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A Mission Revived: Lessons Learned from Starshine 4 Re-design, Assembly, Test, and Integration.

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ABSTRACT

In 2002 an effort between Project Starshine, the Naval Research Laboratory (NRL), and students from across the world worked to design, build, and test the Starshine 4 satellite. The purpose of the mission was twofold; engage students in a flight mission and measure upper atmospheric density. The mission was manifested on the Space Shuttle [STS-114] but before Starshine 4 was launched the Shuttle was retired and the spacecraft was put into storage at Planetary Systems Corporation (PSC).

In 2017 Principal investigator and founder, Gil Moore, negotiated an opportunity to launch a newly developed launch vehicle. Mr. Moore reached out to PSC for help.

Due to experimental launch vehicle constraints only a minimal on-orbit life was available. Orbit lifetime is critical for students to observe the spacecraft and take data. To increase orbital life, engineers increased the satellite's mass to maximize the ballistic coefficient. The structure was redesigned to support a traditional ring-based separation system. Starshine spins slowly and requires critical separation dynamics. Engineers designed custom spring assemblies to enable tip off rates. Verifying separation dynamics is also very challenging but the separation adapter enabled streamlined testing.

The integration process was taught to the launch vehicle's integration and test staff in a fraction of the time required for traditional integration. Flight hardware integration was completed in less than 3 hours. This paper will go into details about the lessons learned preparing an 18-year-old spacecraft back to flight readiness in addition to the integration process.

I. Introduction and Background

Formed in 1997, Project Starshine is an informal volunteer group of researchers, engineers, educators, and students. The director and founder of the program is R. Gilbert Moore, an adjunct professor at Utah State University in Logan, Utah. Starshine is an acronym for Student Tracked Atmospheric Research Satellite for Heuristic International Networking Experiment. The project designed, developed, and successfully launched Starshine 1, Starshine 2, and Starshine 3. Each of these satellites is a sphere populated by hundreds of Aluminum mirrors the size of a quarter, ground and polished by grade school students from schools all over the world. The mirrors are precisely attached facing radially outward. The satellites are made to slowly spin about one axis in lower earth orbit, and combined with the effect of sunlight reflecting off the mirrors, the satellites twinkle. This twinkle effect can be observed on the ground using the naked eye and observers (typically students) measure and submit the satellite's location to researchers. Due to atmospheric drag, the satellite's orbit slowly decays and with a database of many observations over time, researchers are able to measure fluctuations in upper atmosphere density caused by solar storms.

Figure 1: Starshine 1, 2

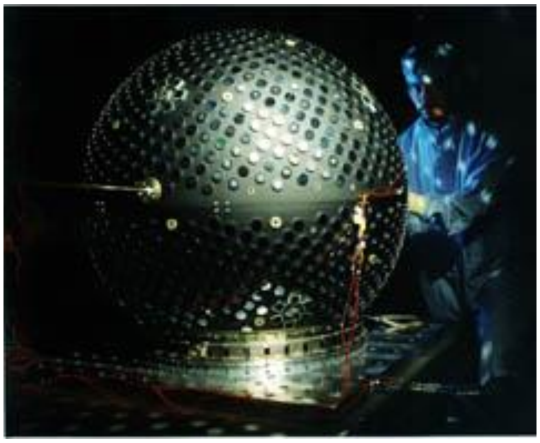

Figure 2: Starshine 3

II. Starshines 4 and 5

Beginning in May 2001, the Starshine 4 and 5 satellite's missions were designed to engage students in satellite component manufacturing and teach them how to take orbital observations to help measure the earth's upper atmospheric density. While each of the five satellites had a similar mission and design, they also had some measurable differences as shown in Table 1 below.

