

**COUNTING DOWN TO THE LAUNCH OF POPACS (POLAR ORBITING  
PASSIVE ATMOSPHERIC CALIBRATION SPHERES)**

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**ABSTRACT**

The main objective of Project POPACS (Polar Orbiting Passive Atmospheric Calibration Spheres) is to measure the changes in density of the auroral zone upper atmosphere, in response to various solar stimuli, such as flares and CMEs. The mission consists of deploying three 10 cm diameter Aluminum spheres into an elliptical polar orbit and tracking them as they make repeated perigee passes in the upper atmosphere, with special emphasis on perigee passes within both the northern and southern auroral zones. The spheres have identical external dimensions and surface compositions, and thus identical drag coefficients, but they have different masses (1, 1.5, 2 kg) to vary their ballistic coefficients, which will cause them to spread out in right ascension along the original orbit. The Aluminum spheres will be coated with space-rated flat white paint so they can be both radar tracked by the U.S. Space Command and optically tracked by a world-wide network of university students and amateur observers with “Go To” telescopes. The observers will track the spheres, exchange their observations with each other, and calculate the density of the atmosphere above 325 km at the location of the perigee passes. POPACS will be launched during Solar Maximum 24, which is expected to peak in early 2013, and accordingly, the mission will be on a fast-track timeline: project start to launch and operation in 12 months! One of the mission enablers is the 3U Canisterized Satellite Dispenser (3U CSD) developed by Planetary Systems Corporation. While having similar internal dimensions to the P-POD (CubeSat launcher) design, the 3U CSD has key features that provide higher payload mass capability (6Kg), tabbed preload system to guarantee a stiff and modelable load path to the CubeSats, a higher ejection velocity, lower overall volume, mounting features to allow fastening of the CSD at any of the six faces, a 15 pin in-flight disconnect allowing battery charging and communication from the outside of the CSD into the payload while in the launch pad or on orbit, and a reusability that allows a separation test to be conducted at will without any consumables hundreds of times to guarantee reliability. The CSD will be qualified to levels exceeding Mil-Std-1540 for thermal vacuum, vibration and shock. The paper will provide details of the dispenser and POPACS designs, as well as descriptions of the mission concept of operations and the program’s scientific research objectives.

**MISSION DESCRIPTION**

The use of data derived from radar and optical tracking of high-altitude rocket-launched spheres is a commonly used method of determining the total density of Earth’s upper atmosphere, dating back to V-2 launches at the White Sands Missile Range in New Mexico in the 1940s and 1950s. The method

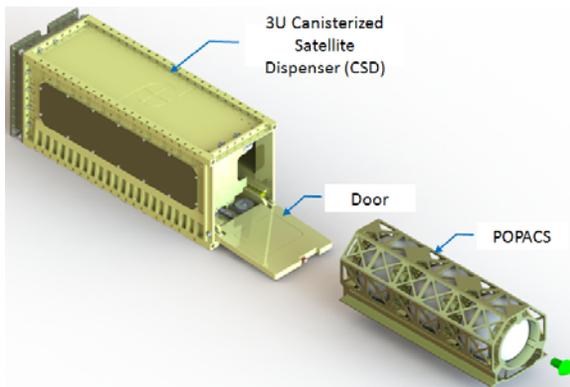
was extended to orbital flight by the launches of Sputnik and Vanguard in the late 1950s<sup>1</sup>.

An interesting variation of that method will be used for Project POPACS (Polar Orbiting Passive Atmospheric Calibration Spheres), in which three 10-cm-diameter, Aluminum spheres, weighing 1, 1.5 and 2 kg, respectively, and painted with AZ-93 white paint (Figure 1), will be deployed from a Planetary

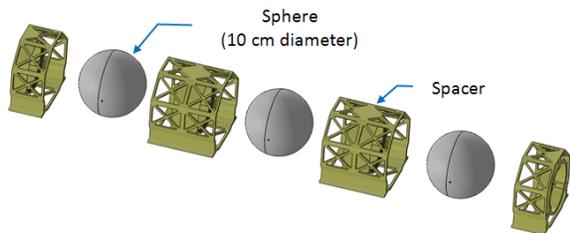
Systems Corporation 3U Canisterized Satellite Dispenser (CSD) on a SpaceX Falcon 9 launched from Vandenberg AFB into an elliptical orbit with a perigee of 325 km, an apogee of 1500 km and an inclination of 80 degrees to the equator. This launch is planned to occur during Solar Maximum 24. A depiction of this payload is shown in Figures 2 and 3.



