

NASA's 5.5K Rotator

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The Balloon Program Office (BPO) desired a rotator designed explicitly for super pressure balloons (SPB), with a maximum suspended payload of 5,500 lbm, that was at least 25% lighter than the legacy rotator. The legacy National Aeronautics and Space Administration (NASA) rotator is a coarse azimuth pointing system for balloon payloads; it separates the rotation of the gondola from the balloon. Super pressure balloons have a maximum payload capacity lower than the NASA standard zero pressure balloons. Thus, reducing the mass of the legacy NASA rotator would allow more instrumentation to be added to an SPB payload. A broad overview of the development of the 5.5K rotator, which has successfully met the BPO requirements with a mass reduction of 34%, will be discussed.

I. Introduction

The legacy rotator is a standardized balloon flight subsystem mounted right above the payload (see Figure 1), and it separates the rotation of the gondola from the balloon. The rotator functions as a coarse azimuth pointing system for the payload. The rotator integrates with a balloon platform (see Figure 2) that flies in the stratosphere—at altitudes between 110,000 and 130,000 ft, which is above approximately 99.5% of Earth's atmosphere. The primary customers interested in incorporating the coarse-pointing system into missions include astrophysics and planetary science projects. The legacy rotator—known as the Solar Pointing System (SPS), Long Duration Balloon (LDB) rotator, or Rotator_96—was developed in the mid-1990s. It was designed to support a maximum payload of 8,000 lbm, withstand a 10G axial load, and the motor plus the avionics could not exceed 5 watts average continuous power draw.

In the mid-2010s, the electronics package, called Improved Rotator Azimuth Control Electronics (iRACE), was revamped. Modifications allowed the rotator flight software to integrate better with the Wallops Arc-Second Pointing (WASP) system. Improvements in the isolation of the rotator rate sensor from motor-induced chassis voltages resulted in significant tightening of the rotator pointing performance. The legacy rotator and 5.5K rotator use the iRACE avionics for controlling the azimuth pointing at float. The iRACE avionics use three different types of sensors to achieve within +/-2 degrees pointing capability:

- Eight solar sensors give absolute sun relative azimuth (+/- 5 degrees)
- a global positioning system (GPS) gives absolute true-north relative azimuth (+/- 0.1 degrees)
- an inertial rate sensor measures the angular rate with respect to an inertial reference frame (+/- 0.01 degrees/second).

In 2016, the Balloon Program Office (BPO) desired a rotator specifically for super pressure balloons (SPB), with a maximum suspended payload of 5,500 lbm, that was at least 25% lighter than the legacy rotator. SPBs have a maximum payload capacity lower than that of zero-pressure balloons (see Figure 3). Thus, reducing the mass of the rotator would allow more instrumentation to be added to an SPB payload. A lighter rotator could also be used on a zero-pressure balloon, which would provide scientists the option of either more instrumentation on the payload or a longer flight duration than a legacy rotator.

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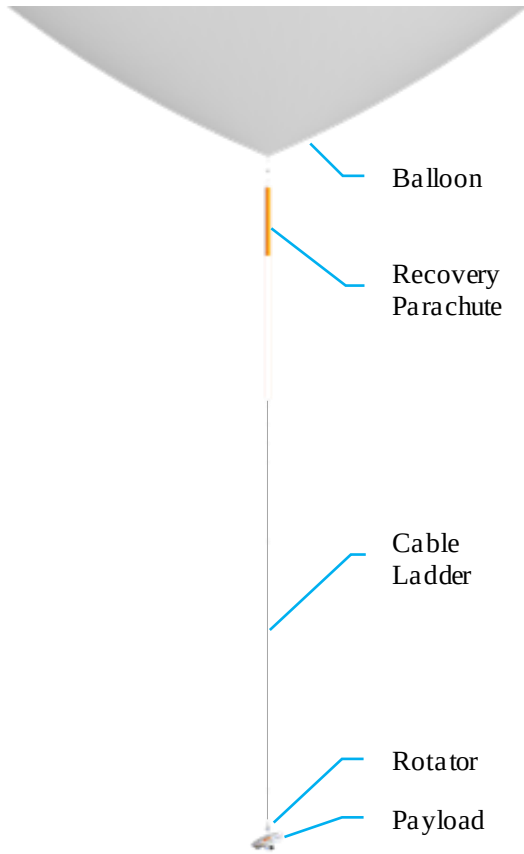


