 2.7°/s per axis
All Feet Top Heavy: 4 Feet – High COM	Up to -4.9°/s +/- 0.9/s per axis
Tab Only Centered: 0 Feet – Centered COM	Up to -7.6°/s +/- 2.8°/s per axis
Tab Only Top Heavy	Up to -11.5°/s +/- 2°/s upwards
Unbalanced: 3 Feet – Centered COM	Up to -6°/s +/- 3°/s per axis

METHODOLOGY

AFIT researchers developed a CSD dynamic simulation model using lab experiment measurements. (3) (4) The dynamics model uses Euler's equations of motion written in the body frame:

$$\vec{M}_b = \mathrm{I_b}\dot{\vec{\omega}}_b^{bi} + \vec{\omega}_b^{bi} \times \mathrm{I_b}\vec{\omega}_b^{bi} \quad (1)$$

These nonlinear, coupled, first order differential equations in three dimensions relate externally applied torques to angular velocities and accelerations. Kinematic equations (Eq. (2)) define the relationship between spacecraft attitude (in quaternions $\bar{\boldsymbol{q}}$), and angular velocities $\vec{\omega}$ in three dimensions.

$$\dot{\bar{\boldsymbol{q}}} = \frac{1}{2}\begin{bmatrix} \boldsymbol{q}^{\times} + q_4 1 \\ -\boldsymbol{q}^{T} \end{bmatrix}\vec{\omega} = Q(\bar{\boldsymbol{q}})\vec{\omega} \quad (2)$$

The model's state vector for the above kinetic and kinematic EOM, respectively, is written as.

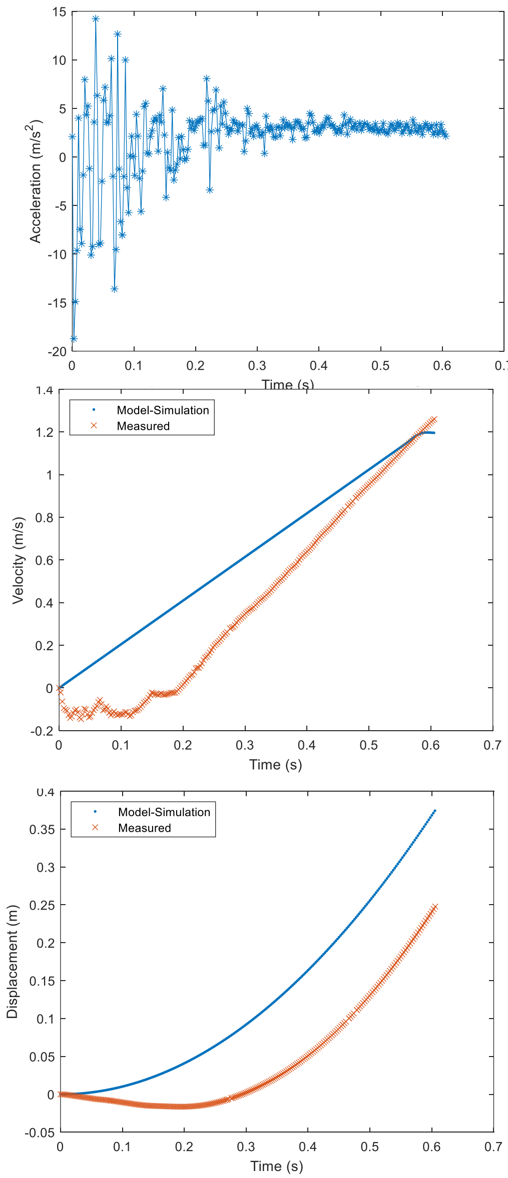
$$\bar{x} = [q_1\ q_2\ q_3\ q_4\ \omega_1\ \omega_2\ \omega_3]^T \quad (3)$$

The model also includes linear equations of motion, $\vec{F} = m\vec{a}$, to predict linear acceleration, velocity, and distance as a function of time. Linear acceleration was measured from triaxial accelerometers in the experiments and were determined to be consistent with predicted deployment forces. The CubeSat payload only experiences positive acceleration over the internal rail length of the CSD of 13.3 in (0.338 m). From original data in 2017, it was determined that the CSD had an average ejection force of 9.9244N. (3) Using the set ejection acceleration (since it is assumed acceleration is constant), ODE45 in MATLAB is used to model anticipated velocity and displacement profiles throughout the entire CSD rail length as a function of time. On the other side of the code, the trapezoidal rule is used to integrate measured accelerometer data, once to yield velocity, and twice to yield displacement.