**Figure 1: Three 10-cm Diameter Hollow Aluminum White Painted POPACS**

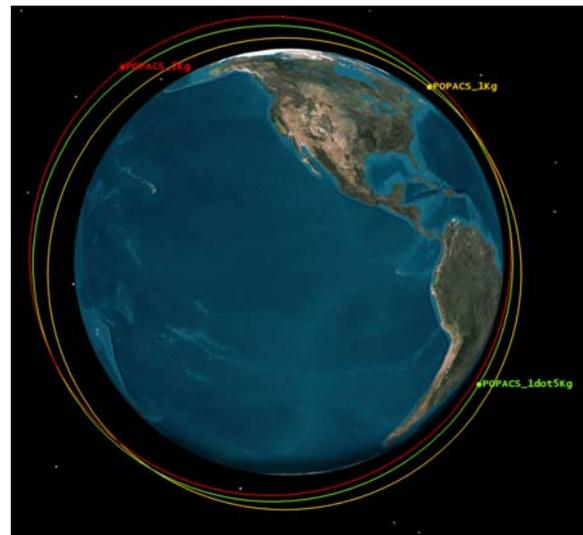


**Figure 2: Once On Orbit, the CSD Dispenses POPACS**



**Figure 3: Immediately After Dispensing, the Spheres Are Freed From the Spacers. The Science Mission Begins.**

The apogee of each sphere's orbit will shrink a slight amount each time the sphere passes through perigee of its orbit, due to atmospheric drag, with the lightest sphere experiencing the greatest rate of orbit decay. This orbit decay can be interpreted as a direct measure of atmospheric density above 325 km. The drag will also cause the three spheres to spread out in right ascension because of their different ballistic coefficients. At the same time, apsidal regression will slowly cause the perigees of the spheres to separate from each other in azimuth. The result of these effects will be that the sphere's perigee passes will occur at approximately 100-minute intervals at three different times and three different geographic locations in the earth's upper atmosphere, thus increasing the breadth and frequency of the density measurements. Figure 4 shows a computer simulation of the orbital decay.



**Figure 4: Analytical Graphics, Inc. Simulation of POPACS Orbits Three Years After Launch**

Approximately ten years after launch, depending on the way the Sun behaves during Solar Cycles 24 and 25, the orbit of the 1 kg sphere will become circular

at an altitude of 325 km and will shortly thereafter de-orbit and be consumed, while the 1.5 kg sphere will de-orbit in 12.5 years, and the 2 kg sphere will de-orbit in 15 years.

The U.S. Space Command will radar track the metallic spheres throughout their lifetimes and periodically publish their two-line orbital element sets (TLEs). Student groups in participating universities around the world will use these element sets to optically track the spheres with “Go To” telescopes and calculate their own orbits of the spheres, measure the way in which the orbits decay, and thereby determine the density of Earth’s atmosphere at the location of each sphere’s perigee passage. The students will pay particular attention to the way in which the density of Earth’s upper atmosphere in its northern and southern auroral regions responds to solar flares and coronal mass ejections (CMEs) and the way that those effects propagate equator-ward. Software for computing these effects will be provided to the students by the Center for Space Standards and Innovation of Analytical Graphics, Inc. in Colorado Springs.

The E.O. Hulburt Center for Space Research at the U.S. Naval Research Laboratory (NRL) will make their own computations of atmospheric density from the Space Command’s tracking data, and will provide their results to the students for comparison purposes. Prizes will be awarded by the POPACS Project to the student groups whose results most closely match those of NRL.

