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Near Earth Asteroid Scout - Mission Update

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ABSTRACT

After its deployment from NASA's Space Launch System (SLS), the Near-Earth Asteroid (NEA) Scout mission will travel to and image an asteroid during a close flyby using an 86m^2 solar sail as its primary propulsion. Solar sails are large, mirror-like structures made of a lightweight material that reflects sunlight to propel the spacecraft. The continuous solar photon pressure provides thrust with no need for the heavy, expendable propellants used by conventional chemical and electric propulsion systems. Developed by NASA's Marshall Space Flight Center (MSFC) and Jet Propulsion Laboratory (JPL), the NEA Scout is based on the industry-standard CubeSat form factor. The spacecraft measures 11 cm x 24 cm x 36 cm and weighs less than 14 kilograms. Following deployment from the Space Launch System (SLS), the solar sail will deploy, and the spacecraft will begin its 2.0 – 2.5-year journey. About one month before the asteroid flyby, NEA Scout will search for the target and start its Approach Phase using a combination of radio tracking and optical navigation and perform a relatively slow flyby (10-20 m/s) of the target. A summary of the mission, sailcraft, mission design, and its first several months of deep space operation will be described.

INTRODUCTION

The NASA Near Earth Asteroid (NEA) Scout will demonstrate the first use of a solar sail propelled spacecraft to perform an interplanetary science mission. Solar sails have the potential to provide high ΔV for many types of missions. Solar sails are large, mirror-like structures made of a lightweight material that reflect sunlight to propel a spacecraft. The continuous solar photon pressure provides thrust with no need for the heavy, expendable propellants used by conventional chemical and electric propulsion systems.

The solar sail is based on the technology developed and flown by the NASA NanoSail-D2 in 2010. Funded by NASA's Exploration Systems Development Mission Directorate (ESDMD) and managed by NASA MSFC in partnership with JPL, the NEA Scout mission will be launched on the first flight of the Space Launch System (SLS), Artemis 1, in 2022.

Originally conceived to provide a low-cost survey of a candidate asteroid for a future human visit, the NEA Scout has evolved into a science-driven mission that will study one of the smallest NEAs, and the smallest ever visited by a spacecraft.

The NEA Scout uses a 6U CubeSat form factor, developed by JPL, to house a fully functional, though miniaturized, interplanetary spacecraft. The complete NEA Scout spacecraft bus measures 10 cm X 20 cm X 30 cm and weighs less than 14 kilograms. It is propelled by an 86 m^2 solar sail described in more detail below. The asteroid observations will be achieved using a JPL-provided camera that will observe the asteroid during a close (< 1 km) flyby.

The spacecraft will be placed on an Earth escape trajectory by the upper stage of NASA's SLS during its first flight in 2022. The primary mission for the flight is a test of the Orion crew capsule, which will be sent into a lunar flyby before it returns to Earth. Within the upper stage are 10 6U CubeSats with their own unique mission requirements. After the Orion is on its way to the Moon, the CubeSats will be deployed, one by one, from the SLS.

The NEA Scout will be tumbling after ejection, and the onboard attitude control system will use cold gas thrusters to stabilize the spacecraft and provide ΔV sufficient for a lunar flyby. Next, its solar panels and antenna will deploy to allow communication with Earth and to recharge the batteries, as needed. After checkout, the solar sail will deploy, and the transfer mission will begin.

MSFC, in partnership with NeXolve, developed the solar sail propulsion system and the guidance, navigation, and control (GN&C) algorithms needed to control it during flight. Supported by JPL for mission design and navigation, mission operations will be controlled at NASA MSFC.

MISSION SCIENCE

Objectives

The NEA Scout science objectives are about retiring strategic knowledge gaps for the future exploration of NEAs with a crewed mission.[1] These gaps include the NEA position, global size and regional morphology, rotational properties (spin period, spin position, and spin state), local environment (dust, debris within 10 radii of the target), and characterization of its regolith properties via photometric observations over various phase angles), as shown in Fig. 1. These observations drove the imaging resolution (ground sampling distance) to be 40 cm on a near global scale and 10 cm over about 30% of the surface. This information would be used by a crewed mission to plan safe and cost-effective operations. Characterization of a NEA a few tens of meters across would complement our sampling of NEAs and potentially shed some insights into their internal properties (monolithic or rubble pole). Physical and rotational properties also inform planetary defense strategies. The recently release Planetary Science and Astrobiology Decadal Survey (NASEM 2022) recommends a rapid response NEA mission.

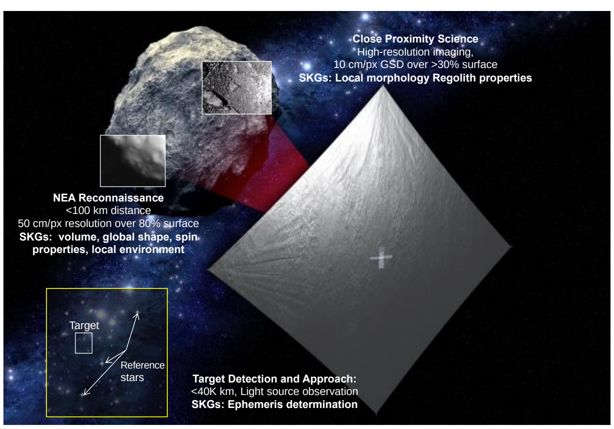

Figure 1: Main science observations to be performed by NEA Scout at a small (5-20 m) NEA.

NEA Scout's target has changed along with the shifting Artemis-1 launch window. Thanks to the vast increase in ground-based facility capabilities over the past 10 years and support from NASA's Center for Near Earth Objects (CNEOS) and the Very Large Telescope (VLT), at least one accessible target has continuously been available. To be "accessible," an NEA position needs to be known within ~3000 km 1-sigma and encountered at a distance less than 1 AU from Earth, due to telecom limitations. An additional filter gives preference to targets that can be encountered with a relative velocity of the order of 10 m/s and under a phase angle between 5 and 25 deg. to ensure enough light and shadows.

