

Near Earth Asteroid Solar Sail Engineering Development Unit Test Program

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The Near Earth Asteroid (NEA) Scout project is a 30x20x10cm (6U) cubesat reconnaissance mission to investigate a near Earth asteroid utilizing an 86m² solar sail as the primary propulsion system. This will be the largest solar sail NASA will launch to date. NEA Scout is a secondary payload currently manifested on the maiden voyage of the Space Launch System in 2018. In development of the solar sail subsystem, design challenges were identified and investigated for packaging within a 6U form factor and deployment in cis-lunar space. Analysis furthered understanding of thermal, stress, and dynamics of the stowed system and matured an integrated sail membrane model for deployed flight dynamics. This paper will address design, fabrication, and lessons learned from the NEA Scout solar sail subsystem engineering development unit. From optical properties of the sail material to folding and spooling the single 86m² sail, the team has developed a robust deployment system for the solar sail. This paper will also address expected and received test results from ascent vent, random vibration, and deployment tests.

Key Words: TRAC Booms, sail deployment, deployer, optical properties, tests

1. Introduction

NASA Marshall Space Flight Center (MSFC), in partnership with NASA Langley Research Center and the Jet Propulsion Laboratory is currently invested in developing the NEA Scout solar sail subsystem (Figure 1) by leveraging experience with the technology demonstration mission called Nanosail-D, launched in 2010. The 3U cubesat Nanosail-D, deployed a 10m² quadrant sail in low Earth orbit.

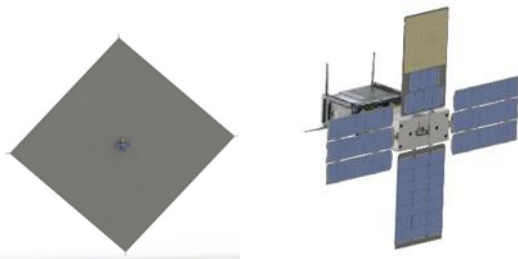


Fig. 1. Near Earth Asteroid (NEA) Scout deployed sail configuration (left) and flight unit (right). Credit: NASA, Jet Propulsion Laboratory

This paper addresses the engineering development unit test program that expands previous testing performed on solar sail systems to date. Past programs focused on packaging and demonstrating sail deployment capabilities; this test program seeks to verify and validate the system to survive launch conditions and in-space deployment environments prior to flight hardware build.

2. Design and Fabrication

The solar sail team developed an incremental approach to evolving the deployer mechanism design for the solar sail. The solar sail deployer design is based on the single spool deployer used on Nanosail-D, a 3U cubesat designed and built at NASA MSFC (Figure 2).



Fig. 2. Early Prototype of TRAC boom deployer, single spool

The Nanosail-D team leveraged Triangular Rollable and Collapsible (TRAC) boom technology from the Air Force Research Laboratory (AFRL) and manufactured by Mantech NeXolve Corporation at a length of 2 meters each. The booms deployed a four quadrant, 10m² solar sail from a 1U form factor. The NEA Scout flight mission utilizes the same TRAC boom technology on a larger scale: 86m² solar sail with four 6.8m booms deployed from a 2U form factor.

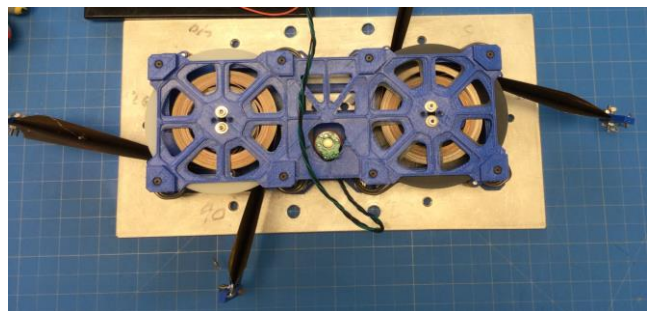


Fig. 4. 3D printed boom deployer, full scale, 4m TRAC booms

To demonstrate the design going from a 1U form factor to 2U, the incremental approach went as follows: 1) prototype dual deployer spool; 2) 3D print dual deployer spool (Figure 3); 3) deploy half-scale sail with 3D printed spool; and 4) build flight-like, full-scale spool for environmental testing and deployment. The move from 1U to 2U came from the necessity of fitting four, 6.8m TRAC booms into the 2U form factor without violating the volume constraints on the system (Figure 4). Placing two booms on each spool allowed the system to stay within the 2U form factor.