The POPACS project is an upgraded continuation of Project Starshine, in which mirrored half-meter and one meter spheres were deployed from Space Shuttles into 51.6 degree, 325 km circular orbits and from an Athena I ELV into a 67 degree, 450 km circular orbit during Solar Maximum 23 in 1999-2001. These mirrored satellites were radar tracked by the U.S. Space Command and by a worldwide eyeball network of student observers. Data from those missions were used by scientists at the Naval Research Laboratory to refine their NRL MSIS codes for determining variations in atmospheric density in response to solar storms<sup>2</sup>. Additional Starshine satellites were originally manifested on Space Shuttle flights but were de-manifested, along with other “non-essential” cargo bay experiments, following the Columbia accident in 2003. Attempts over the past ten years to find launches for these smaller POPACS spheres with smooth, uniform surfaces (in order to make determination of their drag coefficients and the resultant atmospheric density more precise), into highly inclined elliptical orbits have been

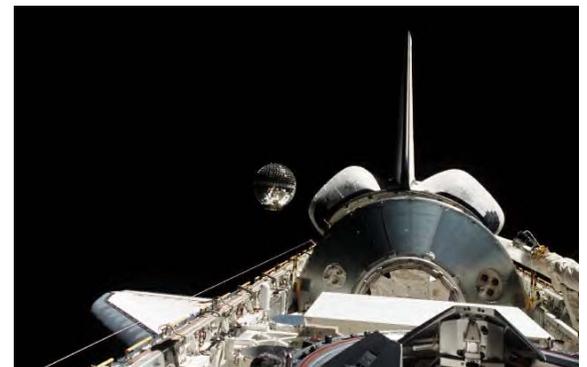
unsuccessful until a SpaceX Falcon 9 flight became available. Due to launch during Solar Max 24, the launch has become available at just the right time to maximize POPACS’ scientific relevance. Figures 5 to 8 show pictures from the Starshine Project.



**Figure 5: Starshine 1 on NRL Vibration Table**



**Figure 6: Starshine 2 in Space Shuttle Cargo Bay Hitchhiker Canister**



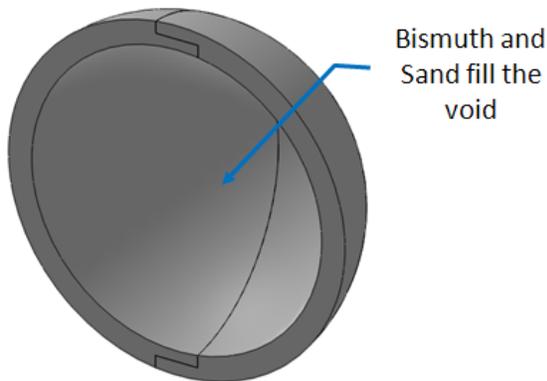
**Figure 7: Starshine 2 Being Ejected From Space Shuttle Cargo Bay**



**Figure 8: Starshine 3 on Athena 1 Payload Deck**

**THE POPACS SPHERES**

Following the “Design for Demise,” dictum of Dr. William Ailor of Aerospace Corporation, the outer shell of each hollow POPACS sphere has been machined by C & G Machine of Colorado Springs, CO to a thickness of one cm and a mass of 680 gm from Aluminum 6061-T6, which will readily melt upon atmospheric re-entry at an altitude of approximately 80 km. Figure 9 shows the cross-section of the sphere design and Figure 10 shows the actual hemispheres of the final sphere. The spheres have also been ballasted to their design masses of 1.0kg, 1.5kg and 2.0 kg with tiny particles of Bismuth shot, which will also melt at re-entry, and sand, which will be harmlessly dispersed at re-entry. Figure 11 shows the ballast and bismuth shot that fill the interior of the spheres.