Satellite Name	Diameter [cm]	Mass [kg]	Number of Mirrors
Starshine 1	48	39	878
Starshine 2	48	38	858
Starshine 3	94	90	1500
Starshine 4	48	45*	1000
Starshine 5	10	-	0

* Initial design mass for STS-114 lauch

Table 1: Summary of Starshine satellite measurables

Starshine 4 was composed of two hemispheres connected by a mid-deck to create the complete spherical space craft. Space at the aft end of the lower hemisphere was allocated to a separation adapter. The mission also added a hosted payload called Starshine 5 that was to be housed within that dedicated separation adapter. The entire Starshine 5 assembly was mounted within the Starshine 4 body at the south pole. Starshine 5 was designed to deploy approximately 1 minute after Starshine 4 deployment and while the small sphere had no mirrors that could be seen with the naked eye, it did contain optical retroreflectors mounted upon its surface that enabled it to be tracked by the International Satellite Laser Ranging network (ISLR). The combined orbital decay data from the two satellites orbiting coincidently would allow for a more precise determination of the upper atmosphere's density.

Figure 3: Gil Moore stands next to a hemisphere of Starshine 4

Figure 4: Starshine 5 shown stowed in its deployer.

III. Hardware Requirements and Redesign

Unique challenges were realized immediately.

a. Due to launch vehicle constraints on its first orbital launch attempt, the original orbital requirements could not be met; the launch could only support a shorter on-orbit life.
b. The structure required redesign to support a new separation adapter.
c. Starshine 5 could no longer be included as a hosted payload and the spacecraft had to be completely passive. All electronics, including

a system to sustain Starshine's spin rate enabling it to remain twinkling, were removed.

d. An ambitious schedule would leave no margin for gross errors.

e. The budget was $0

a. Increasing orbital life.

Maximizing orbits has critical benefits. The data used to calculate upper atmospheric density is dependent on the number of sightings taken on the ground. People need time to mobilize, understand, and actually take measurements. A loss of even a few days is costly. To increase orbital life, engineers increased the satellite's mass to maximize the ballistic coefficient. Significant mass had already been removed with the loss of Starshine 5 and all non-passive components. Ultimately the maximum mass was dictated by the launch vehicle team. To solve the mass issue, a series of thin aluminum discs were designed and manufactured. This design enabled engineers to rapidly change the total mass as requirements from the new launch vehicle continued to be updated. The final mass after separation was 44.lb. The orbital lifespan remained a variable as the launch vehicle was continuing to be developed after Starshine 4 was delivered. However, by maximizing the ballistic coefficient engineers were able to maximize Starshine's orbital life.

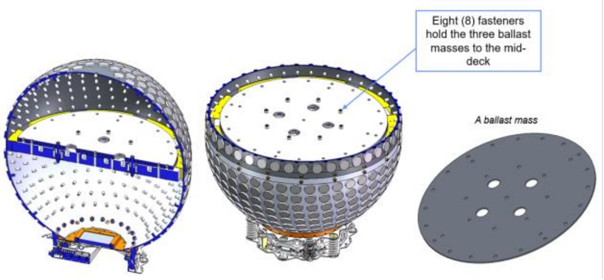

Figure 5: Ballast mass.

b. Adapter redesign.

A new separation adapter called the Advanced Lightband (ALB) was donated to the program. The ALB is an advanced version of the MkII Motorized Lightband developed by PSC.

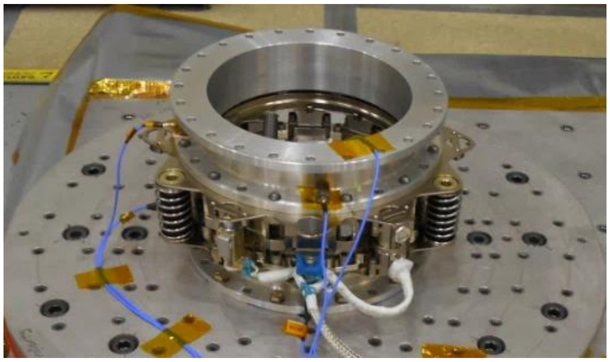

Figure 6: An 8 inch Advanced Lightband is subjected to vibration testing.

The ALB provided many advantages. Its ease of use and swift integration made it a perfect fit for Starshine 4. The ALB was also used to constrain the satellite in the shipping container, significantly simplifying logistics. An 8 inch diameter ALB also allowed the team to meet all mission requirements. To accommodate the ALB a new interface plate was designed. The plate occupied the area where Starshine 5 resided and transferred load from the ALB to the lower hemisphere. The ALB was test verified and demonstrated a quasi-static load margin of +12.4. The robust design of the ALB made it a great match for Starshine 4.

