Lessons Learned from the Flight Unit Testing of the Near Earth Asteroid Scout Flight System

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Abstract

The Near Earth Asteroid Scout flight mission is set to launch on the maiden voyage of the Space Launch System as a secondary payload. The spacecraft will be jettisoned in cis-lunar space and embark on an ambitious 2.5 year mission to image an asteroid. The spacecraft is uniquely equipped with an 85m^2 solar sail as the main propulsion system. The monolithic sail system is designed to package within a 6U volume for launch and then deploy during flight. The NEA Scout team has presented in the past to the International Symposium on Solar Sailing topics related to the engineering development unit and design efforts to achieve flight hardware build. This paper will focus on the lessons learned from building and testing the NEA Scout flight system. Focus will be on the mechanical, software, and electrical interfaces as well as preparation for subsystem environmental tests, including thermal vacuum. Due to the unique design of the spacecraft, the solar sail subsystem was required to be located in the center of the spacecraft. This requirement lead to design challenges such as designing and accommodating critical cable harnesses to run through the center of the sail subsystem, packaging and deployment design of the sail subsystem, and integrated testing efforts through an avionics test bed to verify and validate a complete system architecture.

Keywords: solar sail, deployer. software, thermal, volume, test

1. Introduction

The Near Earth Asteroid (NEA) Scout mission [1] uses a small, ~14kg spacecraft to image an asteroid while utilizing a monolithic solar sail for primary propulsion. The challenging and unique aspects of the mission are not limited to the solar sail. Perhaps, the greatest challenge was the development of a fully functional deep space spacecraft that can survive in interplanetary space for up to 2.5 years.

The NEA Scout solar sail posed many challenges in development [2] and yet more during testing. Deployment testing required a clean room large enough to accommodate the fully-deployed sail, a low-friction surface across which the sail would be deployed without sustaining serious damage, and a means to offload the effects of gravity on the long, flexible NEA Scout metallic booms. Fortunately, a suitable facility and deployment table were nearby and an inexpensive method for accomplishing partial gravity offset was accomplished using helium balloons.

The figurative explosion in CubeSat components for low earth orbital (LEO) missions proved that spacecraft components could be made small enough to accomplish missions with real and demanding science and engineering objectives. Unfortunately, these almost-off-the-shelf LEO components were not readily usable or extensible to the more demanding deep space environment. However, they served as an existence proof and allowed the NEA Scout spacecraft engineering team to innovate ways to reduce the size, mass, and cost of deep space spacecraft components and systems for use in a CubeSat form factor.

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2. Progress to Date

During the 4th International Symposium on Solar Sailing in January of 2017, the team presented the engineering development unit of the solar sail subsystem for NEA Scout [2, 3, 4]. The subsystem was in the midst of environmental testing to mature the flight hardware design. The planned tests included random vibration, thermal performance testing of the stepper motor, thermal vacuum testing, and deployment tests. Testing enabled design iterations that helped mature the overall system to flight quality through September 2017 [Fig. 1, 2, 3]. The flight unit integration began shortly thereafter with integration of flight ready mechanical and electrical piece parts. The team was able to integrate lessons learned from the engineering development unit build and completed the flight unit during the fall of 2018.

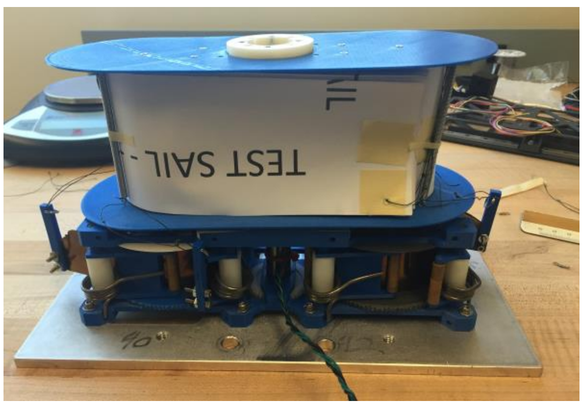

Fig. 1. NEA Scout additively manufactured prototype during initial design maturation activities.