**Figure 9: Section of a POPACS Sphere**



**Figure 10: Section of a POPACS Sphere**



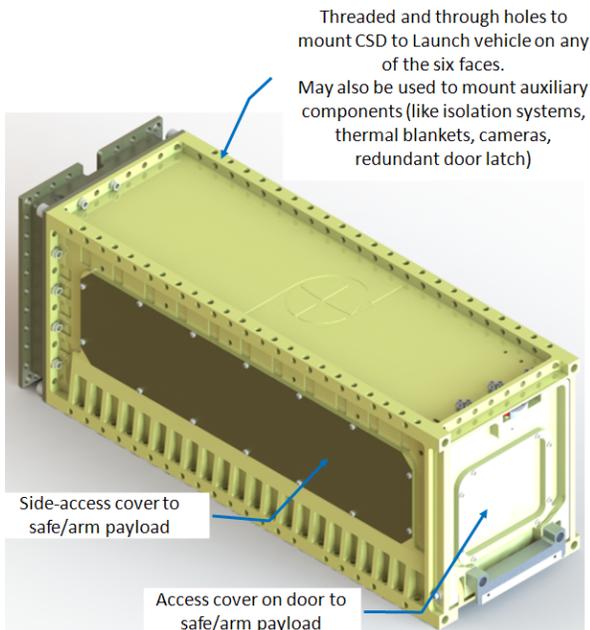
**Figure 11: Ballast Sand and Bismuth Shot**

To commemorate the beginnings of the U.S. space program, the sand has been procured from Robert H. Goddard’s launch site of March 16, 1926, in Auburn, MA and his later launch site of the 1930s in Eden Valley near Roswell, NM, as well as from the White Sands Missile Range, where captured German V-2 rockets were launched in the late 1940s and 1950s on upper atmospheric and solar research missions.

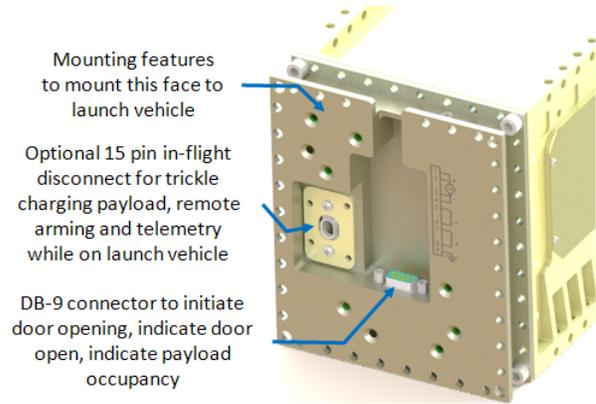
**CANISTERIZED SATELLITE DISPENSER (CSD)**

The CSD (Figure 12) is made of machined aluminum alloys. To aid in mounting to the many Launch Vehicle mounting locations, all six faces may be used. These features also may be used to mount auxiliary components (like isolation systems, thermal blankets, cameras, redundant door latch, etc.). The back is shown in Figure 13. It incorporates the initiation connector (used by the launch vehicle to open the door) and in-flight disconnect (to communicate from the Launch Vehicle to the payload). The door is restrained and initiated with an automatically resettable latch driven by a reusable initiator as shown in Figure 14. By closing the door,

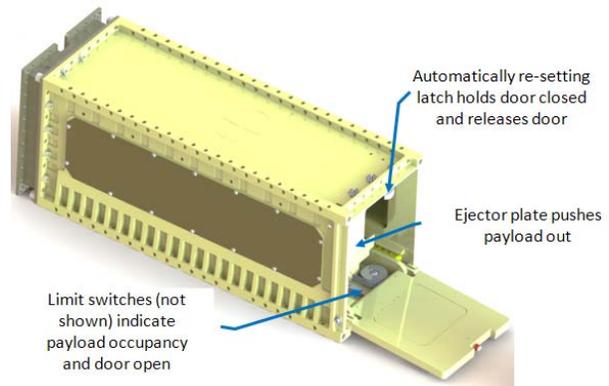
the payload is preloaded to the CSD and ready for flight. The CSD can restrain deployables like solar panels, antennas and camera baffles until ejection using roller bearings which bear upon designated CSD internal surfaces. This is depicted in Figure 15: the payloads are free of burden of complex restrain/release mechanisms. The very low cost (~1\$) of stowing the payload and dispensing it allows for exhaustive testing of the critical dispensing operation such as in thermal vacuum, after vibration, during microgravity (“vomit comet”), in payload fit checks and launch vehicle integration checks. The CSD allows payloads about an inch longer than in competing products but is smaller on the outside than competing products. In addition to the side walls, the door has access cover which may be useful to arm payloads when the sides are obstructed.