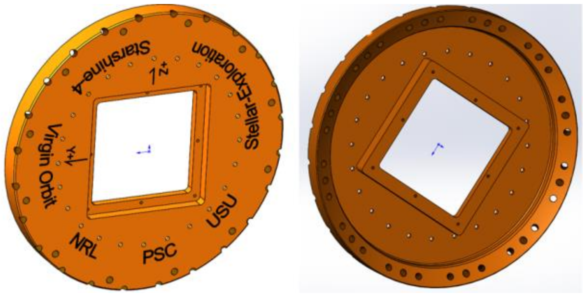

Figure 7: Interface plate to ALB

Figure 8: Starshine 4 with interface plate installed.

c. Removing Starshine 5 and all non-passive components.

Early in the program, engineers determined that Starshine 5 would not be part of the mission. The previous Starshine 4 design hosted the payload at its south pole. Removing the payload and replacing it with an interface plate was conceptually straight forward but required significant structural analysis. All other active components were removed. No batteries, wiring, connectors, fuel, or radioactive materials were a part of Starshine 4. Ballast masses were installed to replace the removed mass. Once fight loading was understood, the strength margin for all junctions was a minimum of +8. Recall that initially the spacecraft was designed and approved for manned flight on the Space Shuttle. Starshine 4 is a simple and robust structure. Occupying the open square space in the center of the interface plate (figure 7) was a small RFID tag developed under DARPA sponsorship. This device allowed the Space Fence radar to identify the satellite.

d. An ambitious schedule.

From revival to delivery, the entire Starshine 4 reboot took 8 months. The team of volunteers managed to redesign, reassemble, test, and deliver a functional assembly while also maintaining full time jobs. There were consistent unknowns throughout the design process as data from the new launcher was being updated and revised. An initial design with wide strength margins enabled the spacecraft to readily adapt to these moving targets.

e. Operating on a budget of zero.

A somewhat unique constraint to this program was the operating budget of zero. In addition to meeting a tight schedule, there was no budget to pay for parts, analysis, testing, shipping, or the launch. This forced an uncomplicated design as it became very easy to eliminate a feature if the cost was greater than 0. By boiling it down to only the essentials, the spacecraft was delivered on time and on budget. Additionally, many companies provided necessary services at no charge, remaining true to the ideals of Project Starshine. There is not enough space to share the gratitude of the authors for the time and efforts all those involved gave to the Starshine 4 mission.

IV. Testing to Verify Separation Dynamics

Starshine's name comes from the "twinkle" it creates while slowly spinning and reflecting the sun's rays back to Earth. This slow spin requires critical separation dynamics and a rotation rate of approximately 5.0 deg/sec to optimize terrestrial observation. Engineers designed custom spring assemblies to enable tip off rates to meet those required separation dynamics. Typically, verifying those dynamics is very challenging. By design, however, the ALB adapter enables low cost, efficient, and quickly repeatable testing.

The ALB uses compression spring assemblies to provide separation energy to the payload. These springs can be arranged and given specific energies to support a wide variety of separation dynamics including inducing a specific rotation rate about an axis. To meet Starshine 4's unique requirements, the ALB utilized three equally spaced separation springs with a single spring's stroke shortened to provide less energy. The other two springs acted in concert to create a moment, inducing the desired spin rate. The spring height could then be tuned until the final desired rate was achieved.

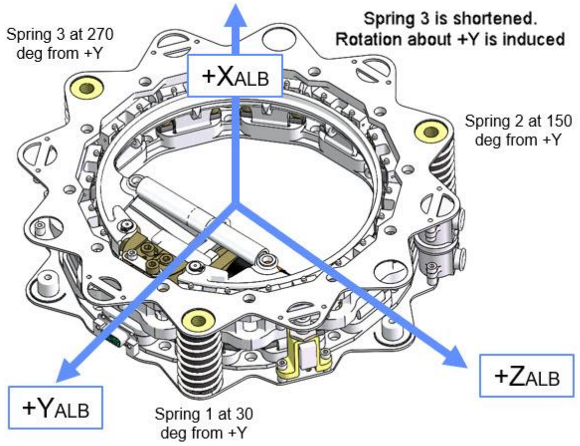

Figure 9: Inducing rotation with a shortened Separation Spring.