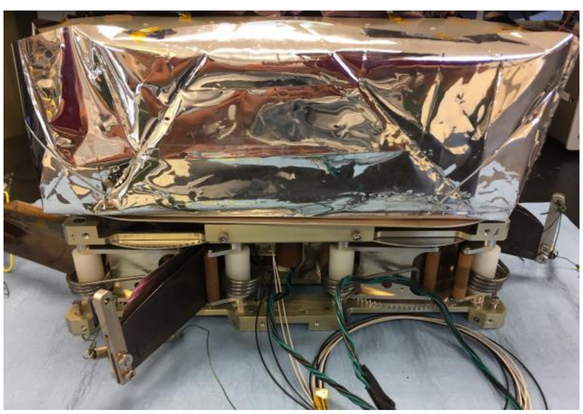

Fig. 2. NEA Scout solar sail deployer high fidelity engineering development unit, full scale with packaged monolithic solar sail.

Balance of personnel was a key challenge. NEA Scout is a small project managed by NASA Marshall Space Flight Center. The solar sail team was the same team that designed, developed, and built the active mass translator (AMT) for NEA Scout. Thermal lessons learned from AMT development activities were incorporated into the solar sail design. Due to personnel availability, the solar sail subsystem and active mass translator had to be built and tested in serial, which allowed ease in implementation of lessons learned from each design. However, this approach required retests and design modifications from one subsystem to another, which caused stress on the project schedule and available resources.

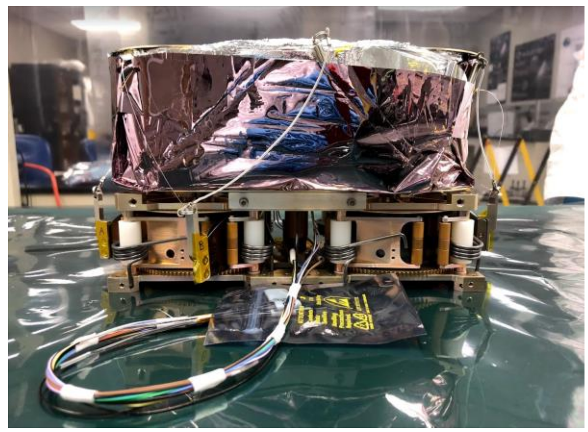

Fig. 3. NEA Scout flight unit assembled with packaged flight sail and flight cable harness.

Today, the solar sail flight unit is complete and awaiting integration into the spacecraft [Fig. 3]. The team is focused on testing and delivering the AMT flight system for spacecraft integration in late summer 2019. This paper will focus on the lessons learned from building and testing the NEA Scout solar sail flight system, with particular interest on the software and mechanical design lessons learned, and thermal design of the NEA Scout flight system.

3. Lessons Learned

3.1 Software

The solar sail deployer (SSD) is controlled through a custom designed motor controller board (MCB). The board runs software through a processor that manages deployment, temperature readings, power management, processes commands and telemetry, and fault management [Fig, 4]. The MCB software is an embedded element within the overall spacecraft flight software architecture. The spacecraft flight software architecture allows for the MCB software to be developed independent of the spacecraft, with dedicated integration tests and checkouts performed at the spacecraft level.

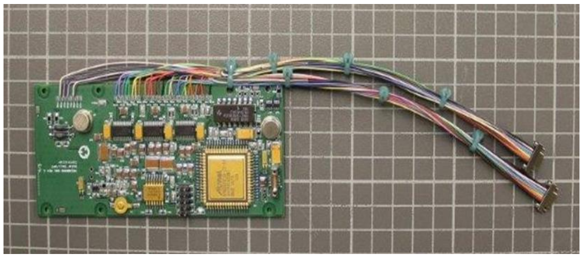

Fig. 4. Motor Controller Board with flight cable harness and micro-D nanoconnectors.

Software and electronics design issues closely pair and are either direct results of or responses to other issues observed in the hardware. The categories for the software and control board are divided into the following categories: (1) test bed and ground testing user interface and (2) accommodations for thermal limitations of the mechanisms.

3.1.1 Test bed and ground testing

The avionics system is designed, developed, and located at Jet Propulsion Laboratory (JPL) in Pasadena, California. The team needed to develop a local graphical user interface (GUI) to operate the engineering development unit (EDU) and flight motor controller boards. This provided an early on opportunity to involve the solar sail team with the flight software team. The teams had bi-weekly meetings to help understand and align development activities happening at the same time.

The flight system team at JPL established an avionics test bed (ATB) for development testing of the spacecraft design. The ATB simulated the spacecraft flight computer and major components with flight-like hardware and software. Two MCBs were developed: one for test and development at MSFC, and second for test and development with the ATB at JPL. As the solar sail team updated software for the MCB, the MSFC team would coordinate with the team members at JPL to update the avionics test bed. Coordination of release dates and test activities were critical to maintain project schedule and produce consistent test results.

