Lessons for Interstellar Travel from the G&C Design of the NEA Scout Solar Sail Mission

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Abstract

NASA is developing the Near Earth Asteroid (NEA) Scout mission that will use a solar sail to travel to an asteroid where it will perform a slow flyby to acquire science imagery. A guidance and control system was developed to meet the science and trajectory requirements. The NEA Scout design process can be applied to an interstellar or precursor mission that uses a beam-propelled sail. The scientific objectives are met by accurately targeting the destination trajectory position and velocity. The destination is targeted by understanding the force on the sail from the beam (or sunlight in the case of NEA Scout) over the duration of the thrust maneuver. The propulsive maneuver is maintained by accurate understanding of the torque on the sail, which is a function of sail shape, optical properties, and mass properties, all of which apply to NEA Scout and beam propelled sails. NEA Scout uses active control of the sail attitude while trimming the solar torque, which could be used on a beamed propulsion sail if necessary. The biggest difference is that NEA Scout can correct for uncertainties in sail thrust modeling, spacecraft orbit, and target orbit throughout the flight to the target, while beamed propulsion needs accurate operation for the short duration of the beamed propulsion maneuver, making accurate understanding of the sail thrust and orbits much more critical.

Introduction

The Near Earth Asteroid (NEA) Scout mission has two primary goals. One is to image and characterize a NEA during a slow flyby. The other is to demonstrate a low cost method of performing asteroid reconnaissance[1]. To achieve this goal, a spacecraft has been designed and developed that deploys an 86 m^2 solar sail from a 6U cubesat bus that will sail to the asteroid after launch as a secondary payload on the first Space Launch System (SLS) launch. NEA Scout then uses a series of propulsive maneuvers, sail thrusting, and lunar gravity assists to depart the Earth-Moon system. The NEA Scout mission requires an end-to-end spacecraft and mission design that accounts for all the uncertainties in navigation, attitude determination and control, thrust and torque of the sail, and target orbit while still allowing a successful science campaign.

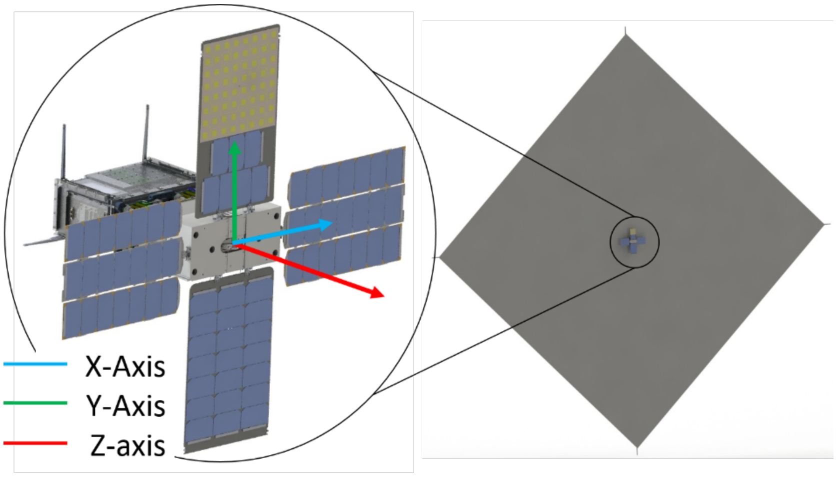

Figure 1. NEA Scout solar sail and spacecraft bus showing body axes that are in plane (X and Y) and out of plane (Z).

Precursor and initial interstellar missions employing beamed propulsion similarly require an understanding of how uncertainties in the various elements of the system affect the ability to perform a scientific reconnaissance of the target. Early interstellar missions may be to characterize a target star or stars and their planets, so that follow-on missions can pursue more comprehensive or targeted scientific objectives. Interstellar precursor missions may demonstrate interstellar capabilities by, for example, surveying Kuiper Belt or Oort Cloud objects. In either case, the spacecraft need to accurately target specific bodies, and flyby within a range of times, distances, or velocities that allow successful observation. To do this, the uncertainties of the beamed propulsion system, spacecraft orbit determination, sail forces and torques in response to the beam, gravitational and other perturbations on the spacecraft orbit, and knowledge of the target bodies need to be accounted for in designing the spacecraft and mission.

Precursor missions to explore the space environment where the outer heliosphere interacts with interstellar space are less constrained by their destination. They still require accurate enough guidance of the beam on the sail, accounting for all the same uncertainties as a flyby except for the target orbit.