Rates were verified by executing two tests using a separation reliability test fixture located at PSC. The first test used a standard setup in which a model was used to simulate the satellite's mass, center of mass, and inertia. The second auxiliary test used the actual satellite. The test fixture was modified to accommodate a non-standard spherical payload. A custom printed bracket supported Starshine 4 and the inertial measurement unit (IMU) used to measure the rotational rates. This bracket enabled Starshine to translate on air bearings simulating zero resistive force. During the first test the spacecraft simulator was separated repeatedly and rotation rates about the desired axis were measured. The spring stroke was adjusted until the desired rate of approximately 5.0 deg/sec was met.

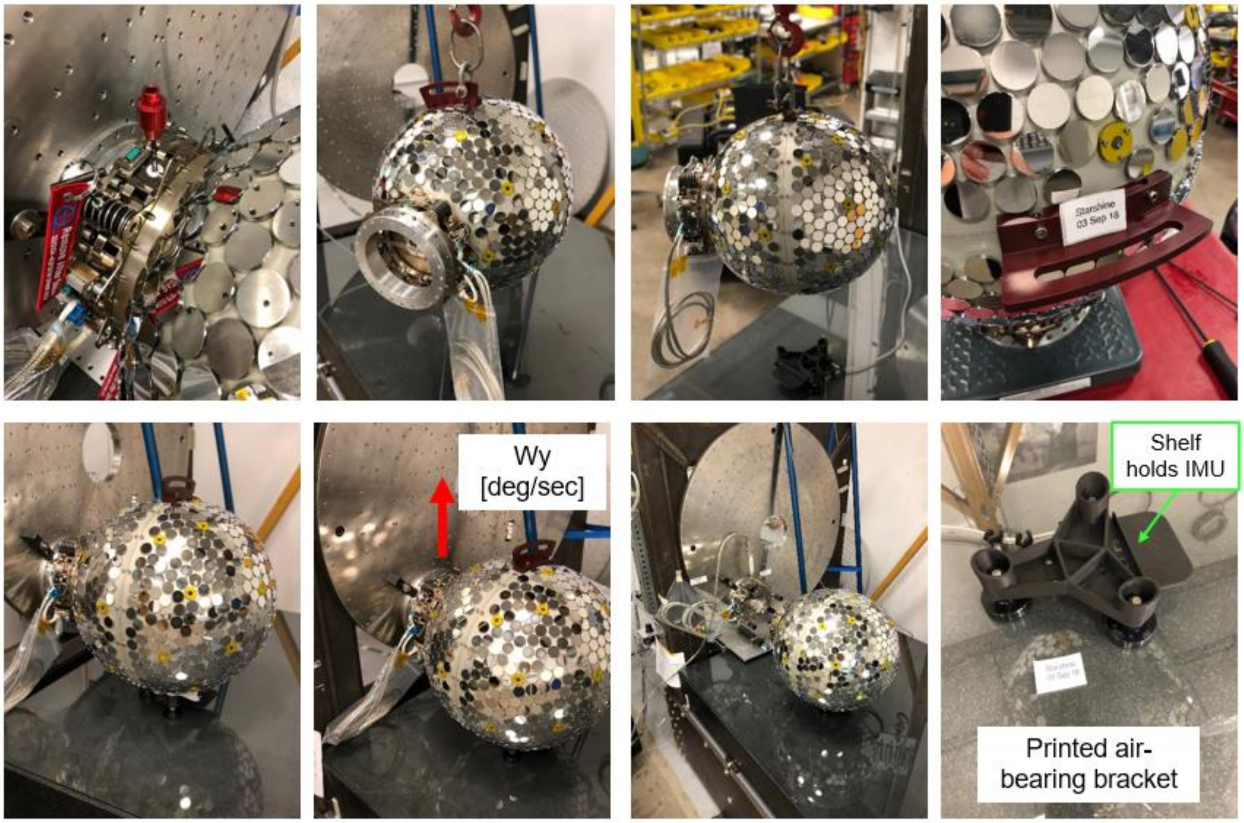

Figure 10: Auxiliary test setup to verify rotation rate about the Y axis.