The NEA Scout target, as of Spring 2022 is called 2020 GE. It is less than 20 m across. Its rotation properties are unknown, but it is likely to be a fast spinner (order of 1 rpm), as generally observed for small NEAs.

Instrument Selection and Heritage

NEA Scout flies a low resource but high-quality camera (NEACam). It is based on the design of the OCO-3 [Orbiting Carbon Observatory] context imager on-board the International Space Station but is qualified for deep space with the addition of a latchup board. [2] NEACam is only ~0.5 U, ~0.5 kg and uses about 3 W peak power. An important feature of NEACam is its CMOS detector with a large ~14 MPx array that allows to have both a wide field of view (FOV ~28.05 x 15.95 deg) and a relatively small instantaneous FOV (iFOV ~0.127 mrad). The large FOV allows capturing large target position uncertainties while the small iFOV yields a ground data sampling of 10cm from ~800 m altitude. This instrument was selected among various products, including Malin Space Science Systems' ECAM model. Developing an in-house products allowed extensive calibration and testing.

NEACam is used both for science and optical navigation. Hence, this camera was subject to extensive radiometric and geometric calibration. Commissioning activities to be performed in the cislunar phase will complete its calibration with the characterization of possible straylight, which can degrade optical navigation images.

NEA Scout also flies science software for on-board image processing intended to decrease data volume. Indeed, there is almost one of magnitude difference between the data volume generated by the camera and the downlink capability of the spacecraft, due not only to its limited antenna, but to its limited power that allows only about 30 min of data downlink per telecom session. Science software performs on-board image processing and feature extraction. For example, the target may occupy only up to 10% of the FOV. Science software includes a functionality about identifying the target (a bright object) against the dark background and extract a box surrounding the NEA. Similarly, to optimize the downlink of optical navigation images over a short turnaround during the approach phase, science software extract boxes around a subset of starts. These snippets are downlinked and the partial OpNav image is reconstructed on the ground, effectively decreasing the data volume by 1000x.

Instrument Accommodation, Integration, and Lessons Learned

The original science requirements included color imaging. Because of the limited volume and mass offered by the 6U CubeSat form factor, a volume of 0.5 U was allocated to the camera in the early design of the bus. This small volume drove the wide field of view design. The color filters could not be accommodated and were discarded (also for cost and schedule reasons). NEACam was tested and calibrated per the same standards as regular science cameras. It did not pose any challenge during integration and testing. Its sensitivity requirements were met by a factor of several (e.g., 0.2 s vs. <0.7 s required exposure time during encounter). The main limitation of NEACam is its small internal storage (about 4 images) that limits the image acquisition cadence.

One of the main lessons learned from the NEA Scout target search is that the pool of targets (out of the 1000s identified) within reach of CubeSat is very small, not only due to propulsion constraints. Telecom limitations require that the target position be well known. Indeed, the spacecraft is not capable of performing a broad target search and return a large data volume. Although on-board image analysis is theoretically possible, the processing capability (~RAD 750 class) is not performant enough, making this kind of activity highly risky. Future mission may bring the capability to perform on-board target search to compensate for limited bandwidth.

SOLAR SAIL PROPULSION SYSTEM

Technology Objectives

NEA Scout is both a science mission and a technology demonstration. Mission success will be judged by how well both are achieved and can be seen in the project's success criteria (Table 1):

Table 1: NEA Scout Technology Demonstration Success Criteria

Success Level	Technology Demonstration Success Criteria
Full	Demonstrate navigation of the spacecraft with the solar sail by slewing the spacecraft and traveling from one predetermined location to another after sail deployment
Minimum	Demonstrate solar sail deployment. Demonstrate stable pointing for science and optical navigation via imaging of the Earth or Moon and unresolved objects.

Description and Development Summary

NEA Scout is the next in a line of solar sail technology development efforts led by NASA MSFC over the last 20 years, each building upon the lessons learned and technology developed for what came before.

Two different 400 m^2 solar sail systems were developed and successfully completed deployment and functional vacuum testing during 2005 in NASA Glenn's Space Power Facility at Plum Brook Station, Sandusky, Ohio. The sails were designed and developed by ATK Space Systems and L'Garde, respectively. The sail systems consisted of a central structure with four deployable booms that supported the sails. Life and space environmental effects testing of sail and component materials was conducted.[3]

NASA terminated funding for solar sails and other advanced space propulsion technologies shortly after these ground demonstrations were completed. To capitalize on the $30 M investment made in solar sail technology to that point, NASA funded the NanoSail-D, a subscale solar sail system designed for possible small spacecraft applications. The NanoSail-D1 mission flew on board a Falcon-1 rocket, launched August 2, 2008. As a result of the failure of that rocket, the NanoSail-D1 was never successfully given the opportunity to achieve orbit. In collaboration with the NASA Ames Research Center (ARC), The NanoSail-D2 flight spare was successfully flown aboard a 3U CubeSat in low earth orbit (LEO) in the fall of 2010. The 10 m^2 NanoSail-D2 was made from the leftover sail fabric from the ATK ground demonstration sail and deployed using four metallic booms.[4]

In the early 2010s, both NASA MSFC and NASA JPL independently proposed the use of a solar sail propelled small spacecraft for asteroid exploration. Both were selected for flight on the condition that the teams merge, which is what led to the current NEA Scout project.