Figure 1:
Rotator Integrated in Flight Train

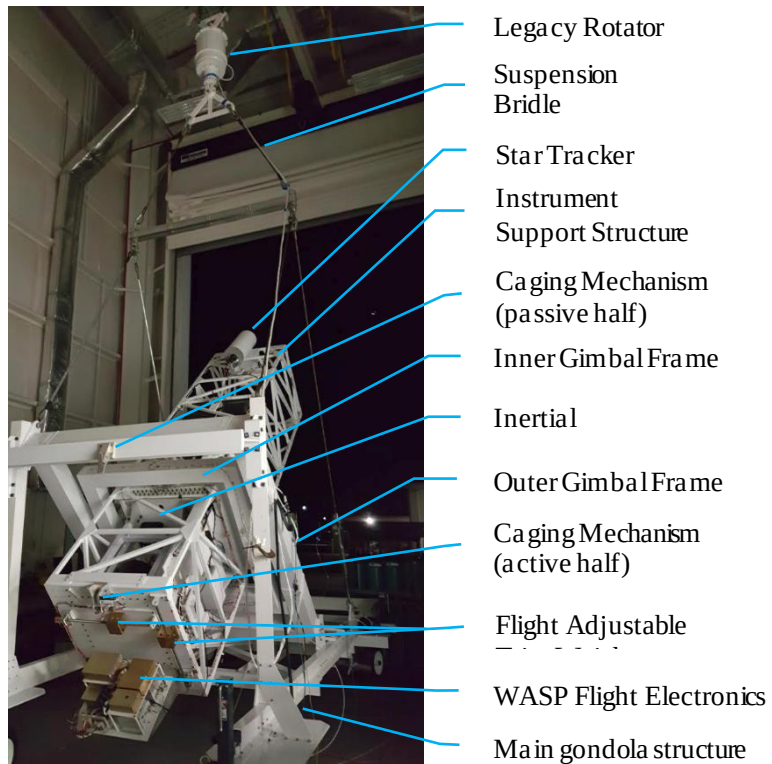


Figure 2:
Legacy Rotator Integrated on PICTURE-C Gondola



Figure 3:
Super Pressure Balloon (SPB) vs. Zero-Pressure Balloon

II. System Requirements

The 5.5K Rotator was intended to be a standardized coarse-pointing system for any balloon-borne platform with a suspended payload no greater than 5,500 lbm. The primary redesign considerations for the rotator included weight, reusability, cost-effectiveness, machinability, and ease of assembly. The goals and requirements of the system are listed in Table 1.

Two loading conditions were crucial to design considerations: loading during operation and loading at termination. The structure will experience 1G during operation, so the axial load is 5,500 lbf. The radial load was calculated using the load induced on the shaft from the motor during operation. At termination, the load factor of 10G is applied, making the axial load 55,000 lbf. The motor is turned off before termination, which makes the radial force 0. The 5G horizontal and lateral termination load factors are not applicable because the universal clevis joints mounted on either end of the rotator prevent bending loads from occurring on the shaft. In order for the system to be reusable, parts cannot exceed material tensile yield.

CSBF's "Structural Requirements and Recommendations for Balloon Gondola Design"² (Franco, 2013) [1] states that "close examination of all materials that have a percent elongation less than or equal to 10% at an ambient temperature of -60°C shall be made to determine if the material is to be considered brittle." Early in the design, no information was readily available on whether Ti-6AL-4V was considered brittle at -60°C. Thus, the designs were re-evaluated to satisfy a 1.5 load factor while the material was investigated further. Therefore, for analysis, the termination load increased from 10G to 15G. Later in the project, the materials used were determined not to be brittle at -60°C; thus, the unit was only tested to 10G.

Table 1:
5.5K Rotator Mechanical Design Requirements

Mechanical Design Criteria		Requirements/ Goal	Design
Maximum Payload	5,500 lbm	Requirement	Met
Satisfy Termination Load Factors	10G Axial		Met
	5G Horizontal at 45°		N/A
	5G Lateral		N/A
	1.4 SF if non-brittle, 1.5 SF if brittle (materials less than 10% elongation at -60 °C, upon consideration)	Requirements	Met
Reusable	Does Not Exceed Material Tensile Yield Strength	Goal	Met
Temperature Range	-80 °C to 50 °C (-112 °F to 122 °F)	Requirement	Met
Motor Power Draw	Daytime Average Does Not Exceed 3.5 W	Requirement	3W
Slip Ring	Minimum 20 Channels	Requirement	Met
Mass Reduction	Minimum 25%	Goal	34%

² Since the design of the 5.5K Rotator the "Structural Requirements and Recommendations for Balloon Gondola Design" has been superseded by 820-PG-8700.0.1 "Gondola Structural Design Requirements"

III. System Description and Updates

The legacy rotator (see Figure 4) weighs about 123 lbm, and the 5.5K rotator (see Figures 5 and 6) weighs about 81 lbm (a 34% mass reduction). Four major components were identified for mass reduction: a redesigned shaft, new bearings/bearing housings, new motor/motor housing, and Li-COR mounts.