Test results:

Table 2 shows the result of the standard test. By using a stack of six O-rings on spring number 3 located at 270 degrees, engineers were able to tune the rotation rate about the Y axis and thus the overall RSS rotational rate of the model. See figure 9.

	Flight Rotation Rates [deg/sec]	Flight DeltaV [m/sec]
Mean	5.84	0.861
Maximum	6.20	0.863
Minimum	5.43	0.860
Standard Deviation	0.31	0.001

Table 2: Flight prediction in flight configuration. The rotation rate is the magnitude of rotation about all three axes.

The maximum rate exceeds the flight allowable by 1.2 deg/sec in the standard test configuration. This corresponded to six O-rings under spring number 3. If only 5 O-rings were used to retard the energy of spring number 3, the flight rotation rate would be too low. The higher rate was chosen as slightly better because the spacecraft was known to slowly spin down on orbit due to eddy current dampening. The predicted flight separation velocity was 0.861 m/sec.

The second, auxiliary test predicted mean rotation rates to be 5.37 deg/sec about +Y in the flight configuration. This was a lower prediction than the Standard test, but the standard tests allowed rotation about the pitch and roll axis, which when RSS'd produced a higher mean of 5.84 deg/sec. This auxiliary test only allowed rotation about the +Y axis.

I. Lessons Learned from Shipping

Shipping a spacecraft anywhere and for any reason is non-trivial exercise. The shipping strategy must be sound and well considered to ensure hardware is not damaged. The shipping container must have a design as robust and reliable as the satellite itself. Unfortunately, there were precious few resources to focus on shipping for Starshine 4. A previous container was no longer sufficient due to changes to the satellite. Early on, engineers realized they could use the ALB system to fasten and constrain the space craft inside a shipping container. To add compliance, a set of cable isolators were installed in the base, in between the ALB mounting plate and the floor of the shipping container. Four straps were installed from each corner of the shipping container to a 3/8 threaded lifting eye located at the north pole. Cursory analysis was completed.

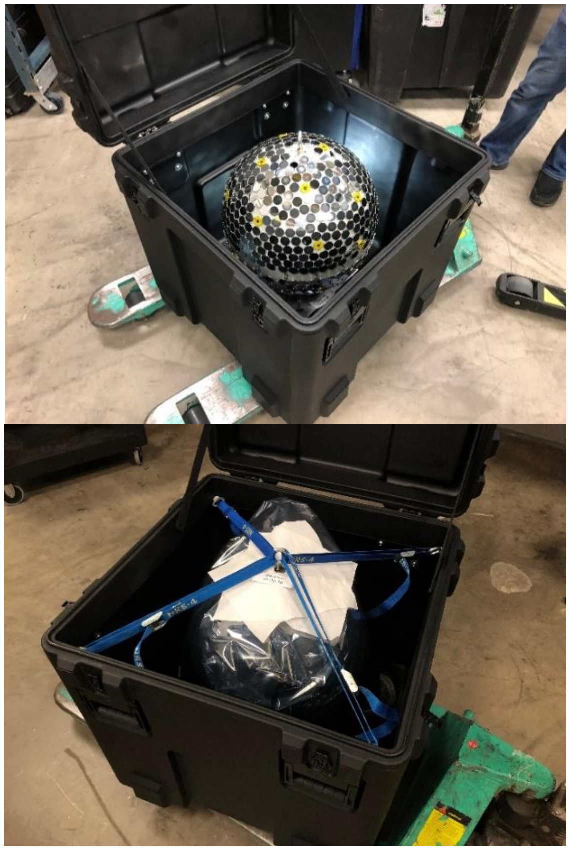

Figure 11: Starshine 4 shipping container.