The team developed an interface control document that captured the software design and requirements between the spacecraft flight software and the motor controller board. The MCB was considered a secondary software component within the overall flight software architecture. This meant that the motor controller board could be run autonomously through the flight computer via scripts and run with direct contact with the ground during flight operations.

However, the GUI developed by the solar sail team was not the same GUI the flight software team was using to develop the spacecraft flight software. This caused difficulties during software testing with the avionics test bed at JPL. The solar sail team highly recommends future teams use consistent GUIs and flight software team members, even if the systems are being developed in two separate locations at the same time. Co-location is key with software teams, which improves communication and shortens schedule during troubleshooting and testing.

3.1.2 Accommodations for thermal limitations

The solar sail team learned the importance of integrating mechanical requirements into the software functionality early in the project. Subsystem level thermal vacuum testing exposed the lack of fidelity produced by the thermostat chosen for EDU testing. The thermostat generated a large amount of noise, thus degrading the quality of temperature readings during the test. The MCB was designed to pause the operation of the stepper motor once the temperature sensor on the boom deployer reached operational temperature limits. The MCB did stop the operation of the stepper motor; however, the temperature readings oscillated between above and below the operational temperature limits. With visual observations, the deployment was not smooth and continuous; instead, it was jerky and slow.

The fix was to widen the operational temperature range to account for the noise generated by the thermostat. The flight unit MCB had a higher quality thermostat planned for use. The project originally went with the lower fidelity thermostat for the EDU to save cost and schedule. Due to the experience working with the EDU thermostat, the team was prepared to handle any noise generated during thermal testing and was able to hone into the correct output. During flight thermal vacuum testing, the team was able to test up to the operational limits of the hardware successfully.

3.2 Mechanical

The greatest area of lessons learned was in the mechanical design. These lessons came in quick succession and impacted project schedule due to process complication, hardware failures, and workarounds. Lessons learned categories for the mechanical systems will be discussed in the following categories: (1) Obsolete boom selection; (2) monolithic sail design; (3) flight system layout and interfaces; and (4) mechanism telemetry and status. Even with the four separate topics of focus, each issue and design solution generation had the potential to affect the system as a whole. The team remained cognizant of potential cascading effects that could negatively impact the performance of the system.

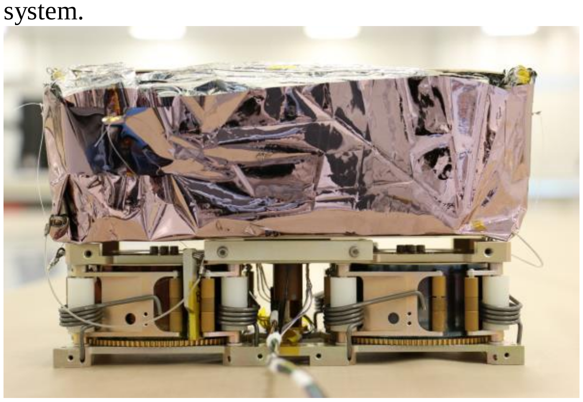

Fig. 5. As-tested solar sail deployer

3.2.1 Obsolete Boom Selection

The structure that deploys and supports the sail consists of four stainless steel booms attached at the root within the spacecraft. The booms were selected during a trade study in 2015, when Technology Readiness Levels (TRL) for other designs and materials were considered low. The project had a recommendation of selecting manufacturing proven and flown designs. Stainless steel booms have flown on a few sail missions, including the NEA Scout predecessor, Nanosail-D, with success [6]. With flight heritage and analyzed TRL level of 6, the team selected the same Triangular, Rollable and Collapsible (TRAC) stainless steel booms as Nanosail-D, instead of alternatives evaluated at the time [11]. In the time since the selection and build of the EDUs and flight units, other technologies have shown clear superiority in stiffness per unit mass, thermal stability, and durability.

During a weeklong study of the 6.8m TRAC boom design, the team determined and quantified numerous failure modes for a metallic TRAC boom design. These modes were reduced to a few causes: (1) weak root conditions allow the boom to kink and collapse during deployment; (2) strain energy in the spooled booms produce blooms during deployment, requiring retraction of the spool to prevent binding; and (3) metallic booms are susceptible to damage near welds if tight bends are formed [Fig.6].