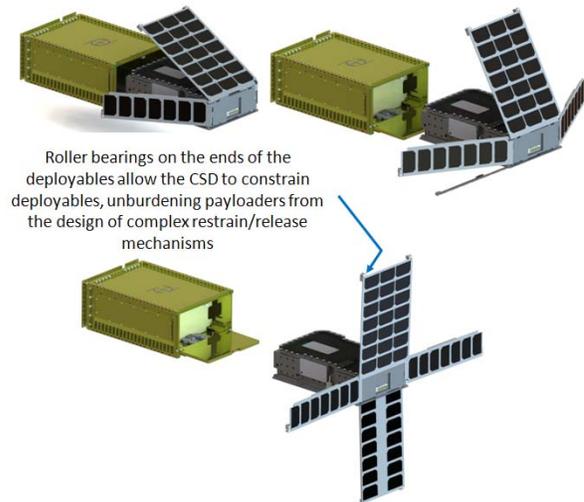
**Figure 12: 3U CSD**



**Figure 13: Back Plate of CSD**



**Figure 14: CSD Door and Associated Features**

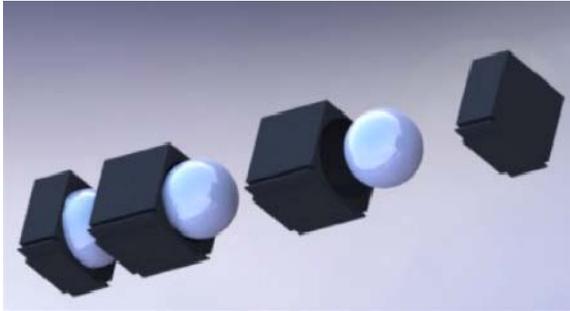


**Figure 15: In an Example of the 6U CSD, the CSD Internal Walls May Constrain Deployables until Ejection**

POPACS SPACERS

### Design Process:

The spacer assembly is designed to deploy linearly from the CSD. The first design iteration, shown in Figure 16, was made of solid pieces that cupped the spheres. The cup was lined with Viton to reduce the risk of surface scratching. Spring plungers will ensure the spheres do not stick to the Viton, as the force they exert upon deployment will ensure they separate from the spacer. The spring plungers provide minimum points of surface contact to reduce the risk of surface scratching, while still bearing the load of the spheres. The Acetal nose is used to prevent marring on soft materials like the aluminum used for the spheres. The spring has an 8-32 thread size, and a 0.625 in. long body. Each spring plunger has an end force of 7.3 lbf. The plunger is pictured in Figure 17.



**Figure 16: First Iteration of Concept Design Using Solid Spacer Pieces.**

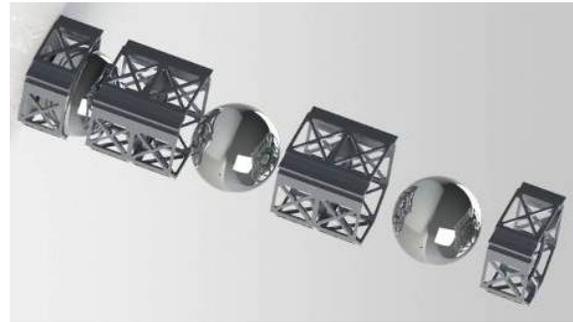


**Figure 17: Acetal-Tipped Spring Plunger**

The design measures 340 mm in length with a clearance of 1 cm between each sphere or the ends of the structure, which gives about 26 mm of extra room in the CSD. There is a clearance of 1.27 mm (0.050 in.) between the spheres and the sides of the spacer pieces, such that the other dimensions accommodate the dynamic envelope for the structure contained in the CSD. The mass of this initial structure was too high at 7.7 kg without spheres or spring plungers.