Starshine 4 was shipped across the USA from Maryland to California. Upon arrival at destination it was discovered that the lifting eye had been extruded from the top of the satellite. A thorough investigation yielded fortunate results. The hemispheres were made from a ductile 6061-T0 and are manufactured by a process called spinning. Analysis demonstrated that 400lbs of loading would damage the lifting eye but that yielding was localized and no other bolted joints or mirrors were damaged. The damaged location was not part of the flight load path. However, there was no longer a method to lift the assembly from the top.

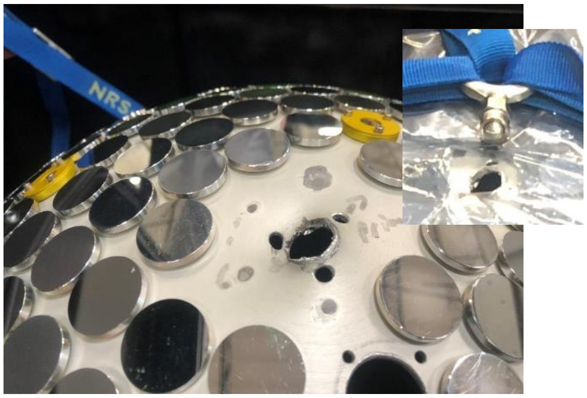

Figure 12: Starshine 4 lifting eye damage

Engineers rapidly designed and employed a field repair. A larger hole was punched out of the damaged area and a threaded lifting insert was installed and torqued. The process was tested and vetted prior to on site installation. Fortunately, the program was not seriously delayed and a low-cost reliable fix was applied. From experience, this was an atypical anomaly.

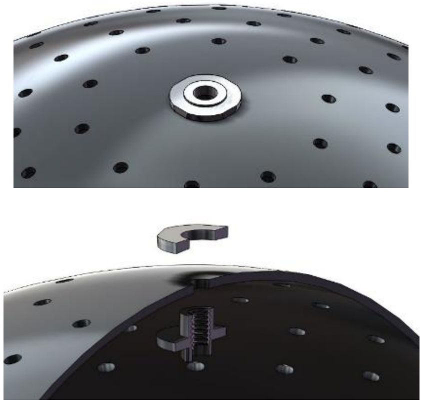

Figure 13: Starshine 4 field repair.

I. Integration and Launch

Starshine was initially manifested for launch not long after being shipped to the launch provider. This left only a few short months from delivery to launch date. The integration process was very carefully planned prior to execution. By using the ALB separation system, final integration took only a few hours on a single day (a remarkable feat in today's integration climate). The launch and integration team was subjected to a pre training and concept of integration operations at a previous date and PSC supported the integration.

Starshine 4 was air launched on LauncherOne's inaugural orbital launch on May 25th 2020 from Cosmic

Girl, the Boeing 747 host jet. Unfortunately, the rocket suffered a failure soon after main engine ignition and Starshine 4 did not make it into orbit. Although we were disappointed that Starshine 4 never reached operating orbit, the journey was rewarding and experience gained invaluable. The next Starshine satellite is already in the works.

Special Acknowledgements

Starshine 4 was realized by a team that goes well beyond the mentions within this paper. Without their valuable insights, resources, and commitment this project would have remained in storage. This list is far from complete as there are countless others who made meaningful contributions.

Dr. T.S. Kelso and Dr. David Vallado - Orbital mechanics leads. Verified Starshine 4's mission orbit while the specifics of such continued to be fluid and often times challenging.

Brookelynn Russey – Starshine 4 lead at Virgin Orbit. Without her efforts Starshine 4 would have been left without a launch opportunity.

Scott Heritsch – Starshine deputy director. Scott developed an app for tracking Starshine to enable observers from around the world to use their cell phones to collect data. A constant source of positive energy for the program.

Dr. Tomas Svitek – Developed and donated the RFID tag attached to Starshine 4. This novel technology may transform the way space objects are tracked and cataloged.

Steve Baran – Donated resources and skills to build Starshine 4 components at no cost to the program. Manufactured key parts after shipping damage to repair Starshine quickly while maintaining the highest quality.