Scientific Objectives

NEA Scout

The scientific objectives of NEA Scout are to perform long range optical navigation of the target asteroid, medium range reconnaissance, and close proximity imaging. The target asteroid is 1991 VG. It is a small ~5-12 m diameter asteroid with unknown albedo and an Earth-like orbit that is reachable by NEA Scout within a 2.5 year mission duration.[1]

Optical navigation is performed starting at 50,000 km from the asteroid, and is used to update the orbit estimate of the asteroid as the sail approaches. During approach, optical navigation data is downlinked to Earth, the orbit of the asteroid is updated, and the steering guidance of the solar sail is updated to more accurately target the close approach. Medium range observations within 100 km of the asteroid and 50 cm/pixel resolution over 80% of the asteroid, will characterize the volume, shape, spin properties, and local environment. Close proximity imaging at 10 cm/pixel resolution over 30% of the surface will characterize the asteroid’s local morphology and regolith properties. The minimum scientific objectives will be met with a closest approach of 28 km, although the goal is to target under 1 km. Achieving these goals will fully demonstrate an ability to perform asteroid reconnaissance with a small solar sail spacecraft, employing cubesat technologies, and allow the identification of high science value targets to visit with follow-on missions.[2]

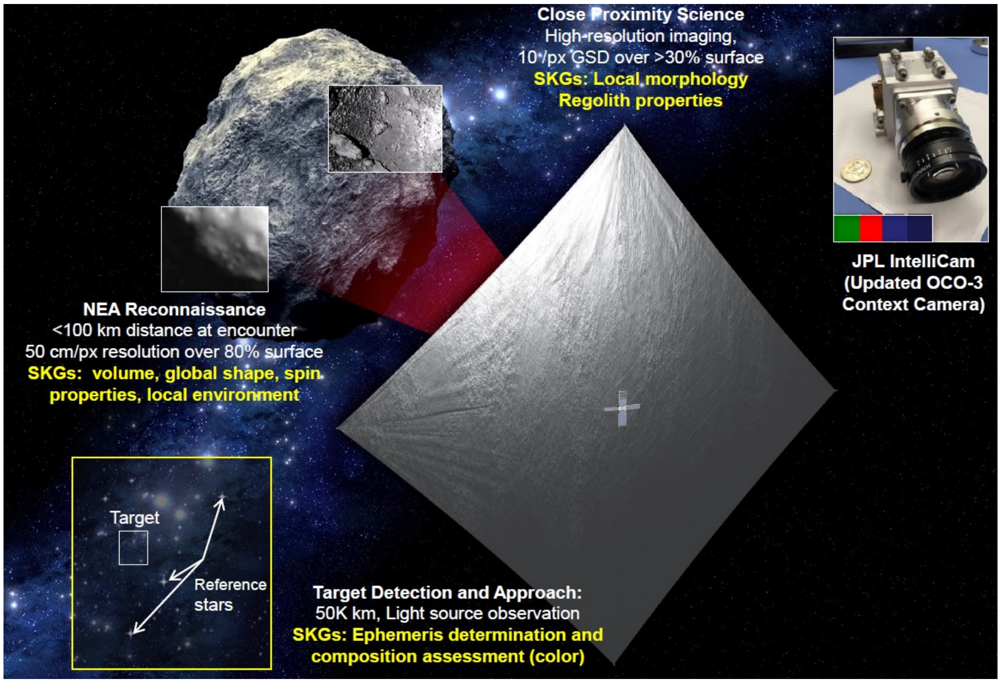

Figure 2. Phases of NEA Scout science, from target detection and optical navigation, mid-range reconnassaince, and close proximity science imaging.

The key drivers for the design of the mission are to target a close enough distance to the asteroid at a slow enough relative velocity, with knowledge of where to point the science camera, to acquire the images required to resolve the physical properties. Additionally, the attitude control must be accurate and stable enough to point at the asteroid without jitter blurring the images.

Interstellar and Precursor Missions

Interstellar and precursor missions to perform reconnaissance of another star or an outer solar system body will have similar scientific objectives. These requirements need to be developed in order to determine if the technology and design of the interstellar mission are sufficient to achieve useful results. If not, less ambitious goals can be pursued first, to gain experience for follow-on missions.