Although all parts were designed to satisfy a 15G load, further research determined that all Ti-6Al-4V and Al 6061-T6 parts are ductile at -60°C and hence only need to satisfy a 10G load. Thus, all load-bearing parts have positive margins of safety. The tolerance fits of all parts were analyzed at the hot extreme of 122°F (50°C) and the cold extreme of -112°F (-80°C). All the fits were intended to be slip fits, except for the bearing housings, which were intended to be slip-fit at room temperature and interference-fit at the temperature extremes.

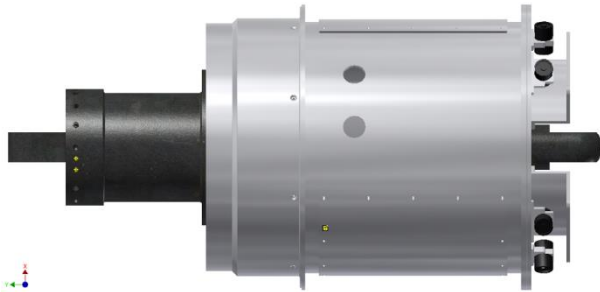


**Figure 4:
The Legacy Rotator**



**Figure 5:
The 5.5K Rotator**

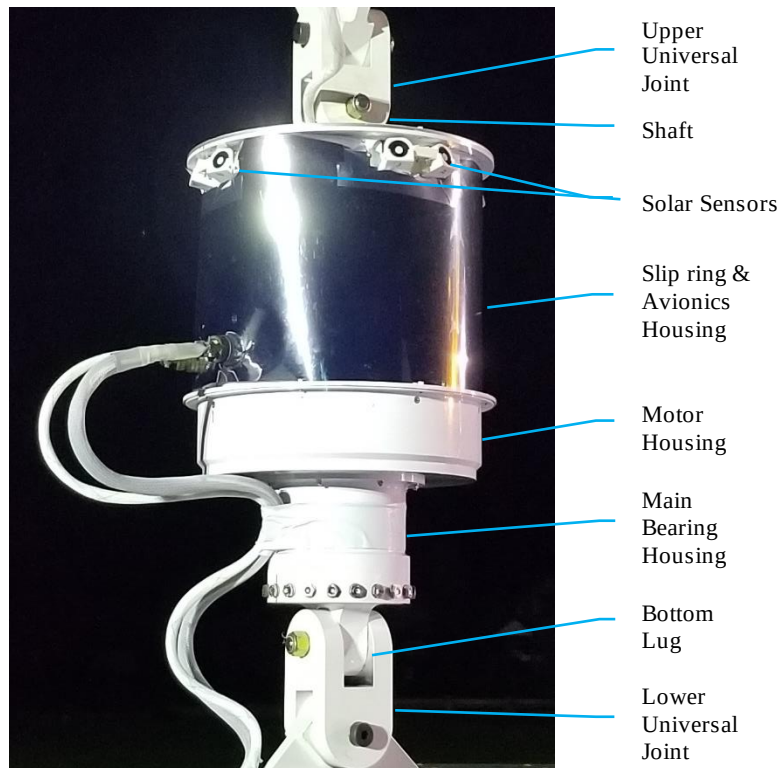


**Figure 6:
The 5.5K Rotator Integrated for a Test Flight**

A. Material Selection

The legacy rotator load path hardware was made of AISI 4340 steel, which is a very dense and heavy material with high strength. Additional materials were considered to find something that was lightweight, high strength, cost-efficient, durable, and functional at low temperatures (see Table 2).

Table 2:
Material Comparison (MMPDS-11) [2]

	AISI 4340 Steel	Aluminum 6061-T6	Aluminum 2024-T351	Aluminum 7075-T651	Ti-6Al- 4V	Ti-6Al-2Sn- 4Zr-2Mo
Density $\left(\frac{lb}{in^3}\right)$	0.283	.098	0.100	0.101	0.160	0.164
Ultimate Tensile Strength, F_{tu} (ksi)	260	42	62	76	130	125
Tensile Yield Strength, F_{ty} (ksi)	217	35	42	67	120	120
Young's Modulus, E (10^3 ksi)	29	10.1	10.7	10.3	16	16.5

Many iterations of the design were made with various grades of aluminum and titanium. The titanium alloy, Ti-6Al-4V, had the most strength while still saving weight compared to AISI 4340 steel. It is also one of the most common grades of titanium stock available. Thus, Ti-6Al-4V was selected for the load path hardware—shaft, bottom lug, and bearing housings—for the 5.5K rotator.