The second iteration, shown in Figure 18, accommodates the late request from PSC to cut the payload length to make room for an additional payload of 6.35 cm (2.5 in.) in the CSD. To accommodate this request, the spacing between each sphere was reduced to 0.05" (0.127 cm). We were able to greatly reduce the mass of the structure by removing material to create a truss structure and

switching to a Viton-lined O-ring rather than a cup, which removes mass and supports the sphere in a circular fashion, evenly distributing the load. If the spheres were supported in a non-circular way, the contact points can move, causing the spheres to slip. The design uses three spring plungers spaced  $120^\circ$  around the O-ring. They are angled at  $45^\circ$  to the normal through the spacer. Having multiple points around the O-ring distributes the load evenly and prevents the sphere from sliding. Again, the spring plungers will ensure the spheres do not stick to the Viton lining. This O-ring cradle is depicted in Figure 19. With these changes the mass of the structure itself, including spring plungers, is 786 g.



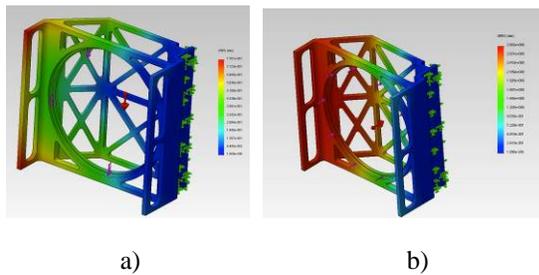
**Figure 18: Second Iteration of Spacer Design Using Trusses**



**Figure 19: Spacer Piece With View of O-ring Groove and Spring Plunger Holes.**

Structural analysis was conducted in SolidWorks<sup>5</sup> to assess the deformation under loading on the individual spacer piece level. The order of the spheres in the assembly will be the 1 kg sphere at the top to deploy first, the 2g sphere in the middle so as to align the center of mass, and the 1.5 kg sphere in

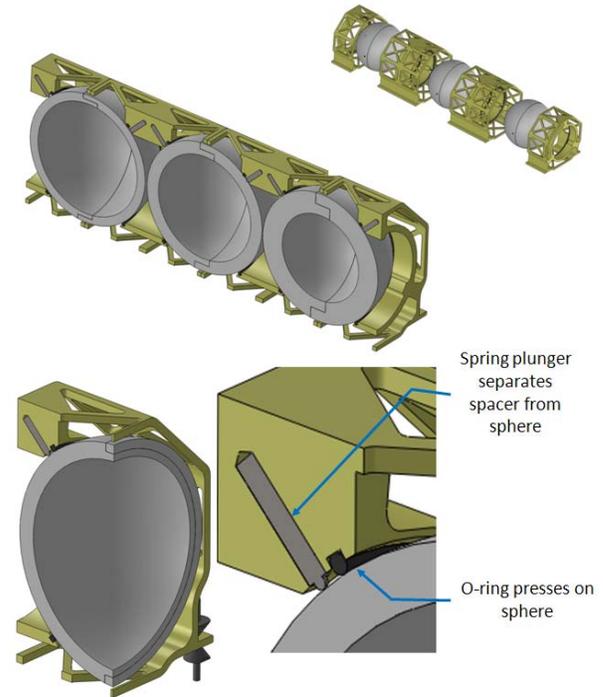
the back to deploy last. As such, the location of the highest loading would be in the middle spacer where the 2 kg sphere acts on the O-ring. The assembly will be subjected to 50 G in each axis, which equates to 1000 N of force acting on the O-ring. The spacer was fixed at the tabs in each case, as it would be in the CSD. Figure 20 a and b depicts the vertical and lateral deformation cases, respectively. The maximum assessed deformation is in the lateral direction at 1.4 mm as compared to 1.1 mm in the vertical. Though the lateral deformation is near the limit of 1.5 mm, it was deemed acceptable for the structure to be considered moving forward.