The NEA Scout solar sail uses the same Colorless Polymer-1 (CP1) as the base polyimide substrate with an aluminum coating that was flown on NanoSail-D2 and metallic booms of the same configuration, but much longer (7.3 m). During the design process, it was discovered that 4-quadrant configuration used on previous sail demonstration missions would cause thermal deformations in the exposed metallic booms, altering the deployed shape of the sail, essentially destroying its planarity and usefulness as a propulsion system. To mitigate this problem, the design from NanoSail-D2 had to be modified. A single sail approach that would continuously shade the metallic booms from sunlight was selected.[5] The system design went from a single spool for the booms and single round spool for the sail material to a dual mounted boom deployer and racetrack shaped sail spool that allowed deployment of the large, single sail as the booms extended.

Unlike NanoSail-D2, NEA Scout will be flying beyond LEO and must navigate from an Earth escape trajectory to rendezvous with its target asteroid. To do this, the sail must be capable of slewing in the x, y, and z planes to alter the angles of incidence and reflection of sunlight to precisely use the resultant thrust force (necessary for getting from ‘here’ to ‘there’). More information on how this is achieved will be described in the Guidance, Navigation, and Control section below.

Testing and Integration

The Solar Sail Propulsion System (SSPS) benefited from Integrated Testing on both an Engineering Development Unit (EDU) and a Flight Unit.

The goal of the EDU test activities was to address mechanical functionality, sail packing efficiency and to demonstrate the overall solar sail subsystem. The environmental testing for the solar sail propulsion system consisted of ascent vent testing, random vibration testing (to Generalized Environmental Verification Standard (GEVS) requirements), and thermal vacuum testing.

After environmental exposure, there were boom deployment, CP1 Sail deployment, and Mylar sail deployment tests. These tests examined the functionality of the motor controller board, burn wire mechanism, launch lock hold down release mechanism, sail restraint release, boom only deployments, and full sail deployment.

One of the primary challenges associated with testing a large solar sail system is gravity. Gravity causes the booms to buckle, and the sail to drag on the floor during deployment tests. The sail system is quite large, so it is challenging to find an open space large enough to accommodate a full sail deployment test. NASA MSFC’s flat floor facility was used for some of the EDU deployment and sail folding development tests. However, while this facility is clean, it does not meet the cleanliness standards required for a flight system. The flight sail system was tested at the NeXolve facility in Huntsville, with a simple gravity offload fixtures attached to the boom tips to facilitate testing in the 1G environment (figs. 2 and 3).

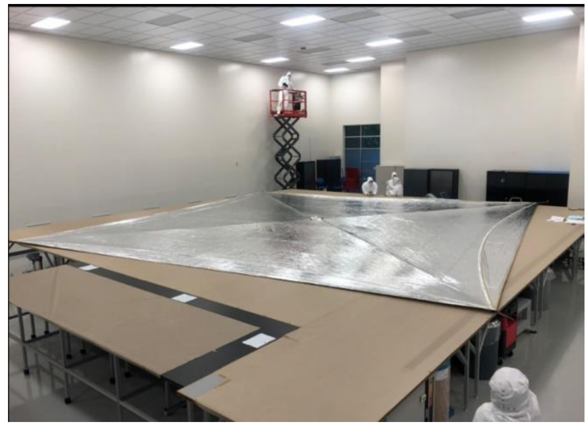

Figure 2: Flight Solar Sail Deployed

For the flight system, verification system level tests included outgassing, electro-magnetic interference (EMI), ascent vent, random vibration, shock, thermal balance and vacuum, and full Active Mass Translator (AMT) and sail deployment test. The full sail deployment was followed by sail repair, refold, and respool.

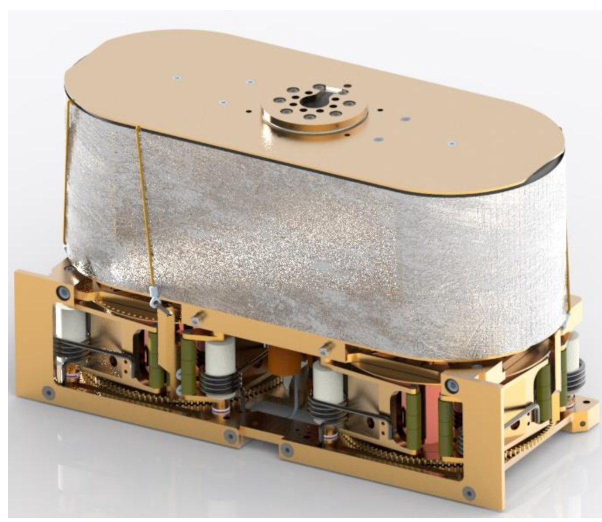

Figure 3: Flight Solar Sail System Spooled

The AMT, as part of both the guidance and control system and the solar sail propulsion system, minimizes disturbance torques and reduces the demands on the attitude control system. It minimizes the Center of Pressure (CP) – Center of Mass (CM) offset by actively changing the location of the CM relative to the CP. The design is a two rail system that breaks the mass of the spacecraft into two segments: avionics box on one side and solar sail plus the RCS on the other. The mechanism "slides" each mass in relation to each other to balance the CP-CM.

Throughout development testing and flight system testing, the AMT motors were an area of focus and sensitivity. Due to the volume and mass constraints of the mission, small stepper motors were selected to drive the AMT. The team encountered issues that had to be overcome with operation of these motors in the flight environments – namely in the vacuum and thermal environments. After about a year of failure investigations and redesigns, the team was able to resolve the issues with the motors to pass the requirements to perform within the operational temperature environments and vacuum. After development testing, the AMT functional test was performed on the flight unit using a protoflight temperature and vacuum environment. After this functional test was completed, the AMT was integrated with the SSPS and the spacecraft.

Lessons Learned for Future Missions

Through the course of sail development and testing, a series of lessons have been learned that are applicable for future solar sail missions. The lessons fall into three categories: dealing with the deployer mechanism, the sail itself, and general observations.