A primary goal of a first interstellar mission may be to characterize the orbits and general physical properties of the target stars and planets, so that follow-on missions can perform more comprehensive observations. This would be like performing the optical navigation and limited medium range physical observations of NEA Scout. Once the orbital and physical properties of the target system are better understood, follow on missions could more accurately target the planets and stars themselves for in-depth observations.

Because NEA Scout is an interplanetary mission that operates at ~1 AU from the sun, its trajectory can be continuously updated with steering guidance from ground controllers on Earth to more accurately flyby the target body. Early interstellar and precursor missions may not have this capability, due to onboard mass constraints, propulsion technology limitations, and the severe time lag to Earth.

Precursor missions to survey Kuiper Belt and Oort Cloud objects may perform more in-depth studies of those bodies, because their orbits may be more accurately determined by observations from Earth than exoplanets, and errors in the trajectory may be smaller than interstellar missions because of the shorter distance from Earth and lower velocity required to reach them in a reasonable mission duration.

Precursor missions to explore the heliosphere typically carry in-situ sensors to measure the magnetic field, charged particle population, and plasma properties of the space environment. These sensors do not require precise attitude to point at a particular target, and can be taken over a much larger area of space than imaging a solar system body. For this reason, missions to study the outer heliosphere where it interacts with interstellar space may be an easier testbed for interstellar precursor missions, to employ technologies like beamed sail propulsion, while still generating useful science results.

Navigation and Guidance

NEA Scout

The NEA Scout mission meets the position, velocity, and pointing science requirements by continuously updating the steering guidance of the sail based on trajectory estimates of the spacecraft and orbit estimate updates of the target. This can be referred to as “closed loop” navigation of the sail, and allows for uncertainties in the sail force model, navigation accuracy, perturbations, and attitude control to be corrected for throughout the mission. Radiometric range observations during flight are used to update the trajectory estimate and update the force model used to predict sail acceleration. These are used to solve for new sail steering guidance to target the approach to the asteroid. During the month long approach phase, the navigation includes both radio ranging and optical navigation relative to the asteroid, with observations of the asteroid made twice a day, and three times a day during the final approach.

Interstellar and Precursor

Unlike NEA Scout, early interstellar or precursor missions will have limited opportunities for “closing the loop” between observations of errors in the trajectory, sail thrust, and beam properties with changes to the beam guidance or sail attitude (assuming the sail has active attitude control). For the sake of discussion, the following assumptions are made about an early beamed propulsion system. It consists of a laser or other frequency beam system, located on Earth or in orbit, and a spacecraft with a sail on it. The spacecraft may have active attitude control during beamed propulsion, or rely on passive stability on the beam. Due to mass constraints, there may be little or no onboard active trajectory maneuver capability. While the spacecraft could sail on close approach using light from the target star, the trajectory must first be accurate enough to get close enough for useful solar pressure.

Unless a beamed sail mission is done in multiple phases with an opportunity to perform trajectory estimation and update beam guidance between propulsion phases, there will be only one chance to perform the thrust phase accurately enough to reach the destination. Once all propulsion phases are complete, the sail will coast to its destination, subject only to the gravitational and other environmental perturbations. The accuracy of the final orbit state at completion of the propulsion phase must be high enough to ensure the position, velocity, and timing requirements of the target flyby are met.

Before firing the laser, the orbit of the spacecraft needs to be known with enough accuracy to target it with the beam. The beam steering needs to be accurate enough to point it at the predicted location of the sail. Because of the speed of light and time it takes to perform orbit determination, there will not be time to update the beam steering in response to the observed trajectory of the sail. The sail trajectory in response to the beam needs to be accurate enough that sail stays on the beam, and the thrust over the course of the maneuver is accurate enough to put the sail on course to the target.

Force and Torque Modeling

NEA Scout

The NEA Scout force and torque model predicts the thrust relative to the direction of sunlight a function of the sail shape and optical properties. These determine linear and angular accelerations the sail experiences when illuminated by sunlight. This model is currently an estimate, and is based on measurements of sail membrane optical properties and finite element modeling of the sail booms and membrane when subject to thermal heating from sunlight. Imperfect reflection results in a significant in-plane force component when the sail is at an angle to the incoming sunlight because of the difference between absorbed and reflected light. This in-plane component results in a significant solar torque that must be controlled.[3]

After deployment, the sail torque model will be calibrated by slewing to a variety of sail attitudes, and observing the reaction of the attitude control actuators to solar torque (see section “Attitude Dynamics and Control”). During the early phase of the mission, the sail thrust will be estimated by using radio ranging to observe the actual trajectory and estimating the acceleration required to produce it. Differences in thrust will show up in deviations of the actual trajectory from that predicted using the pre-launch thrust model. These refinements will be used to make the steering guidance more accurate during the flight to the asteroid.