B. Design Updates

For a circular shaft, the shear stress induced by torque is directly proportional to the radius. So, a hollow shaft with the same cross-sectional area is and can resist more torque than a solid shaft of the same length and material. The original legacy rotator shaft is solid AISI 4340 steel and weighs 29.5 lbm. Iterative calculations were completed to compare and determine which cross-section of a hollow titanium shaft reduced the weight while maintaining stiffness in the structure. The 5.5K shaft is Ti-6Al-4V and weighs about 13.8 lbm, which is 53% lighter than the legacy shaft. Other minor design changes also made the shaft stronger. The bolt hole in the lug end of the shaft was updated to ensure that $\frac{e}{D} > 1.5$ to be conservative in shear or tear-out cases. There was an undercut radius on the collar of the shaft to ensure that angular contact bearings sat flat against the shoulder of the shaft. That undercut radius was increased to bear the load and dissipates the stress around that corner. A trade study was conducted to select a smaller and lighter motor that met the max power draw requirement—the shorter form factor motor also decreased the shaft's height.

The bottom lug and bearing housings were updated to make them lighter, resistant to corrosion, stronger, and easier to assemble the rotator. The legacy bottom lug and main bearing housing were made from AISI 4340 steel and weighed about 9 lbm and 8 lbm, respectively. The bottom lug was analyzed by hand and FEA to determine if it could be manufactured from a different material while still enduring a 15G load factor. Based on the analysis, a Ti-6Al-4V bottom lug and bearing housing would endure the 15G load, and each would weigh about 5.7 lbm, which is 37% and 29% lighter, respectively. The major bolt hole in the bottom lug was also updated to ensure that $\frac{e}{D} > 1.5$ to be conservative in shear or tear-out cases.

A trade study to select new bearings was conducted to support a smaller maximum axial force than the legacy rotator. The smallest double direction thrust bearing that fit on the shaft was deemed too heavy, so angular contact bearings were utilized for the 5.5K rotator. The dynamic load rating of bearings must be greater than or equal to the axial load to have a margin of safety ≥ 0 . The tandem and back-to-back orientation of the angular contact bearings support axial loads in both directions, increasing stiffness and load-carrying capacity. A deep groove ball bearing was also selected to support radial and axial loads in both directions in order to decrease the frictional effects induced on the shaft from the motor.

The objective of redesigning the sun sensor mounting assembly was to eliminate the upper sensor plate and crash shields and allow for a reduction of housing and shaft height. The new sun sensor mounts were 3D printed to reduce the number of parts required for assembly and reduce the overall mass of the assembly. The brackets that mount the avionics packages (internal) were also 3D printed to the curvature of the 5.5K rotator housing. Thus, the brackets for the 5.5K rotator were lighter weight and improved upon the isolation of the rate sensor from motor-induced chassis voltages, which aids in pointing performance.

IV. Path to Flight Qualification

Ground qualification of the prototype unit for a test flight included a tensile test, thermal test, and friction assessment test. The tensile test verified the strength of the load-bearing hardware. The thermal test ensured that the shaft would not bind under extreme environmental conditions. Finally, the friction assessment test verified the rotator performance. To flight qualify the 5.5K rotator for use on science missions, the system must complete three flight tests. The 5.5K rotator has successfully completed two test flights on zero-pressure balloons during the 2018 Fort Sumner (FTS) and 2019 FTS campaigns, respectively. The 5.5K rotator attempted to fly on the SPB test flight during the 2022 New Zealand campaign but did not get a flight opportunity. Thus, the 5.5K rotator is set for its third test flight attempt during the 2022 FTS campaign.

A. Tensile Test

The rotator and a digital displacement indicator were mounted inside the horizontal pull test machine for the tensile test (see Figure 7).