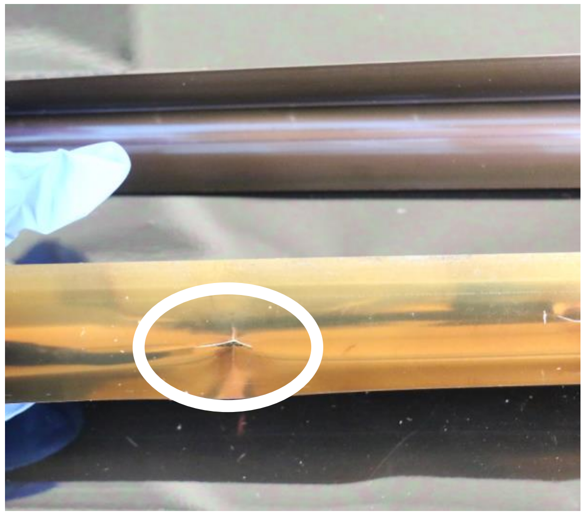

Fig. 6. Damage to TRAC boom observed during handling due to improper bending.

Composite booms could reduce the sail system mass by about 1 kg and the team could allocate about 400 grams of that mass to double the thickness of the sail, which would reduce risk of sail damage during manufacturing, spooling, testing and flight deployment.

The team recommends to future missions to consider a composite boom designs. Composite booms require a larger boom cross section, as compared to stainless steel booms. However, the savings are captured by the reduced deployment system mass and require less structure to contain the strain energy and overcome friction during storage and deployment. Furthermore, to address the weak boom root, future designs should consider trading added complexity to strengthen the root conditions by adding small deployable structures to help form the boom cross section and constrain the root.

3.2.2 Monolithic Sail Design

The TRAC booms must remain shaded at all times. Thermal and structural analysis showed that the 6.8m booms could deform near 1 meter out of plane if exposed to sunlight due to differential heating over the boom cross section [3]. To prevent the thermal effects distorting the boom shape, the team moved from the original quadrant sail design to a monolithic sail [Fig. 7]. The booms are position behind the sun-facing side of the solar sail. The sail material is able to block the boom from direct sunlight and removes the thermal distortion.

Fig. 7. Deployed NEA Scout monolithic solar sail.

The monolithic sail design required a different approach to manufacturing, folding, and stowage within the spacecraft. When compounded by the ultra-thin sail—about 2.5 microns thick—the manufacturer required 6 weeks to refold after all deployment tests and an additional week to spool. By comparison, smaller sail missions have observed sail folding and stowing process on the order of hours. Permanent creases to ease folding were discouraged to promote a smooth, uniform surface to maximize thrust performance [4].

3.2.3 Flight System Layout and Interfaces

The implementation of a single sail complicated the sail spool design, sail folding scheme, and boom tip interfaces. The sail had to unfold and deploy such that the booms were producing a congruent force across all four boom tips and unwound the sail from a spool rather than pull it from a cavity. The spool spins passively during deployment around a central spindle that also serves as the cable harness pass through and structural backbone that connects the reaction control system to the boom deployer [Fig. 8]. This spool position complicates spacecraft integration. The spool will need to be integrated early in the spacecraft assembly process without the ability to be removed or replaced. Access to the sail spool post spacecraft integration would require a de-integration of the spacecraft. Put simply, once the sail is integrated, it cannot be removed.

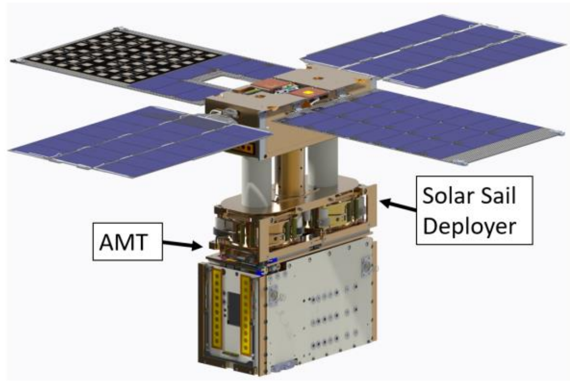

Fig. 8. CAD rendering of the integrated NEA Scout spacecraft.