The team manufactured a 36m², half-scale mylar sail. The mylar sail had the same thickness, 2.5 microns, as the designed flight sail and behaved similar to the sail to be manufactured for flight. The flight sail will be made from Colorless Polymer-1 (CPI) Polyimide, a high performance elastic membrane with vapor deposited aluminum for reflective properties.

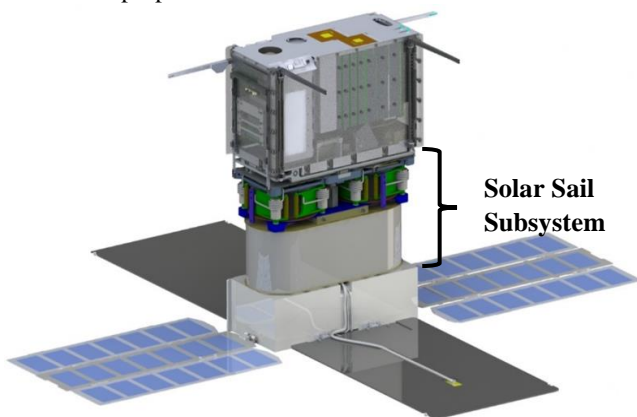


Fig. 4. Solar sail flight system is confined to ~2.5U volume

The team utilized rapid prototyping tools to build the first sail deployer for deployment testing. Mantech NeXolve Corporation (Huntsville, AL) manufactured several four meter TRAC booms for development activities and provided them for initial deployment procedures. The first deployment took place in December 2015 in the Flight Robotics Laboratory Flat Floor at Marshall Space Flight Center (Huntsville, AL). The Flight Robotics Laboratory Flat Floor enables air-bearing technology to allow free movement around the surface of the floor.

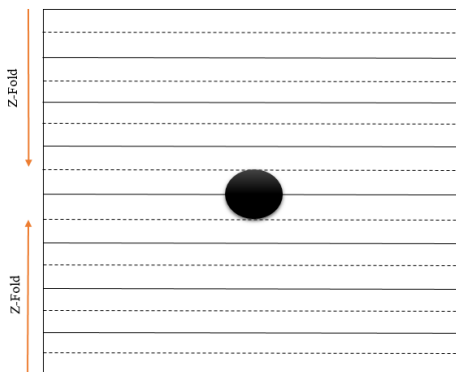


Fig. 5. 36m² mylar sail during the folding process

The team had a 36m² mylar sail built by team members from NASA Langley Research Center (Hampton, VA). The

team used the sail to develop a new approach to folding a single sail configuration (Figure 5). The team would fold along the length of the sail in a Z pattern to the center hole, then repeat the same fold pattern on the other side of the sail until it met the middle. (Figure 6) The two folds would meet together and then spool up on a single spool (Figure 6). The sail would deploy from the four corners by being pulled out with the booms.