Well before launch, expected deviations in the shape and optical properties need to be accounted for, to ensure that the sail as manufactured is sufficient to complete the mission to the asteroid. To ensure this is the case, mission planning assumes a reduction factor in the thrust due to variations in sail size, shape, optical parameters, and time spent pointing towards Earth for communication. In this way, there is confidence that the sail has more thrust than is needed to complete the mission, to cover unforeseen problems with the sail deployment or mission operations that result in less thrust than expected. Sail models that were deformed or had holes in them at the corners of the sail were analyzed to ensure the attitude control system had enough margin to control sails with unexpected deployment problems.

Interstellar and Precursor

Because of the limited opportunities to correct for uncertainties in the thrust of the beamed propulsion sail, the thrust on the deployed sail should be estimated before launch with enough accuracy to ensure the manufactured sail combined with the beam system can achieve the trajectory to the target. Like NEA Scout, the sail thrust and torque model and beam power properties can be calibrated after deployment in space with a low power test using the beam. Without calibration, the beamed propulsion system could produce too much or too little acceleration, resulting in a trajectory that is too far from the target, moving too fast or too slow, or possibly result in the sail failing to stay illuminated by the beam for the full duration. Without torque model calibration, the sail could become unstable on the beam, or have oscillations that are too large and reduce the average acceleration on the sail.

Stability of the sail position on the beam is needed to keep the beam on the sail for the duration of all propulsion maneuvers. This requires a restoring force that sends the sail back to the center of the beam. NEA Scout has no such requirement; it just requires accurate knowledge of the force model to plan sailing maneuvers using a prediction of the thrust model before launch and calibration after sail deployment in response to the source of illumination. Both will be critical to ensure stability of a beamed propulsion sail.

Attitude Dynamics and Control

NEA Scout

NEA Scout steers the sail using an active attitude control system. It uses reaction wheels for precise attitude control, which are small flywheels that spin up opposite the direction the spacecraft needs to steer. A star tracker camera measures attitude relative to the background stars. Solar torques would eventually drive the reaction wheels to hit the speed limit of their bearings, so an Active Mass Translator (AMT) shifts the center of mass in order to keep wheel speeds and solar torque under control about the two body axes that are aligned with the sail booms. A reaction control system (RCS) uses small thrusters with cold gas propellant to manage torque accumulation about the axis normal to the sail (Z axis in Figure 1), which is much smaller than torques about the booms (axes X and Y in Figure 1). Design of this control system requires the solar torque model of the sail. The control actuators need to be sized with enough margin to handle reasonable uncertainties in the solar torque, due to the same factors that affect sail thrust – size, shape, and optical properties – as well as shape differences not reflected in sail thrust and location of the center of mass.[6]