One of the most significant impediments to successful deployment tests in a 1-G environment was drag experienced by the sail as it slid along the deployment test table. This was despite the implementation of several drag mitigations, such as helium balloons to offset the deployer boom weight, and a low-friction cover for the deployment table. An air table could have further reduced sail drag during deployment tests. A related challenge was the loss of sail boom positional certainty during deployment testing, due to unexpectedly high loads that led to deployer motor stall. As a result, the deployer mechanism was driven to a hard stop that placed the boom roots beyond their intended final position, impacting the predicted dynamics of the deployed sail. Future designs should ensure that mechanism hard stops align with the desired end-of-travel.

During thermal bakeout of the flight sail, one axis of the sail shrank more than the other, due to the arrangement of the sail's seams. As a result, the lanyards that attached the sail to its booms were too short, and the lanyard springs were deformed during the flight sail deployment test, requiring replacement. Future sail teams should anticipate nonuniform shrinkage in bakeout due to sail architecture and be prepared to size connecting hardware to accommodate. Another sail lesson regarded long term storage. When NEA Scout's sail requirements were drafted, the delay between final stowage of the flight sail and Artemis-1 launch was anticipated to be up to 24 months. At the time of writing, the flight sail's stowed duration is nearing 48 months. While multiple "long-stowage" sail deployments were tested over the years, none of the sails were stored for longer than 16 months prior to deployment. Future missions should consider creating a long-term storage test article prior to a flight sail's final stowing; such an article could be inspected or tested as launch approaches, to mitigate any risks for the flight sail deployment. A last sail lesson concerns the value of an on-orbit verification of the deployed sail configuration. Due to strict volume constraints, NEA Scout was not able to incorporate a context camera or similar device to determine the state of the deployed sail in flight. The team plans to determine sail shape by comparing spacecraft momentum management telemetry to predicted values generated from a range of potential sail shapes, but there remains substantial uncertainty in this approach. The presence of a context camera would reduce sail shape uncertainty considerably, as well as provide insight into how the deployment mechanism behaves in microgravity and generate high-value imagery for the team and agency's use.

A critical detail for sail design is to ensure that all flight environments are known and characterized before designs are finalized. NEA Scout only confirmed that lunar eclipses were possible, depending on the launch timing of Artemis-1, after the flight sail was built and delivered to spacecraft integration. As a result, the sail booms were not designed to manage the tension loads the sail will induce due to thermal contraction in lunar eclipse. Subscale testing indicated that the booms have adequate margin against the eclipse tension load, but a finding otherwise would have driven severe schedule and cost impacts. A final lesson concerns the benefit of preserving flight-similarity in any Engineering Development Unit (EDU) hardware that a project builds. NEA Scout built an EDU sail that was last deployed in September 2017. As that was the final planned test, the EDU sail was stowed in a non-flight-like configuration for expediency. In hindsight, stowing the EDU sail in the same manner as the flight sail would have allowed further inspection or testing with direct applicability to the flight sail.

SAILCRAFT GUIDANCE AND CONTROL

Guidance and Control has learned many valuable lessons in the development of the spacecraft control system for NEA Scout. Early in the project, it was discovered that the metallic TRAC booms on NEA Scout would suffer a considerable deformation for the quadrant-sail design, which would be on the order of ~ 1 meter tip deflections for the 7.2 meter-booms. Using a sophisticated sail model derived from Abacus, the G&C team learned that the solar disturbance torque on the sail could be greatly increased by the departure in shape from flat surface, and for the deformations predicted for the quadrant sail shape this led to a solar torque about 2 orders of magnitude higher than the control system could handle. Accordingly, the project redesigned the sail to be a single sail to insulate the booms from the thermal deformations. The nominal deformations of the booms were reduced from ~ 1 meter at the tips to ~ +/1 cm, with a subsequent decrease in anticipated solar torque of about 2 orders of magnitude.

Even after making that major design change, the residual solar torque was predicted to be on the order of ~ 5e-6 Nm worst case, which was still too much for the control system to handle over the maximum 2.5-year time of flight required for NEA Scout. Accordingly, the G&C team recommended the addition of an Active Mass Translator (AMT) to provide the capability of changing the Center of Mass (CM) of the spacecraft and allow the control system to manage the solar torque. The AMT was added, which enabled the control system to be able to control the solar torque in Pitch and Yaw. Specifically, the AMT helps manage the momentum of the reaction wheels. The reaction wheels are the primary control actuator for NEA Scout but rapidly accrue momentum from the solar torque; the AMT allows the momentum of the wheels to be off-loaded by periodically changing the CM of the spacecraft.

The G&C Flight Software (FSW) for NEA Scout has been verified by numerous reviews and tests, including two independent Peer Reviews, a Design Review at the spacecraft level, Unit Tests, Performance Tests, Level 4 Requirements Verification Tests, testing with a ground replica of the spacecraft called the Avionics Test Bed (ATB), and with testing on the integrated vehicle. The G&C FSW has parameters that can be overwritten in dynamic memory during the mission. For instance, we can adjust control gains or even reverse the polarity of a reaction wheel if necessary. Currently we are doing the final testing of FSW Rev 6.0 in the ATB, and this update will be up-linked early in the mission.

The G&C FSW will be critical to the success of several events early in the flight, with several key events occurring on Day 1. This includes de-tumbling the spacecraft after deploying from SLS, pointing the spacecraft at the sun for power with the first maneuver, maintaining that attitude for comm and power, performing an RCS Calibration, performing an AMT Calibration, executing a Trajectory Control Maneuver (TCM) and if necessary, de-saturating the reaction wheels. Currently the G&C team is focused on preparing for these Day 1 challenges and other aspects of mission support.

MISSION DESIGN AND NAVIGATION

Mission Design and Navigation

The mission's phases correspond to different configurations of the spacecraft and to different circumstances and objectives during each period. Each has its own challenges, but the over-arching trajectory challenge is solar sailing to a particular objective.