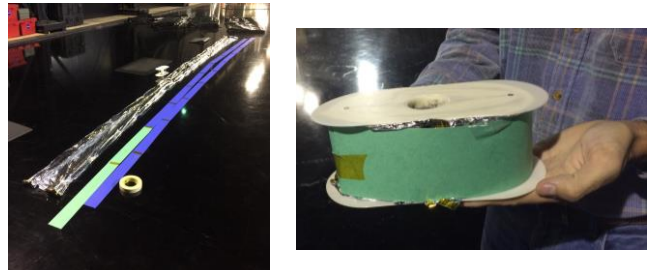


Fig. 6. 36m² mylar sail folded (left), spooled (right)

3. Engineering Development Unit

The engineering development unit (EDU) is the as-built, flight-like replica of the solar sail deployer, sail spool, four TRAC booms, and 86m² CPI solar sail. Due to the project schedule and time restraints, the EDU serves as the lead test article prior to flight hardware build. The test article is slated to undergo several environmental and functional tests to correlate analysis models, perform risk reduction activities, verify some subsystem requirements, and finalize the flight design.

The deployer is designed to push the TRAC booms out of the center of the spacecraft and pull the sail off of the sail spool. It is the only active component of the sail deployer system; the sail spool rotates freely while the booms pull the sail (Figure 7). The boom deployer consists of two hubs with two TRAC booms wrapped around each hub. The booms are deployed outward, 90deg of each other.



Fig. 7. Demonstration of sail unspooling during deployment

The EDU design is updated based on lessons learned during manufacturing and environmental testing. All changes will be incorporated into the flight unit. The EDU test suite consisted of reflectivity of the CPI material, half scale deployments, functional tests, ascent vent, random vibration, thermal vacuum, and full scale deployments.

3.1. Optical Tests

Optical performance of the CPI material manufactured by NeXolve (Huntsville, AL) was key to verifying the thrust model used to predict the overall sail performance during the

mission. The guidance and control team were interested in the overall reflectivity and diffusivity of the sail material. The team developed an optical test plan to examine the optical properties of the sail material. Multiple coupons were manufactured from the CP1 stock used to manufacture the EDU sail.

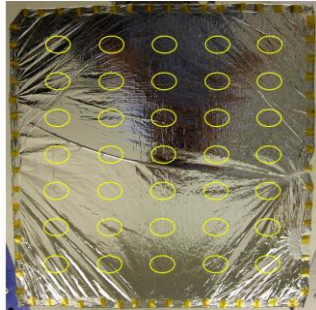


Fig. 8. Sample CP1 material for optical tests with targets

Three optical samples were developed for testing: a pristine sample, a seam plus ripstop sample, and a corner design which included the catenary and compliant border design. The goal of the test was to measure the reflectivity and diffusivity of the sail material in the three main regions of the sail: outside the catenaries, the catenary and compliant border area, and the center of the sail (Figure 8). All three areas experience independent stresses in the sail material which could impact the overall sail performance.

The results of the test sail coupons determined that the CP1 reflectivity varied due to variability in the thickness of the vapor deposited aluminum, approximately on average 900 angstroms thick, manufacturing defects, and wrinkles. Macro wrinkles were defined as large wrinkles >10cm and micro wrinkles were defined as wrinkles between 5-10cm in size. Nano wrinkles were less than 5cm. The test determined the presence of wrinkles in the sail membrane will not degrade overall sail performance but must be accounted for as a sail performance knockdown when performing mission design analysis.

3.2. Ascent Vent

The solar sail EDU was subjected to the expected ascent vent profile of the Space Launch System Engineering Mission-1 (SLS EM1) at the Marshall Space Flight Center Environmental Test Laboratory.

The ascent vent test determines the survivability of the sail system in a launch-like environment. The survivability of the sail material with rapid depressurization and removal of air was the purpose of the test. The solar sail dimensions were measured prior to the start of the test and afterwards. The solar sail relaxed after the removal of the protective cover for transport. The sail relaxed a few inches prior to the start of the test.

Movement occurred in the first part of the test, prior to the depressurization due to the relaxation of the sail from the spool, post protective cover removal. Video of the sail shows minimal movement during the depressurization portion of the test. Afterwards, the sail was measured to have relaxed to 2 inches on each side, outside of the sail spool (Figure 9).



Fig. 9. Sail spool during ascent vent testing (left) and post evaluation (right)

The test engineers determined the effects of gravity and lack of compressive force from the protective cover pushed the sail outside the sail spool. Tightening of the sail restraint would prevent the sail material from creeping outward.