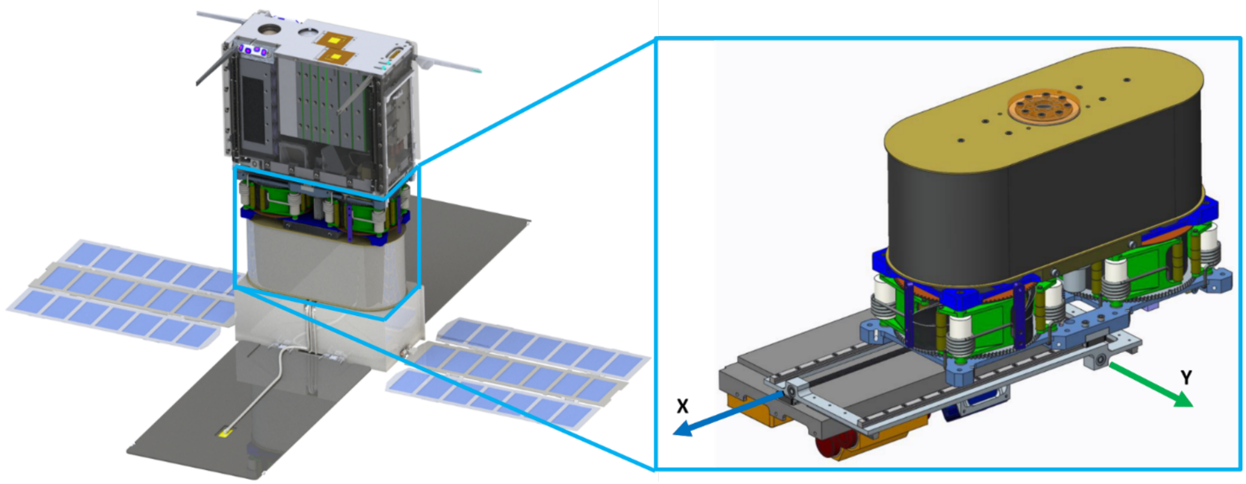

Figure 3. Active Mass Translator (AMT) for shifting the center of mass of NEA Scout to control the solar torque on the vehicle.

Japan's IKAROS solar sail used liquid crystal diode (LCD) reflective control devices (RCDs) to control solar torque about the two body axes that lie in the plane of the sail, like the AMT does for NEA Scout.[4] The RCDs work by electronically controlling the amount of sunlight reflected along the different edges or corners of the sail, resulting in a torque on the sail. NASA MSFC is working with the University of Maryland to develop similar RCDs for possible use on future NASA solar sail missions.[5] Without active control by the reaction wheels, AMT, or RCS, NEA Scout is not passively stable, and the attitude would deviate if uncontrolled.

Interstellar and Precursor

Proposals for near-term beamed propulsion do not assume active attitude control, to keep onboard mass low. Rather, the sail is designed to be passively stable, by generating restoring torques to return to the needed attitude on the beam for generating thrust to achieve the required trajectory accuracy. If the sail is not stabilized (actively or passively), it could fail to generate the thrust to stay on the beam and reach the target. Even if the sail is stable, oscillations about the stable point will reduce the average thrust, and may fail to meet the trajectory requirements if they are too large.

One limitation of a passively stable sail is that it may not be able to generate the attitude needed to thrust towards the target destination. Solar sails like NEA Scout regularly need to point at an angle to the incident sunlight to generate sideways thrust for changing the orbit energy. If a beamed propulsion sail can steer to attitude at an angle to the laser, it may open up much more flexibility for generating the thrust needed. This is an area that requires further study. Actuators like center of mass shifting or reflectivity control may be considered for actively maintaining sail attitude and possibly position of the sail on the beam. Even with active control, passive stability helps maintain the commanded attitude with less effort by the control system.

Conclusions

The design and implementation of the NEA Scout solar sail mission to visit an asteroid highlights several aspects of sail propelled missions that are in common with beamed propulsion missions to the outer solar system and to nearby stars, despite the large differences between the missions. Accurate knowledge of the spacecraft and target orbits are needed for both missions, while the accuracy for interstellar and precursor missions are far higher, because of the limited opportunities to correct the trajectory to account for uncertainties. Calibration of the force and torque model improves the navigation and attitude control performance of NEA Scout, and may be essential to meeting navigation requirements for an interstellar mission.

References

1) Johnson, L., Dervan, J., and McNutt, L.; *Near Earth Asteroid (NEA) Scout*; 4th International Symposium on Solar Sailing (ISSS 2017); January 17-20, 2017; Kyoto, Japan
2) Bach, V., Becker, C., Dervan, J., and others; *Near Earth Asteroid (NEA) Scout Solar Sail Implementation*; Small Satellite Conference, 2016, Logan, UT
3) Heaton, A., Ahmad, N., and Miller, K.; *Near Earth Asteroid Scout Solar Sail Thrust and Torque Model*; 4th International Symposium on Solar Sailing (ISSS 2017); January 17-20, 2017; Kyoto, Japan
4) Mori, O., Sawada, H., and others; *First Solar Power Sail Demonstration by IKAROS*; 27th International Symposium on Space Technology and Science, July 5-10 2009, Tsukuba, Japan
5) Ma, D., Murray, J., and Munday, J.; *Controllable Propulsion by Light: Steering a Solar Sail via Tunable Radiation Pressure*; Advanced Optical Materials, Vol 5, Issue 4, 2017
6) Orphee, J., Diedrich, B., Stiltner, B., Becker, C., and Heaton, A.; *Solar Sail Attitude Control System for the NASA Near Earth Asteroid Scout Mission*; 4th International Symposium on Solar Sailing (ISSS 2017); January 17-20, 2017; Kyoto, Japan