Initial spacecraft design did not account for the relationship between the center of mass (CM) and sail center of pressure (CP) by placing the sail system near the center of the spacecraft. This design choice early in the project development process had significant complication to the guidance, navigation. and control systems and necessitated a new mechanism to control and reduce disturbance torques. At program infancy, the design required the sail to reside in the middle of the vehicle. Previously published papers have discussed the relationship between NEA Scout's CM and CP and how that problem was addressed with a system called the Active Mass Translator [9, 10, 12].

The team advises any future sail mission to place the sail system on an external interface near the anti-sun side of the vehicle to optimize sail stability, ensure a power-positive safe mode, and simplify integration processes. The sail system should include CP altering devices such as vanes or variable reflective membranes or larger reaction wheels to address small disturbance torques or attitude adjustments. The team had to design the sail system to handle the vehicle structural loads while also allocating volume for harnessing to pass through the center of the sail interfaces and volumes [12].

3.2.4 Sail System Health and Status

Deployment status and health data for all stages of deployment and flight including boom length deployed, motor health, photograph capabilities of sail quadrants and feedback from all restraint and/or locking mechanisms. Though the team observed consistent shape functions during sail deployment, photographs could confirm the 1G vs zero-G deployment assumptions and help future missions understand how sails behave during the deployment process [Fig. 9].

The deployer has one source of telemetry during deployment: an optical sensor counting boom spool revolutions. This is helpful to know when the system has completed deployment and can give an alert if a deployment is stalled. A motor encoder could be used to count motor revolutions and the control board and software should have features to read motor current, resistance, and/or voltage to determine coil temperature and torque demand. The data points would allude to elevated motor temperatures, show elevating friction or torque demands, and perhaps determine if a retraction or pause is required.

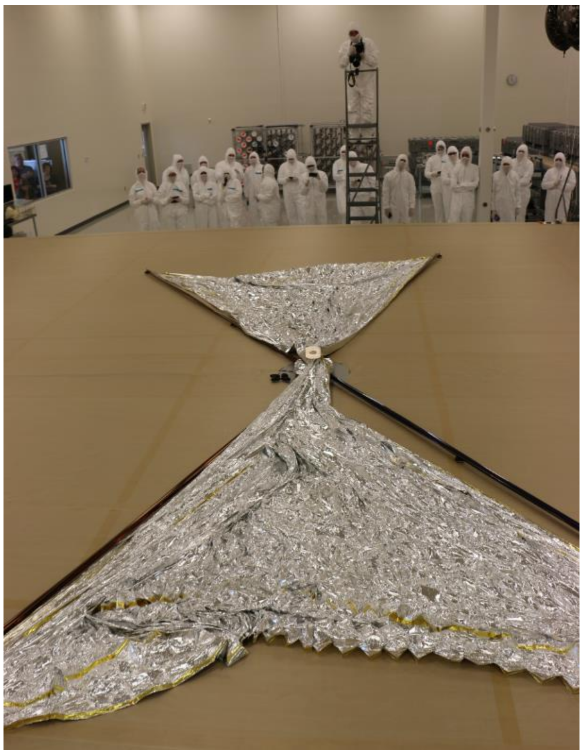

Fig. 9. Observed shape during ground demonstration of sail deployment.

The NEA Scout stepper motor was chosen due to the torque output and ability to fit within the volume constraints of the subsystem [Fig. 10]. The system requires about 3 in-lbs of torque to deploy and about 7 in-lbs to retract. Though much of this is due to the metallic booms and friction forces, the team suggests sizing motors an order of magnitude higher than required for the sake of durability and robustness. The NEA Scout deployer motor, at 15 mm, produces about 9 in-lbs with our board inputs. This small margin does not meet NASA mechanism standards, but the team simply did not have the volume to accommodate a 22 mm motor with a larger transmission.

An added benefit of a larger stepper motor is the motor detent can serve as a locking mechanism. The initial deployer design included a burn wire mechanism to retain booms during launch. After component testing and observations during random vibration testing, the burn wire mechanism was removed from the subsystem. The team observed during random vibration testing the detent of the motors were able to lock the booms in place, thus removing the need for a redundant locking feature.

Fig. 10. Approximate sizes of qualified flight (top) and unqualified stepper motor.

3.3 Thermal

Design deviations from assumed properties in the thermal model to the as-built properties on the flight hardware was the biggest lesson learned while completing analyses and correlating models. These changes in the assumed properties lead to components exceeding their maximum Allowable Flight Temperatures (AFT). Exceeding these temperatures can lead to subsystem failure that negatively impact the spacecraft's ability to complete the mission. The systems that caused the most concern are the Reaction Control System (RCS) and the Medium Gain Antenna (MGA).