3.3. Random Vibe Part I

The solar sail EDU was subjected to the estimated launch environments predicted from the Space Launch System and Tyvak dispenser system dynamic envelope environments. The test was performed in the MSFC Environmental Test Laboratory. At a minimum, the team decided to test the unit to workmanship levels plus 3dB for margins. The unit underwent random vibration about each axis: X, Y, and Z.

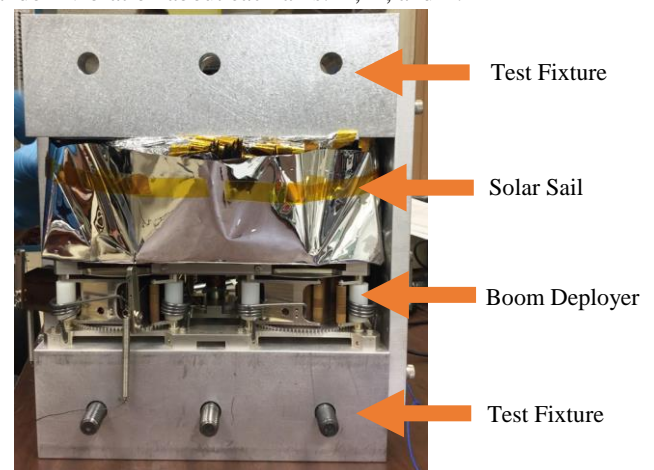


Fig. 10. Solar sail EDU in the random vibe test fixture

The length of the protruding booms were measured before and after each axis of random vibration.

The random vibration test yielded positive results. Upon initial inspection, the entire unit survived random vibration with no structural damage. The results indicated an unanticipated damping detected. The team theorized that the coiled booms dampened some of the vibrations during the tests. This was observed by the booms moving inward between each axis of vibration by a fraction of an inch. The cantilevered motor and small sensor brackets all survived the test without damage. The motor was able to demonstrate a full boom deployment afterwards during the functional test.

3.4. Random Vibe Part II

The Active Mass Translator (AMT) and solar sail EDUs are planned to be integrated for the combined random vibration test. Due to the small mass and interface constraints of the AMT, the team decided to combine the random vibration tests

to capture estimated launch conditions in a simulated launch configuration. The test will focus on the interface between the AMT and solar sail boom deployer and focus on the implementation of deployer tabs to reduce the launch loads traveling through the AMT system. The test will be conducted in early December and initial results will be included in the presentation material during the symposium (Figure 11).

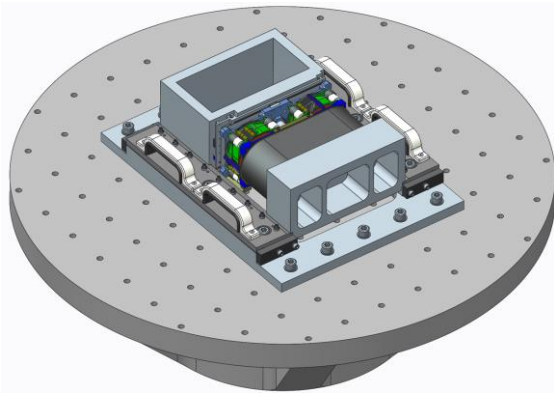


Fig. 11. Solar sail EDU in the random vibrate test fixture

3.5. Thermal Vacuum

The solar sail subsystem EDU will undergo flight-like thermal conditions during boom deployment operations in the Large Chamber located in the Environmental Test Laboratory at Marshall Space Flight Center. The test will go from -70°C to 70°C with partial boom deployments at ambient, cold soak, and hot soak points. The motor will perform a limited deployment and retraction of the booms due to chamber size constraints at each temperature point for 30 minutes to fully exercise the motor capability.