EXPERIMENTAL RESULTS

This final step in this combined research effort to better understand and create a tuned deployment dynamics model using a variety measured deployment data collected from lab, aircraft microgravity, and drop tower experiments. The models will be used to predict deployment dynamics of various tested and future operational cases.

The first step is to input the drop tower data into the model and assess how well the model represents the data and verify that the data was interpreted correctly during initial data analyses. What initially has been seen is that the measured data in the initial dataset (seen in Figs. 17-19) makes no sense, almost like the original IMU dataset in Figs. 1-3, primarily because of the negative motion that is taking place. This first cut also yields RMS errors of 0.2437m/s and 0.0902m, which are notable increases in error when compared to 2017 bench data errors. The final issue is that according to this data, the spacecraft only travelled ~0.2m before release, which is physically impossible since the CSD deployment displacement is 0.338m. What this means is that the data needed to be looked at again to correctly identify the start and end points of deployment motion.



Figures 17, 18, 19. First Look Drop Tower IMU Linear Acceleration, Velocity Model Prediction vs Measured, Displacement Model Prediction vs. Measured (top to bottom)

When assessing the raw accelerometer data from the IMU again, it was noted that the initial tenths and hundredths of seconds after the start point appeared to be noise induced by external motion (likely the release of the drop tower chassis and CSD door slamming open). Moreover, that noise is centered around $0 m/s^2$, inferring that the CSD did not begin deploying the spacecraft. To overcome this, each datapoint was evaluated manually to identify a trend in increase in acceleration, specifically the ramp-up and plateau showing constant acceleration. This is clearly seen starting at ~0.3s in Fig. 17. From this analysis, it was noted that deployment motion was indeed started much earlier than before, and thus the code was modified to consider motion to start later.

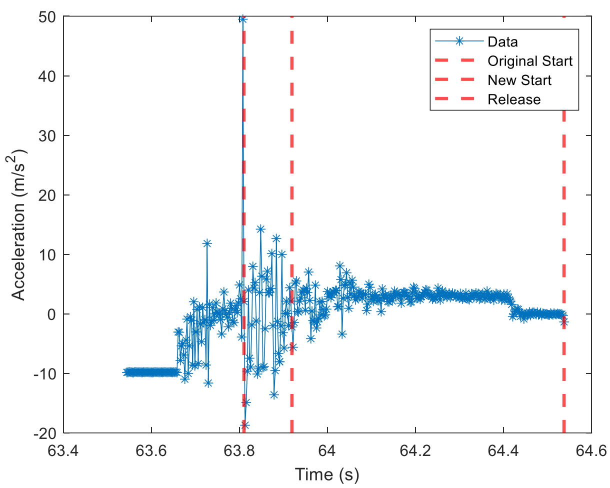
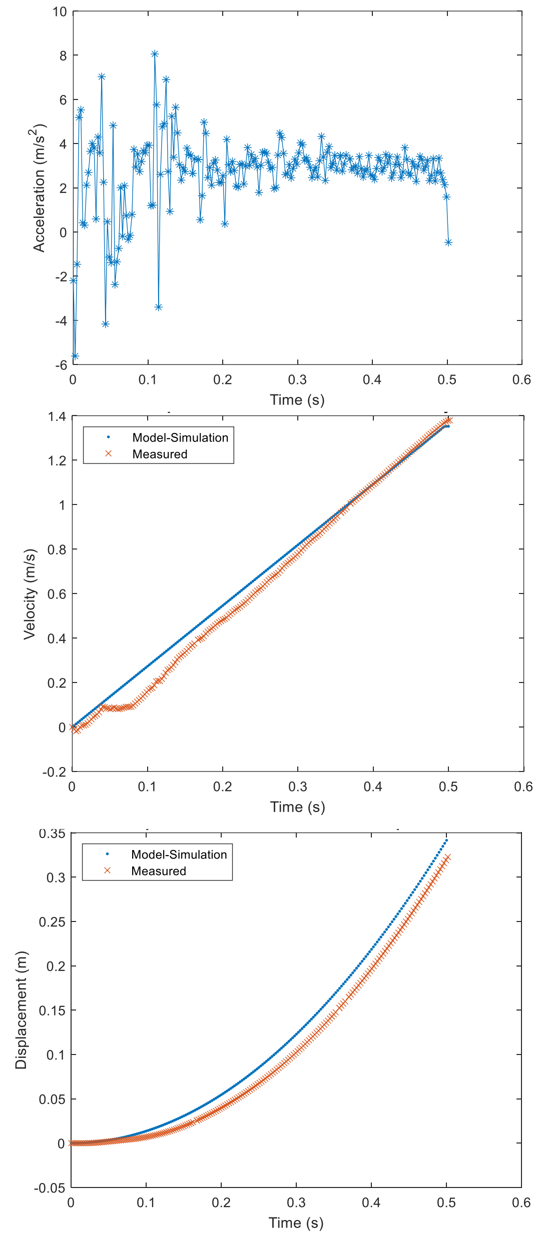