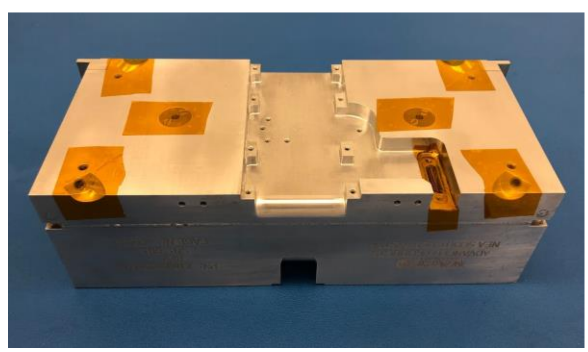

Fig. 11. Flight reaction control system.

The RCS is the cold gas propulsion system located on the bottom of the spacecraft. For the majority of the two year mission, the RCS is Sun pointing at angles that can vary from 0-70° to the Sun depending on the phase of the mission currently being performed. The RCS is coated in an alodine aluminum finish and the optical properties were originally assumed to be α: 0.2, ε: 0.11, α/ε: 1.81. Once a coupon of a similar metal and surface finish were provided by the vendor to be measured by the materials group at MSFC, it was noted the optical properties were actually α: 0.45, ε: 0.12, α/ε: 3.75. This is a two times increase to the α/ε which means that these surfaces will absorb two times more heat from the Sun, which lead to the RCS being above the maximum survivability temperature.

To improve the optical properties of the RCS surfaces, silver Teflon tape was chosen to be applied on the sides of the RCS. The silver Teflon tape decreases the α/ε to 0.115 which increases the radiative capabilities of the heat drastically and keeping the RCS within the allowable temperature range. The 0.010in thick tape will not be applied to the bottom because of concerns that the spacecraft would exceed its allowable volume within the launch vehicle dispenser.

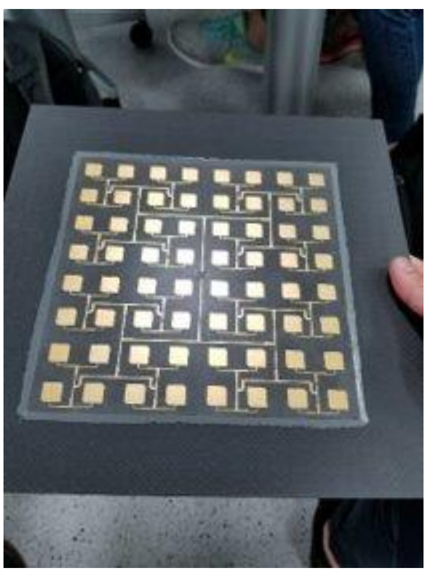

Fig. 12. Medium gain antenna on composite substrate.

The MGA is mounted to one of the solar arrays of the spacecraft. The MGA and solar panels were exceeding their minimum AFT limits during some of the colder phases of the mission. This was deemed to be due to the optical properties that were assumed for the MGA. The MGA is approximately 55% of the total surface area of the solar panel, the temperature of the panel is sensitive to the optical properties of the MGA. The MGA was assumed to be Kapton, which has a high emissivity and low absorptivity. For performance reasons the radio frequency radiating surfaces were not coated with the Kapton, and instead the optical properties are based on the underlying materials. The change in optical properties from designed to as-built for the MGA increased the α/ε by 6 times, which increased the predicted minimum temperatures within the AFT range.

The lessons learned from these problems are to check any property assumptions made early in the analysis process. Any optical property should always be verified through testing. Especially alodine that might be exposed to the Sun, as it is the process of alodining that can cause variations in the optical properties. Always account for beginning of life (BOL) and end of life (EOL) properties with any material that is being used. Solar degradation can lead to a decreased performance of your radiator surfaces which increases the temperatures of your components. The less assumptions that are in the analysis, the greater confidence can be found in the results.

4.0 Conclusion

In conclusion, the team has successfully delivered the solar sail flight system to the project for spacecraft integration. The primary lessons learned in software, mechanical design, and thermal analysis were critical to delivery.

Utilization of an avionics test bed and engineering development unit controller boards assisted in the team gaining better understanding and confidence in the system performance during benchtop and system level testing. Coordination between the flight software and solar sail teams helped ease integration of the solar sail system into the overall spacecraft flight software architecture.