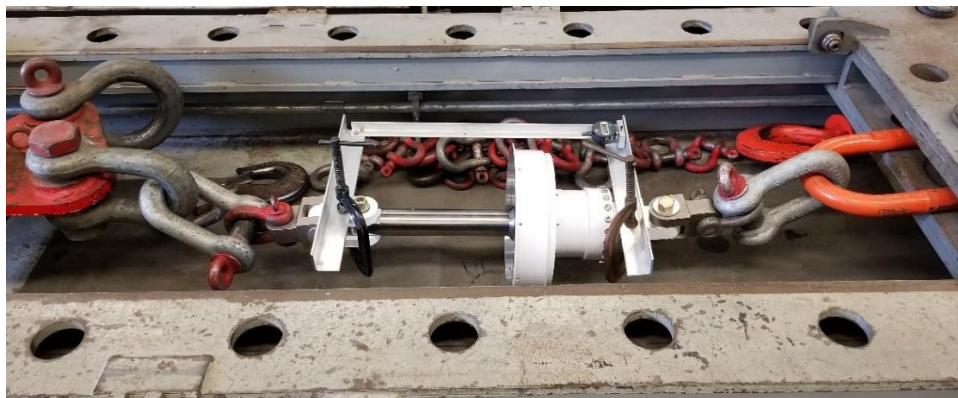


**Figure 7:
Tensile Test Setup**

The tensile test loaded the rotator to 55,000 lbf, or 10G, incrementally three times to observe displacement in the system. The maximum displacement at 55,000 lbf grew with each subsequent test. However, the overall displacement measured between the initial and final load decreased with each test (see Figure 8). The team postulated that the resulting displacement was due to bearing seating.

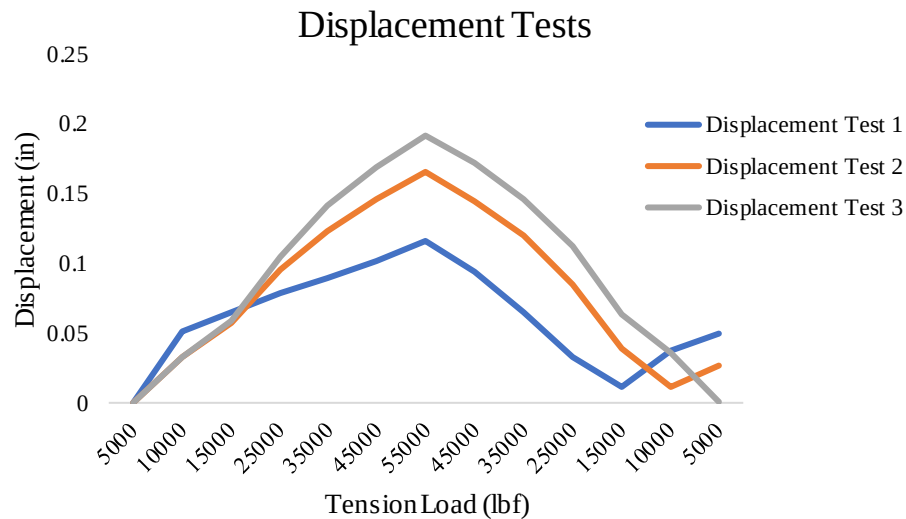


Figure 8:
Graph of Displacement Test Results

Then the test operator rapidly loaded the rotator, trying not to overshoot the 10G condition to mimic balloon termination. The peak load reached 56,590 lbf during the rapid tensile test (see Figure 9).

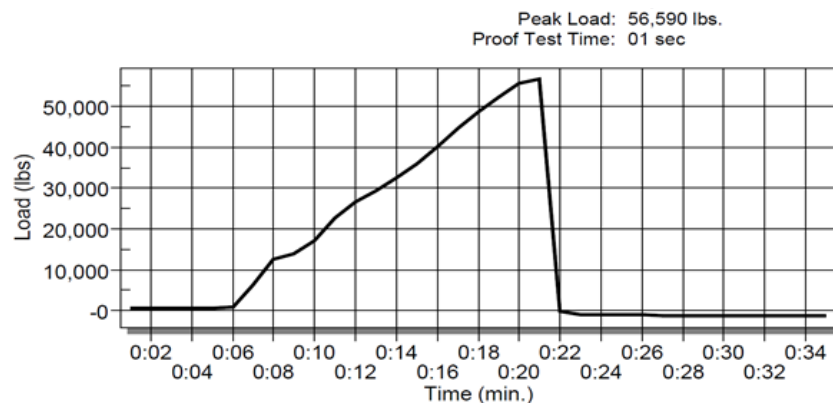


Figure 9:
Graph of Rapid Tensile Test Load vs. Time

After these tests, the hardware was visually inspected. There was no visible deformation or yielding on any of the hardware. The tensile test proved that the load-bearing hardware is capable of sustaining the specified 10G load.

B. Thermal Test

The thermal test loaded the rotator to 5,500 lbf via a universal testing machine (Instron 8500 series) inside a thermally insulated box (see Figure 10). The electronics and the slip ring were removed from the rotator assembly to prevent damage to flight avionics because they were not equipped with heaters. The thermal test measured the voltage and current required for the motor to overcome static friction at various temperature levels when under a 1G load.