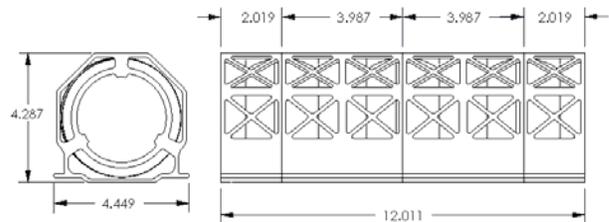
**Figure 20: Displacement Analysis in mm Conducted in SolidWorks for a) Vertical and b) Lateral loading at 50 G.**

**Final Design and Analysis:**

The POPACS payload is an entirely mechanical design; it does not include any electronics. The spacers are designed and built by an undergraduate student team (Kelly Collett, Frank Arute and Tim Wilwert) at Drexel University led by faculty member Dr. Jin Kang<sup>5</sup>. Compressed O-rings are the load path between the spheres and the spacers, as shown in Figure 21. The spacers are machined aluminum alloy. The total mass of the POPACS payload, including the spheres is 5.6 kg. Figure 22 shows the dimensions of the spacers.

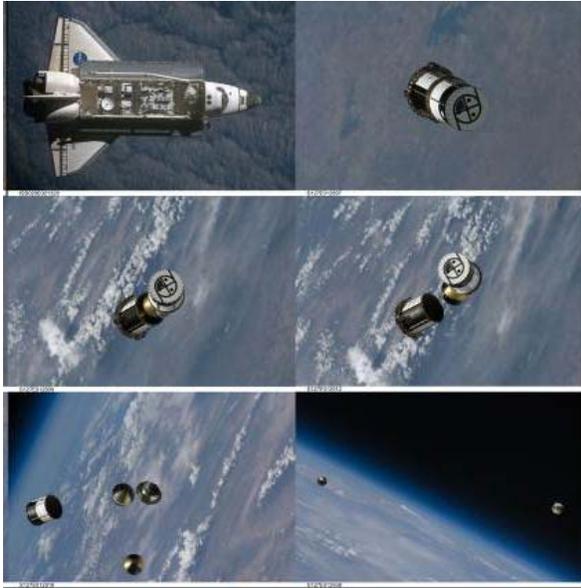


**Figure 21: Boundary Condition on Sphere Prior to Dispensing**



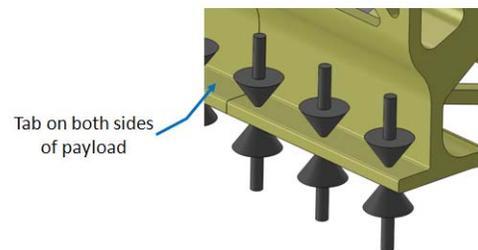
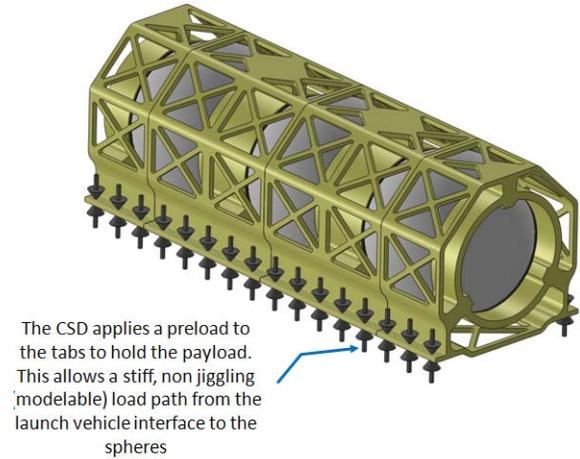
**Figure 22: POPACS Maximum Dimensions in Flight Configuration. Dimensions Are In Inches.**

This design is derived from the much larger CAPE ICU I and II STS launch payloads<sup>3</sup> (Figure 23).