Location of the sail system in the overall configuration of the spacecraft was key to minimize adverse effects caused by the displacement between center of pressure and center of mass. Alternative materials to stainless steel and cross section shape can impact the type of sail that needs to be utilized: quadrant vs monolithic. Composite booms and process-simplifying quadrant sails can reduce the mass of the sail system by at least 25%.

Thermal analysis indicated the importance of aligning the analytical assumptions to the as-built hardware. This impacted coating and tape selections that could adversely affect the overall dimension and performance of the spacecraft. Even though the medium gain antenna and reaction control system are separate subsystems, their thermal properties can greatly impact the needed performance of the solar sail during flight operations.

NEA Scout will be the first interplanetary CubeSat to image and characterize a near earth asteroid, combining the proven capabilities of solar sail propulsion with critical science needs. The team is excited to move forward with the spacecraft integration and test phase of the mission and is on track to deliver for launch on the inaugural flight of the Space Launch System.

Acknowledgements

The authors of this paper would like to sincerely thank the NEA Scout Solar Sail Working Group for their expertise and guidance, the NEA Scout Management for their continuous support through technology setbacks and progress, and NASA Advanced Exploration System for their unwavering support for the solar sail.

The authors would also like to thank the NASA MSFC Environmental Test Laboratory, NASA MSFC Space Systems Department, NASA Engineering and Safety Center, Lightsail and MaRCO project teams, Jet Propulsion Laboratory, and NeXolve Holding Corporation.

References

[1] McNutt, L.; Johnson, L.; Clardy, D.; Castillo-Rogez, J.; Frick, A.; and L. Jones. "Near-Earth Asteroid Scout." AIAA Space 2014 Conference; 4-7 Aug. 2014; San Diego, CA; United States.

[2] Russell Lockett, T.; Few, A.; Wilson, R.; "Near Earth Asteroid Scout Engineering Development Unit Program." 4th International Symposium on Solar Sailing; 17-20 Jan. 2017; Kyoto, Japan.

[3] Stohlman, O.; Loper, E.; Lockett, T.; "Temperature-Driven Shape Changes of the Near Earth Asteroid Scout Solar Sail." 4th International Symposium on Solar Sailing; 17-20 Jan. 2017; Kyoto, Japan.

[4] Heaton, A.; Ahmad, N.; Miller, K.; "Near Earth Asteroid Scout Solar Sail Thrust and Torque Model." 4th International Symposium on Solar Sailing; 17-20 Jan. 2017; Kyoto, Japan.

[5] Les Johnson, Julie Castillo-Rogez and Jared Dervan, "Near Earth Asteroid (NEA) Scout: NASA's Solar Sail Mission to A NEA," 68th International Astronautical Congress, Adelaide, Australia, 2017.

[6] Alhorn, Dean, Joseph Casas, Elwood Agasid, Charles Adams, Greg Laue, Christopher Kitts, and Sue O'Brien. "Nanosail-d: The small satellite that could!." (2011).

[7] Sobey, A; Lockett, T. "Design and Development of NEA Scout Solar Sail Deployer Mechanism." 43rd Aerospace Mechanisms Symposia; 4-6 May 2016; San Jose, CA; United States.

[8] Few, A., Lockett, T., Wilson, R., Boling, D., "Testing and Development of NEA Scout Solar Sail Deployer Mechanism" 44th Aerospace Mechanisms Symposia; 16-18 May 2018; Cleveland, OH; United States.

[9] Few, A.; "Development of a High Performance, Low Profile Translation Table with Wire Feedthrough for a Deep Space CubeSat." 43rd Aerospace Mechanisms Symposia; 4-6 May 2016; San Jose, CA.; United States.

[10] Few, A., Lockett, T., Wilson, R., Boling, D., "Testing and Maturing a Mass Translating Mechanism for a Deep Space CubeSat" 44th Aerospace Mechanisms Symposia; 16-18 May 2018; Cleveland, OH; United States.

[11] Murphey, T. W.; and J. Banik. "Triangular Rollable and Collapsible Boom." The United States Of America As Represented By The Secretary Of The Air Force, assignee. Patent US 7895795 B1. 22 Oct. 2007.

[12] Few, A.; "Development of a High Performance, Low Profile Translation Table with Wire Feedthrough for a Deep Space CubeSat." 43rd Aerospace Mechanisms Symposia; 4-6 May 2016; San Jose, CA.; United States.