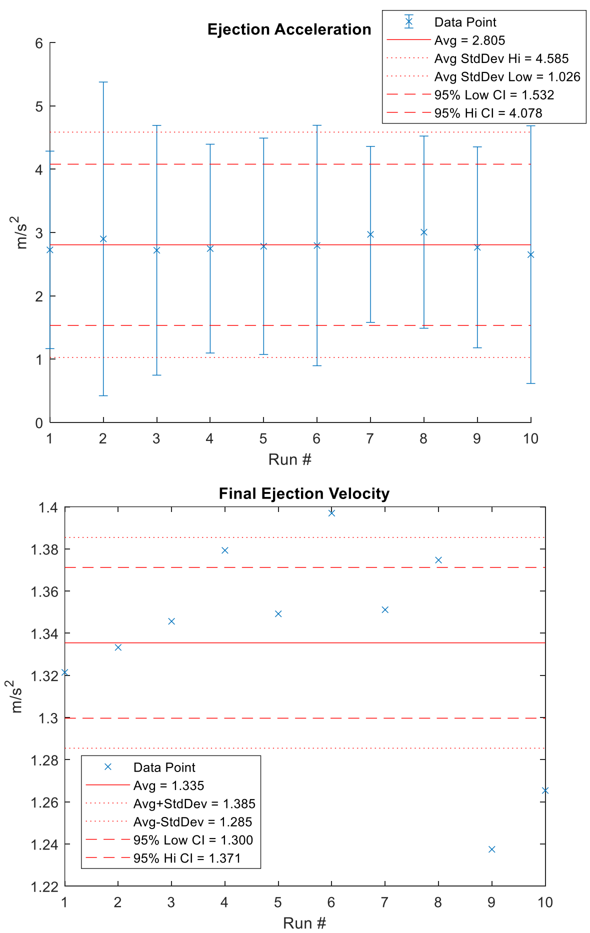
Figure 20. Changes in Linear Motion (Comparing Start Times)

As an example, motion was originally noted to begin in Fig. 20 at 63.81s after IMU start, but after analysis the new start time was set to 63.89s. From visual and data analysis, the period between 63.81s to 63.89s was deemed to be noise from either the CSD door opening, and/or the rattling of the drop tower, and only afterwards was motion data deemed to be consistent with actual motion (and not noise). This was concluded because the drop tower did not activate until 63.66s and entered microgravity around 63.73s. The CSD trigger was set at a delay of 0.2s to give enough time to enter microgravity. (5) That means deployment was not initiate until around 63.88s. With this, adjusting to 63.89s is very reasonable both from both analytical and temporal perspectives. This adjustment yields a significant improvement in motion and model data, as seen in Figs. 21-23.