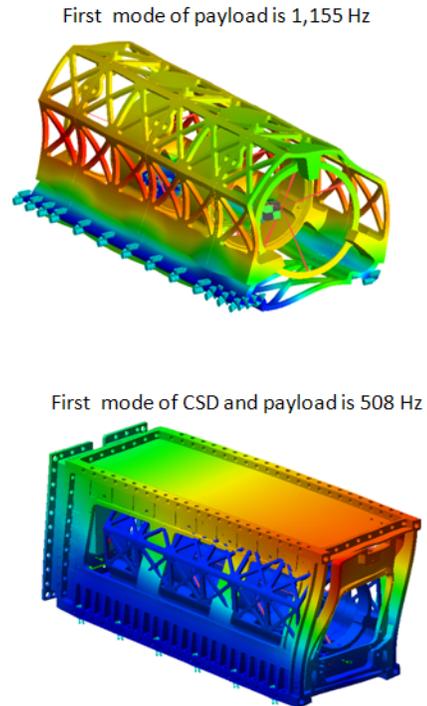


**Figure 23: Two 19 inch diameter Spheres Were Bounded by O-rings, Encapsulated in Two Cylinders and Dispensed from CAPE on STS-127**

The POPACS payload is rigidly fastened to the CSD via the tabs (Figure 24) which are preloaded when the door is closed. This guarantees a stiff and modelable (Figure 25) load path and avoids potentially detrimental jiggling found in other designs where there is a 0.010 gap between the payload and dispenser is typical<sup>4</sup>. Preloading the tabs (which is what bolted joints do to flanges of adjoining structures) will be of great use in vibration and shock environments where model ability could preempt test failure by accurately predicting problematic modal frequencies and responses.

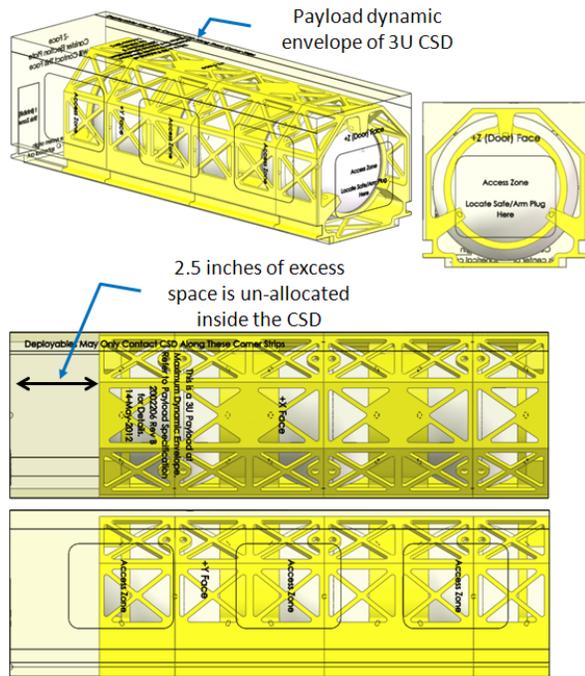


**Figure 24: The Spacers Are Preloaded to the CSD**



**Figure 25: By Guaranteeing an Invariant Load Path, the Preloaded Tabs Allow Accurate Dynamic Modeling in Anticipation of Vibration Testing and Space Flight**

The POPACS payload easily fits within the payload dynamic envelope. Approximately 2.5 inches of un-allocated space exists inside the CSD.



**Figure 26: POPACS Fits Well Within the Payload Dynamic Envelope of the CSD**

**Summary**

An innovative design to measure the upper atmospheric density variations due to solar activity with simple spheres is well on its way to being ready for its mission. The launch will use an advanced Canisterized Satellite Dispenser to dispense the spheres. The design is under final construction, and

will be tested via environmental testing, as well as deployment testing in micro-gravity environment onboard a zero-g flight.

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