A brief description of the mission design

Launch opportunities for Artemis I occur every month when the Moon is above Earth's southern hemisphere, which is when the Moon is on the side of its orbit that is centered on 270 deg ecliptic longitude. This means that the relative geometry of the Earth, Moon, and Sun is different for each launch period as the Earth-Moon system go around the Sun, and the geometry changes likewise within each launch period because of the Moon's motion in its orbit around Earth. Since NEA Scout will use a lunar flyby as a gravity assist to depart the Earth-Moon system, the changing geometry means that the entire trajectory design changes every few days or less.

The only constant is that the launch itself will send the spacecraft toward a near miss of the Moon five to seven days after launch, because that's where Artemis I will head. The spacecraft deploys from the upper stage of the SLS after the Orion capsule has separated and the upper stage has done a disposal maneuver to aim for a lunar flyby that sends the upper stage away from the Earth-Moon system. Unfortunately, there is no chance that the resulting post-deployment heliocentric trajectory of NEA Scout would pass close enough to a near-Earth object within two years to satisfy mission objectives.

Instead, NEA Scout will use its cold gas RCS system to do a series of maneuvers that change the first lunar flyby so that NEA Scout stays coupled to the Earth-Moon system. This allows time for use of the solar sail and possibly additional lunar flybys to set up a final lunar gravity assist that puts NEA Scout on an interplanetary trajectory to a targeted near-Earth object.

Finding such an interplanetary trajectory is key to the entire mission. JPL developed a broad search tool that examined the entire catalog of NEAs to find trajectories to candidate targets, and which runs periodically to consider newly discovered ones. Over the years that the Artemis I launch date has been planned and replanned, several targets have been the objects of mission trajectories. For the past year, as the launch date has slipped month by month, the target body has been 2020 GE, which will be staying close enough to Earth that two different interplanetary trajectories to it have been used—the current one starts with a lunar gravity assist in 2023 September and arrives at 2020 GE in 2024 September.

Given this interplanetary trajectory, the next challenge is to find a path from the initial deployment state to the final lunar gravity assist. For this, a trajectory matching algorithm that operates on each day of the launch period was developed. The process begins by generating two large databases on the order of a million entries each, one database of apogees of all the trajectories that run forward from possible trajectory correction maneuvers (TCMs) about 14 hours after deployment from the middle of the launch window, and a second database of apogees of all trajectories that run backward from all the lunar gravity assists that result in the desired departure from the Earth-Moon system. Each case in each database uses one of a variety of solar sail control laws—for example, one control law keeps the sail normal pointed at the Sun. The apogees of the forward database are then matched to the apogees in the backward database—pairs which have discontinuities that are small enough in time, position, and velocity identified possible trajectory candidates for the next step of analysis.

The above process involved the use of simplifying assumptions which meant that not all the solutions found were actually feasible. Building on existing NASA experience with low-thrust trajectory design, the capability of the low-thrust optimization program Mystic expanded to include solar sail thrust. The cruise from deployment to final lunar flyby is divided into sail management periods, each on the order of a week long, during which the vector normal to the solar sail (assumed here to be flat) is constant. Mystic would use each of the trajectory candidates found above as initial conditions and would attempt to vary the sail normal vectors to remove time, position, and velocity discontinuities and minimize the magnitude of the TCM after deployment. Typically, one or two dozen of the many billions of database pairs would result in an end-to-end feasible trajectory.

Example reference trajectories for March 12 and June 6 launches illustrate the result of the above process in Fig. 4. These trajectories are shown in an Earth-centered rotating coordinate frame in which the Sun and Earth are fixed on the X-axis, with the Sun toward the left. March launch trajectories included a flyby of the Moon in September 2022, and an arrival at the asteroid in September or October 2023. In June and later launch periods, trajectories include a lunar flyby in September 2023, and an arrival in September 2024. In both cases the asteroid encounter is shown by a red star.

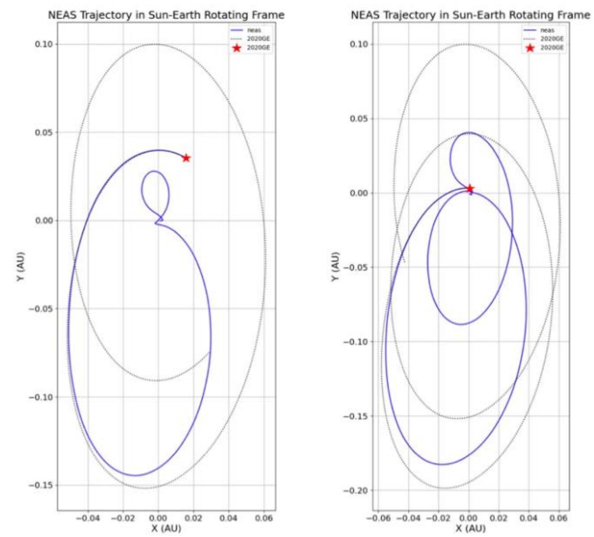

Figure 4: NEA Scout trajectories launching in 2022-03-12 (left) and 2022-06-06 (right)

The Many Challenges of Solar Sailing

Just finding reference trajectories for NEA Scout has been a daunting challenge, exacerbated by NASA's practice of releasing initial state information for Artemis I secondary payloads only two or three months before selected launch periods. But an even greater challenge faces solar sail missions. Even though sunlight can provide free delta-v there is a downside—you can't turn it off! This simple fact has had major effects on NEA Scout mission design.

The NEA Scout rendezvous and flyby strategy had to be redesigned because initially the rendezvous was at a point 40000 km sunward of the NEA; because of the relentless sunlight, the flyby velocity a month later was too high to allow the science imaging that was the goal. Now the rendezvous is 5000 km sunward of the NEA and the flyby velocity is less than half as fast, but it happens less than a week after the rendezvous, presenting its own challenge to mission operations.