Figures 21, 22, 23. Adjusted Drop Tower IMU Linear Acceleration, Velocity Model Prediction vs Measured, Displacement Model Prediction vs. Measured (top to bottom)

Furthermore, RMS error for velocity and displacement reduced to 0.0556m/s and 0.0160m, respectively. For this example, the measured data shows a final ejection velocity of 1.379m/s after travelling 0.3415m in 0.5s, while the model yields a final ejection velocity of 1.353m/s after travelling 0.3227m in 0.5s. Given the noted differences, it was determined that a relook at the linear data would be necessary. For the sake of time, 10 runs of the total 58 were sampled, which is statistically sufficient for a data set (3). This is statistically significant, and it was demonstrated that linear motion was deemed to be consistent from previous research. (5) Since this required a relook at the linear data of all 58 runs from the work previously done (and described in Part I). The corrected acceleration values determined from this sampling during deployment had an average value of 2.805 m/s^2 with a 95% confidence interval (CI) of 1.532 to 4.078 m/s^2, and promptly went to zero when the spacecraft cleared the CSD. This gives us an updated average deployment force of 15.624 N. The corrected final ejection velocity was 1.335 m/s, with a CI of 1.300 m/s^2, to 1.371 m/s^2, which still is close to PSC's predictions for a ~5.5-~5.8 kg payload (per Fig. 16) of ~1.25 m/s final ejection velocity.



Figures 24, 25. Adjusted Drop Tower IMU Measured Ejection Linear Acceleration, and Final Velocity (top to bottom)

Now that we adjusted linear motion modelling of CSD deployment, it will be possible to proceed to adjust angular motion. Given time constraints, this will have to saved that for future papers.

NEXT STEPS

From previous research, the angular rate confidence intervals and standard deviations for all configurations do indicate a reasonable wide angular rate variation. The primary suspect causing this is the flexing of the CSD push plate. For future research, this experimental data from the drop towers will need be used to the tune the analytical CSD deployment simulation model that would incorporate angular motion variety/jostle demonstrated during the drop tests.

CONCLUSION

There exists a driving the need for a better understanding of deployment rates of CubeSats from dispensers. Results from microgravity deployment tests conducted at NASA Glenn Research Center's (GRC's) drop towers bridge data gaps that PSC encountered during their C-9 tests. Once tuned, the analytical CSD deployment simulation model would be available to payload planners to assist in payload design and mission planning. Also, as more mission partners are embracing the 12U construct to suit their needs, the primary author has personally received multiple requests in exploring the feasibility of duplicating this test with the 12U CSD. It would also be beneficial to replicate this test with a 6U, four-spring CSD, as this is the model of CSD used on EM-1.

REFERENCES

1. **Holemans, Walter and Henver, Ryan.** *Canisterized Satellite Dispenser. US 2014/0319283 A1* United States of America, October 30, 2014. Patent Application Publication.

2. **Azure, Floyd, Hevner, Ryan and Holemans, Walter.** *Lessons Learned Measuring 3U and 6U Payload Rotation and Velocity when Dispensed in Reduced Gravity Environment.* 21 April 2015.

3. **Tullino, Stephen K.** *Testing and Evaluating Deployment Profiles of the Canisterized Satellite Dispenser (CSD).* Wright-Patterson AFB, OH : Air Force Institute of Technology, 2017.

4. *Testing and Evaluating Deployment Profiles of the Canisterized Satellite Dispenser (CSD).* **Tullino, Stephen K and Swenson, Eric.** Grapevine : 55th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, 2017. AIAA 2017-0850.

5. *Investigative Microgravity Deployment Tests of the Canisterized Satellite Dispenser (CSD).* **Tullino, Stephen K., Swenson, Eric D. and Tullino, Jessica L. Marshall.** Orlando : 2018 AIAA Space Forum, 2018. AIAA 2018-5121.

6. **Elonen-Wright, Linda C.** NASA GRC 2.2 Second Drop Tower. *NASA Glenn Research Center.* [Online] National Aeronautics and Space Administration, February 1, 2008. [Cited: September 19, 2016.] http://facilities.grc.nasa.gov/drop/.

7. **Henver, Ryan.** Canisterized Satellite Dispenser (CSD) Data Sheet (2002337D). [Online] Planetary Systems Corporation, August 4, 2016. http://www.planetarysystemscorp.com/web/wp-content/uploads/2016/08/2002337D-CSD-Data-Sheet.pdf.

8. **Del Rosso, Dominic.** Reduced Gravity Research. *NASA/JSC Aircraft Operations.* [Online] September 30, 2016. https://jsc-aircraft-ops.jsc.nasa.gov/Reduced_Gravity/index.html.

9. **Neumann, Eric.** *NASA GRC Zero-G Facility Consultation.* October 2016.