Figure 10:
Thermal Test Setup in Instron Machine



Figure 11:
Thermocouples on the 5.5K Rotator

Thermocouples were taped to the bearing and motor housing with Kapton tape (see Figure 11) during the test to confirm if the rotator hardware was properly chilled at each temperature level prior to testing. After the thermocouples displayed the desired temperature level, the rotator chilled for an extra hour before measurements were taken. Operational checks were performed on the rotator loaded at 5,500 lbf at room temperature five times in each direction to establish a baseline of how much current draw and voltage input was needed to overcome static friction clockwise and counterclockwise. While maintaining the 5,500 lb loading throughout the duration of the test, the rotator was then cold-soaked at several temperature levels, including 0°C, -20°C, -40°C, and -60°C. The voltage and current inputs were recorded at each temperature level five times in each direction. The voltage and current inputs were used to calculate the power required to turn the shaft in each direction and at each temperature. As expected, the amount of power required to turn the shaft increased with decreasing temperature. The thermal test proved that the rotator did not bind at -60°C and remained within power requirements at all temperatures tested (see Figure 12).

CW vs. CCW Average Power to Overcome Static Friction

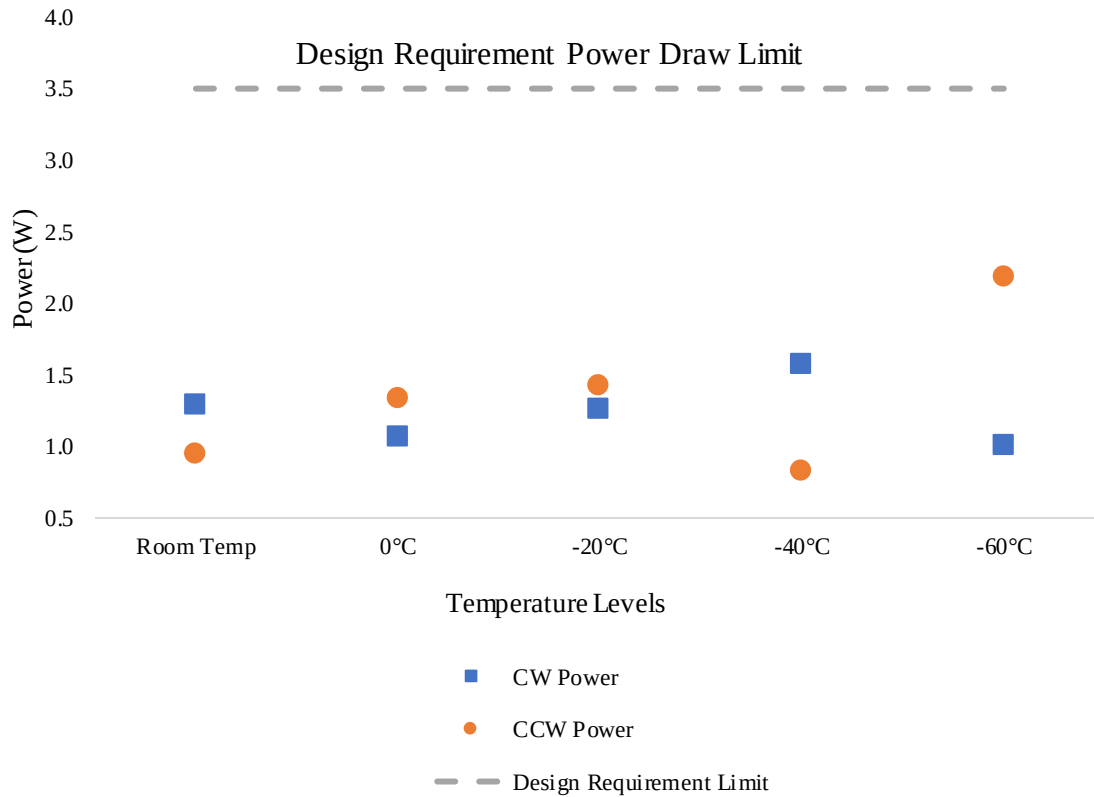


Figure 12:
Graph of CW vs. CCW Average Power to Overcome Static Friction

C. Friction Assessment Test

The friction assessment test (Figure 13) was a room-temperature performance verification test. The balloon simulator mimics the natural behavior of the balloon turning in flight. The flight train was much shorter in this test than for a real mission, but the parallel nylon straps provided comparable torque to a cable ladder. The weights suspended below the rotator serve as the 1G payload for the test. The weights, along with joints and fasteners, produced a total suspended test load of 5,565 lbm. The lamp simulated the sun. The eight solar sensors at the top of the rotator provided a 360-degree view around the 5.5K Rotator. When a pair of sensors was commanded to look at the solar simulator, the command was sent through the avionics packages on board to start the motor and turn the shaft until the sensors indicated that they were at the commanded position. Then the rotator held the payload at that position until commanded otherwise. Three functional qualities were investigated during the friction assessment test:

- Measured motor resistance test
- Static friction maximum and minimum torque clockwise and counterclockwise
- Kinetic friction average torque clockwise and counterclockwise

The measured motor resistance test verified that the DC resistance of the motor at room temperature was as expected. The test proved that the actual measured resistance in the motor is 24.9 ohms. The measured resistance is the slope of voltage versus current, $R = V/I$. The expected resistance was 25.5 ohms; thus, the motor is well within the manufacturer's specified tolerance of $\pm 12.5\%$.

Then the static and kinetic friction tests were conducted with and without the slip ring, with loads of 1,000 lbm and a little over 5,500 lbm. The tests determined that the torque to overcome static friction is load-dependent; more load means more torque required. Through hand calculations, the predicted torque to turn the shaft with a slip ring attached was about 3.2 ft-lb. During testing, about 3.5 ft-lb was observed to turn the shaft with that slip ring. The torque increased until it broke free of static friction, the system recovered for a period, and then it settled as it continued to turn (see Figure 7). Without the slip ring, the team observed less torque required to turn the shaft, as expected. The friction assessment tests proved that the 5.5K rotator performs as required for a 1G load.

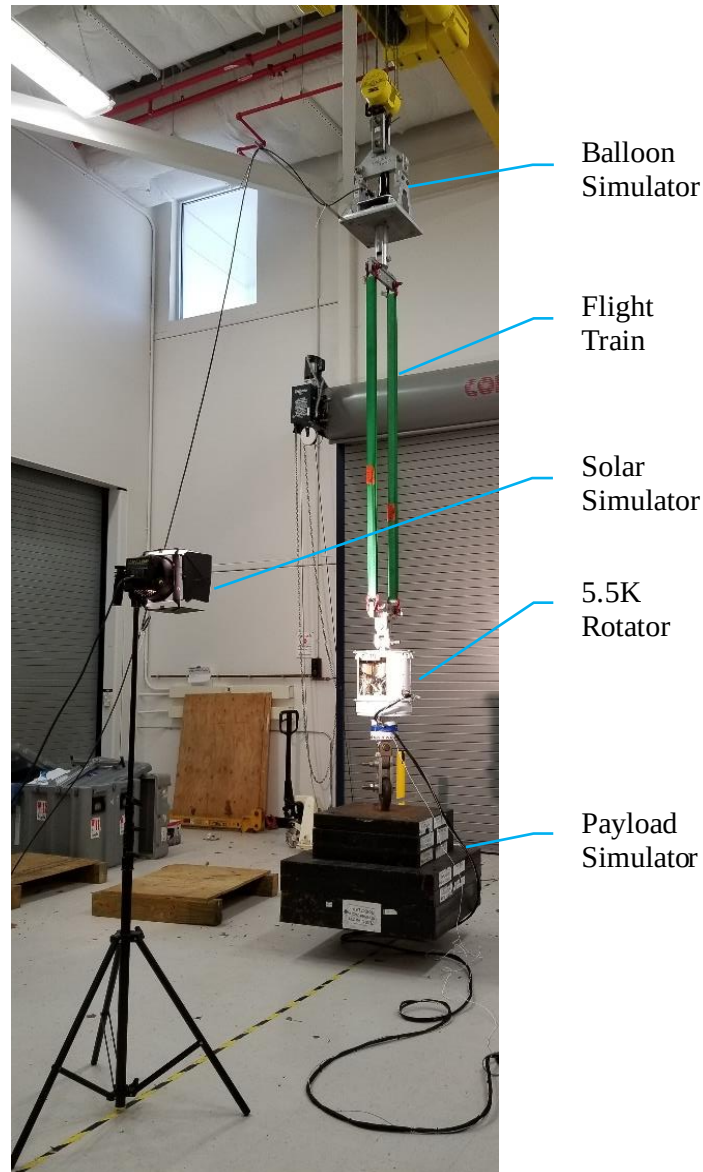


Figure 13:
Friction Assessment Test Setup

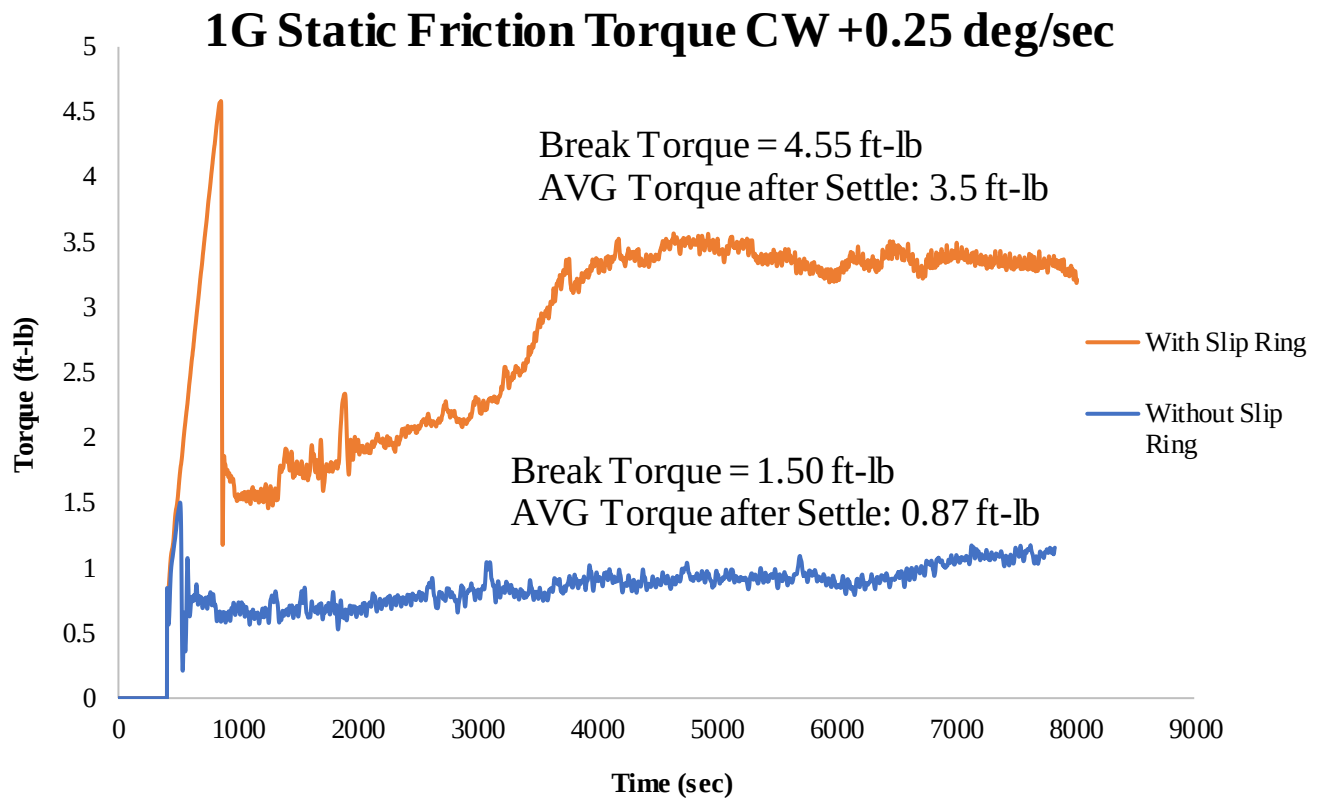


Figure 14:
Graph of 1G Static Friction Assessment Test

V. Conclusions

The purpose of redesigning the legacy rotator was to reduce the mass by at least 25% for a 5,500 lb maximum suspended payload. This redesign resulted in the 5.5K rotator, which is 34% lighter than the legacy rotator. This reduction is essential because scientists can now utilize 34% of the mass budget from the rotator for more instrumentation on the payload or longer flights (specifically for zero-pressure balloon missions). Additionally, the 5.5K rotator requires 20 fewer parts to purchase and assemble. After successfully completing a third test flight during the 2022 Fort Sumner Campaign, the 5.5K rotator will be fully flight qualified and become a standard system that BPO can offer our scientific partners. The light weighted 5.5K rotator directly benefits NASA's goal of learning more about our universe through balloon-born science missions.

Acknowledgments

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References

- [1] Franco, H. (2013) *Structural Requirements and Recommendations for Balloon Gondola Design*. Palestine, TX: Colombia Scientific Balloon Facility.
- [2](2016) *Metallic Materials Properties Development and Standardization (MMPDS)-11*. Battelle Memorial Institute.