Initial tests on a bench top demonstrated the motors ability to continuously deploy and retract the booms for 5 hours straight. This initial test also examined any potential damage to the booms during the test. It was concluded that the motor and booms would be able to perform the limited deployments with minimum impact to the system performance. The test is scheduled to be performed in mid-December and results will be included in the presentation material during the symposium.

3.6. Deployments

A 36m^2 mylar sail was built to vet the initial process to fold, spool, and unspool the solar sail. In late 2015 and early 2016, the 36m^2 sail was deployed twice with 4m TRAC booms, manufactured by Mantech NeXolve Corporation. The first deployment was completed at the Flight Robotics Laboratory Flat Floor at Marshall Space Flight Center. Air bearings were used to help simulate a frictionless environment in the x and y directions during deployment. The mylar sail was able to deploy 2/3 of the way until the motor stopped working. The team concluded the motor was undersized for the test deployment.

With a larger output torque stepper motor, the second half scale test was performed in a different facility. The test was conducted on the basketball court of the Marshall Space Flight Center Athletics building and furniture movers were placed

on the booms as they deployed to reduce the friction between the booms and the floor. The mylar sail was able to fully deploy without booms buckling. This was the first successful deployment of the solar sail system.

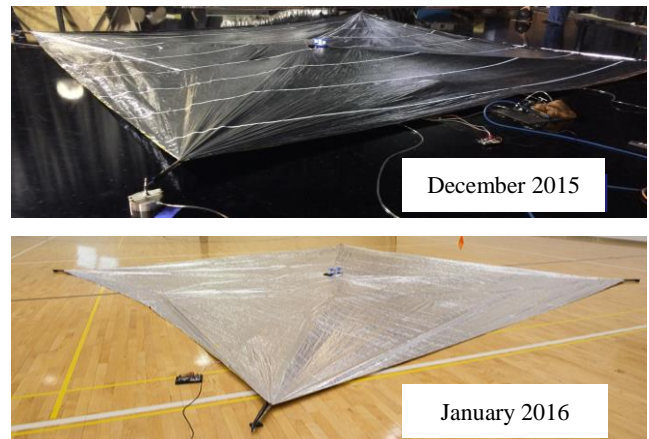


Fig. 11. 36m^2 mylar sails: December 215 (top), January 2016 (bottom)

In the summer of 2016, the full scale mylar and CP1 sails were deployed at the Flight Robotics Laboratory Flat Floor at Marshall Space Flight Center. In lieu of air bearings, the team moved forward with the furniture mover equipment and test set up as the half scale deployment performed on the basketball court. However, during each deployment a single boom buckled during each deployment. The team is in the process of completing a fishbone analysis of the possible causes of the boom buckling. The top issues identified were the static friction between the floor and the sail material, the lack of gravity off-load devices, and the booms manufacturing features that weakened their performance. The deployments are scheduled to be performed in mid-December and early January. Results will be included in the presentation material during the symposium.

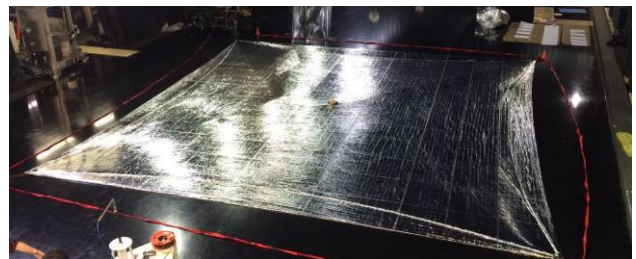


Fig. 12. 86m^2 CP1 sail deployed post deployment in August 2016.

4. Conclusion

Full scale system testing on the ground is the optimal way to demonstrate system robustness, repeatability, and overall performance on a compressed flight schedule. To physically test the system, the team developed a flight sized engineering development unit with design features as close to flight as possible. The test suite included ascent vent, random vibration, functional deployments, thermal vacuum, and full sail deployments. All of these tests contributed towards development of the final flight unit.

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