A more significant challenge emerged late in the mission development. Both electric propulsion and solar sailing present the low-thrust optimization challenge discussed in the previous section; this meant that NEA Scout could adapt existing tools for ion-propulsion trajectory design. It turns out, though, that being unable to turn off the thrust is a major, qualitative difference that shows up in two ways.

The first way that solar sailing is very different is in the handling of safe modes. In a mission with electric propulsion if a problem with the spacecraft causes a safe mode to initiate, the safe-mode sequence on-board the spacecraft turns off the propulsion until the problem is solved. To deal with this possibility, the trajectory design includes occasional coast periods; then thrust lost during any safe modes can be replaced by thrust during the successive preplanned coast periods. It turns out that the analogous strategy for a solar sail mission, which is to include periods when the sail normal points at the Sun, doesn't work because for most solar-sail trajectories there are periods when pointing at the Sun for an extended period causes the spacecraft to reach a state from which there is no feasible solar sail trajectory to reach the NEA. Fortunately, the NEA Scout safe mode sequence includes a transition back to star-tracker control early in the safe-mode sequence. This makes it possible to update the safe mode sequence itself as needed to have the safe-mode attitude point the sail in a direction within several degrees of the direction planned for trajectory.

This sensitivity of the solar sail trajectory to safe mode attitude is related to the second way that solar sailing is different than electric propulsion—solar sail trajectories can be sensitive to errors in trajectory implementation to the extent that the trajectory becomes infeasible by reaching a state from which no trajectory to the NEA exists. The reader can see the cause for this difference in Fig. 5. Because the magnitude and the direction of the thrust from an electric propulsion system can be varied independently, the reachable states at some time in the future fill in a volume surrounding the state that is reached if the nominal control is applied. But as Fig. 5 shows, the reachable set for a solar sail in the future describes a surface in space with the nominal state at the tip of the surface, because the magnitude of the solar sail thrust is correlated with the angle of the sail, leaving only two degrees of freedom in the thrust. As a result, perturbations or spacecraft execution errors can lead some trajectories to a state from which the NEA is unreachable.

To minimize the chance of this happening, Veil, a tool to measure the resilience of a solar sail trajectory in the presence of errors, was updated. Veil essentially runs a monte carlo analysis of each sail management period in the trajectory wherein different final states in the period are generated by applying randomly selected implementation errors or variances such as safe modes; Veil then reoptimizes each state's subsequent trajectory to find out if the asteroid flyby is feasible. We then apply different margin strategies in the design of the reference trajectory to see how they affect the percentage of infeasible states. These margin strategies include assuming various reductions in the size of the solar sail, including periods of time in which the sail is facing full-on to the Sun, and varying the lengths of the sail management periods.

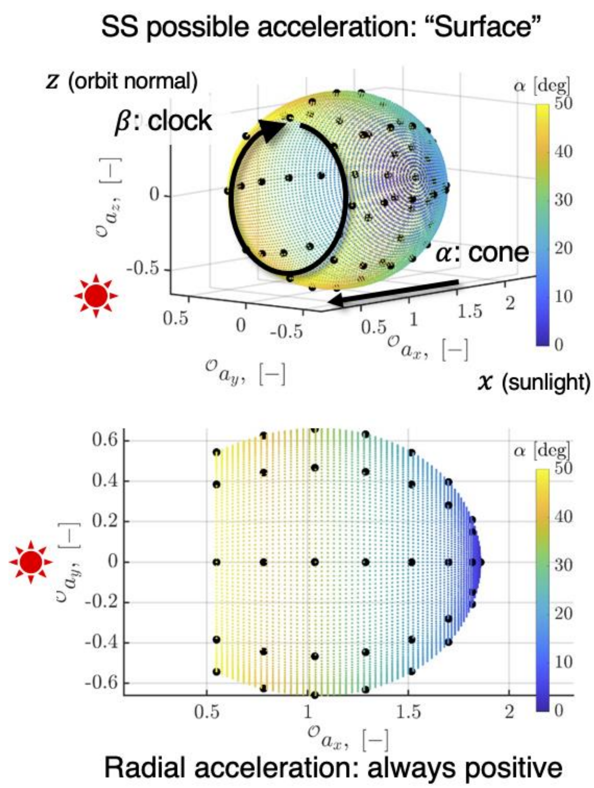

Figure 5: Reachable points using solar sail.

Navigating in a Sea of Light

A special challenge for Artemis I secondary payloads is that competition for deep space network (DSN) resources means navigating with a shoestring of data. The Orion spacecraft has top priority, so only one antenna at each DSN antenna complex is available for the multiple secondary payloads. New receiving equipment at the antennas allows downlinks from four spacecraft simultaneously, but a two-way link can only be done with one spacecraft at a time to allow for radiometric doppler and ranging measurements. This is partially mitigated by generating a new type of radiometric measurement when the spacecraft is visible from two ground antenna at the same time—then received one-way downlinks can be compared interferometrically to get an angular measurement of the spacecraft, which helps in the orbit determination.

Because solar radiation pressure (SRP) is a factor in almost all space missions, NASA's primary navigation software (Monte, at JPL) already has the algorithms in place to solve for SRP effects—the sail magnifies the SRP effects, but the algorithms still apply.

SAILCRAFT FLIGHT SYSTEM

Overview

The NEAS flight system packs a lot of capability into a 6U CubeSat form factor – all the basic spacecraft functionality plus an 86m^2 solar sail and the mechanisms to steer it. Artemis-1 rideshare deployer constraints also imposed a not-to-exceed mass of 14 kg. Fig. 6 identifies the major elements of the flight system and the providers.

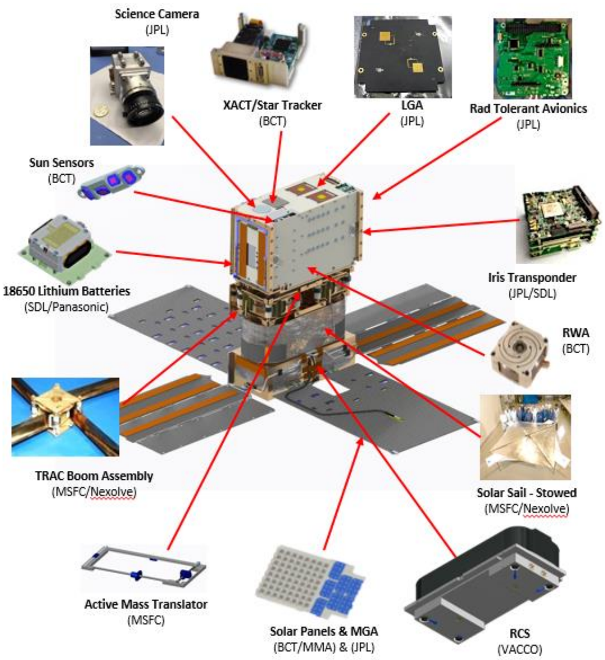

Figure 6: NEAS Flight System

Development

Divided into three major sections, the NEAS flight system was developed as a partnership between the lead center, MSFC, and JPL. The top third of the bus is colloquially known as the "avionics box", although it contains most of the subsystems as shown in Figure 6. The middle third of the bus contains the solar sail and its deployment and steering hardware. The lower third of the bus is the cold gas propulsion subsystem. This section is also where the solar arrays are attached. Low gain antennas are located the top and bottom of the flight system, and one of the solar array panels has a medium gain antenna.

JPL integrated the avionics box and developed or procured several of the elements. MSFC provided the guidance and control subsystem and the solar sail motor controller board to JPL for inclusion in this section of the flight system. MSFC provided the elements of and integrated the solar sail section. MSFC integrated the propulsion subsystem section including the solar arrays procured by JPL. After delivery of the avionics box from JPL, MSFC completed the flight system integration and test (I&T) process.

Testing and Integration

Figure 7: NEA Scout's flight sail unfurls in a bowtie configuration during a deployment test

In June of 2018, the Integration and Test Team successfully completed a full Flight Sail deployment (fig. 7). Critical data was collected relative to boom behavior, overall sail tension, deployment duration and boom extension count. These items have been incorporated into the Mission Operations team flight procedures.

<u>First Full Functional Test</u>

The objective of the first full functional test was to exercise as many functions of the spacecraft as possible, while considering the constraints of gravity and the need to maintain the sail in its stowed form factor prior to integration with the CubeSat Dispenser (fig. 8). The separation switch was repeatedly activated to power on the spacecraft. Inertial Measurement Unit axes were confirmed to match spacecraft body axes. Sail booms were commanded for initial movement and retracted.

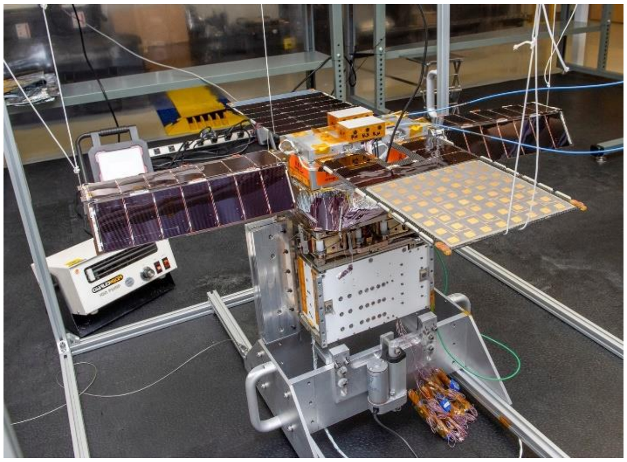

Figure 8: NEA Scout spacecraft during testing

The system level Random Vibration test utilized a custom fixture that replicated the CubeSat Dispenser mechanical interfaces, including hold-down features and clearances, while also allowing access to spacecraft surfaces for instrumentation. This test included all three axes. A System Functional Test was performed before and after the Random Vibration test, to confirm the spacecraft was still functional, and a more limited "aliveness" test was conducted between each vibration axis to the same effect. A laser system was incorporated to understand the deflections of the solar panels and Medium Gain Antenna (MGA) resulting in high confidence during launch.

The Thermal Vacuum Test occurred in March of 2021 and was a 12-day 24/7 event. The objective was to simulate flight thermal conditions after deployment including cold start, Trajectory Correction Maneuvers, cruise phase, RF communications, and science camera operations.

A "hot box" was used for accurate temperature control, ensuring all spacecraft components stayed within survivable limits. This Thermal Vacuum Test correlated and updated the NEA Scout thermal model.

Final Functional and Post-Deploy Sequence Test

After completion of environmental testing, NEA Scout's "Post-Deploy" sequence was uploaded to the spacecraft. The Post-Deploy sequence will execute once NEA Scout is ejected from its CubeSat Dispenser aboard Artemis-1 and will control spacecraft behavior until contact is established with the Deep Space Network. Testing verified that the sequence successfully activates spacecraft subsystems, including the Iris radio.

Lessons Learned for Future Missions

As one of the early deep space CubeSats under development, NEAS is a rich source of lessons learned for future Class D missions. Two of the lessons with the broadest applicability are timing of a design review and harness routing fit checks. The comprehensive project lessons learned archive is maintained by MSFC.

Early in development and in conjunction with the NASA sponsor, NEAS decided to hold only one design review instead of the preliminary then critical two-step design review (i.e., PDR/CDR) process in a traditional project lifecycle. Moreover, the design review was held early (2016) relative to the when the hardware was delivered and integrated in the 2019/2020 timeframe. Both factors led to there being effectively no formal review of a mature flight system design.

In the ideal, every Class D mission would have the traditional PDR/CDR lifecycle reviews. However, this is not always practical or even desired by the sponsor. Given that, the lesson is that if there is to only be one project-level design review, it should be biased later in the development process (i.e., a CDR equivalent) as opposed to earlier (i.e., a PDR equivalent).

CubeSats usually face tight volume constraints, particularly in a ≤6U form factor, and it is crucial that harness routing fit checks are included in the development schedule. Cost effective and readily available 3D printing has made this activity achievable within Class D resources. Essentially, the flight hardware is 3D printed to the greatest fidelity allowed by the printer and then representative cables (appropriately wrapped, etc.) are used to find the optimal routing solution given constraints such as available space and allowable bend radii.

This is one area that NEAS used advantageously – >3 harness routing fit check activities were done at JPL prior to the avionics box integration, and MSFC held several fit checks for the other sections as well as the end-to-end flight system. These activities, performed throughout the development phase, were essential in identifying potential issues and finding solutions early, minimizing resource impacts.

MISSION OPERATIONS

Ground Systems and Testing

In preparation to support the NEA Scout mission, the following Huntsville Operations Support Center (HOSC) ground systems have been established and tested.

MSFC connects to Deep Space Network (DSN) antenna sites through the Restricted IOnet (RIOnet) interface via a Space Link Extension (SLE) Proxy. The SLE Proxy is maintained and operated by the Marshall Data position staffed by HOSC personnel.

The NEA Scout Mission Operations Center (MOC) has been established within the HOSC. The room contains six (6) thin-client workstations that allow the NEA Scout Flight Control Team (FCT) to communicate with the spacecraft during DSN contacts. Specifically, the FCT uses the Advanced Multi-mission Operations System Mission Data Processing and Control Subsystem (AMPCS) software to view telemetry and uplink commands, sequences, and files.

Spacecraft telemetry will be stored on the HOSC's Storage Area Network (SAN) for one year following the end of mission (EOM).

Connectivity has also been established to exchange AMPCS-processed telemetry and imagery files between the HOSC and JPL. This is achieved through an "rsync" connection and scripts to push files from MSFC to JPL.

Lessons Learned

The deployment of multiple payloads from the Orion Stage Adapter (OSA) presents a huge challenge for DSN antenna resources and personnel. For the first few days of the various missions, DSN antennas will operate in a Multiple Spacecraft Per Antenna (MSPA) configuration. This limits antenna resources to four simultaneous downlinks and one uplink, forcing payloads to share contacts and DSN personnel to juggle resources.

MANAGEMENT AND MANAGEMENT CHALLENGES

Mission Selection

NEA Scout is the next in a line of solar sail technology development efforts led by NASA MSFC over the last 20 years, each building upon the lessons learned and technology developed for what came before.

In the early 2010s, after the explosive growth in CubeSats, NASA decided to provide include in the design of the SLS the capability to carry up to 13 6U CubeSats as secondary payloads, providing access to trajectories that would carry them beyond Earth orbit. Many rockets, public and private, were beginning to provide secondary payload rideshares for CubeSats, but almost all of these were for missions in LEO. To make use of this new opportunity, NASA issued a request for CubeSat proposals for the first SLS flight.

NASA MSFC and JPL each developed and submitted solar sail enabled asteroid reconnaissance mission proposals independently of one another. In the selection process, NASA decided that only one such mission would be funded and that both teams should work together to define the technical and programmatic details. At this time, the current roles and responsibilities for NEA Scout were negotiated and implemented between MSFC and JPL.

Challenges of Streamlined Class D Missions

Although there are several proposed alternative methods to payload mission classification [6], NASA Procedural Requirements (NPR) 8705.4 provides the definitive criteria for the classification of NASA payloads according to a four-tiered system (A through D) with varying levels of risk. The lowest risk level is class A, defined by relatively high cost and high national significance (e.g., Hubble Space Telescope). The highest risk level is class D (e.g., small spacecrafts like NEA Scout), defined by relatively low cost and low to medium national significance. Due to the high-risk allowance for a Class D Payload, the Project Manager and Principal Investigator have more freedom to define the resources required and execution of the project as well as an allowance to tailor standards and specifications to meet mission objectives. Although the flexibility provided to a Class D payload to accomplish the mission objectives and managing the project provides many benefits, this flexibility also presents several challenges.

One challenge is the amount of time spent tailoring, documenting rationale, and getting approval for project requirements. A giant effort was made in the beginning of the NEA Scout project to tailor the project requirements to fit the Class D characteristics of the mission. Several challenges presented themselves as each requirement was rigorously examined. However, the upfront time spent and attention to detail proved to be a tremendous advantage in the long run, including the extensive documentation which ensured a 'memory' allowing the project to re-examine the requirements as the project moved through Assembly, Integration, and Test.

Risk Management poses another challenge. Managing risks of smaller spacecrafts are just as difficult, if not more challenging form a process perspective, than a larger spacecraft. Risks on larger projects can, to a large extent, be mitigated by larger budgets. With a smaller spacecraft like NEA Scout, the project needs to focus more time on risks and be more resourceful with risk mitigation to achieve mission success.

In general, although a class D small spacecraft project is allowed flexibility of management, it still holds several different challenges when compared to higher class missions. In summary, smaller spacecrafts do NOT equal smaller challenges.

SUMMARY AND CONCLUSIONS

NEA Scout will provide a new, low-cost deep space science mission capability using the now industry standard 6U CubeSat form factor. The mission, once launched, will be the first to use solar sails as the primary propulsion system for performing a deep space mission. The NEA Scout design is flexible and can be adapted to CubeSat class missions up to about a 12U configuration with a sail up to about 200 square meters.

Once complete, NEA Scout increase our understanding of near-earth asteroids, establish a low-cost capability for science, and demonstrate a new type of deep space propulsion for future missions.

Acknowledgments

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