**NEA SCOUT-X: A COST-EFFECTIVE MISSION PERFORMING FLYBYS OF MULTIPLE NEAR-EARTH ASTEROIDS AND RENDEZVOUS.** R. Sood[1], J. Pezent[1] and A. Heaton[2], [1]Astrodynamics and Space Research Laboratory, Department of Aerospace Engineering and Mechanics, The University of Alabama, Tuscaloosa, AL 35487, USA (rsood@eng.ua.edu); [2]NASA Marshall Space Flight Center, Huntsville, AL 35812, USA.

**Introduction:** As a part of NASA's Exploration Mission One (EM-1), *thirteen* low-cost CubeSats were selected as secondary payloads to be launched with the Orion Multi-Purpose Crew Vehicle. With the delay in the launch of EM-1, NASA's Near Earth Asteroid (NEA) Scout mission has gone through a number of iterations. NEA Scout spacecraft is a 6U CubeSat that employs a solar sail as a low-thrust propulsion system to perform a close flyby of asteroid 1991 VG [1]. Although mission analysis shows that the target asteroid is still within the reach despite a two-year delay, setting the launch date no earlier than December 2019, alternate targets have also been considered. In the current investigation, contingency scenarios for NEA Scout mission are explored. Several additional candidate asteroids, that are of significant interest to the scientific community are also investigated as potential alternate targets. High-fidelity trajectory design and analysis was carried out to perform close flybys and rendezvous with one or more near-Earth asteroids [2].

**Dynamical Model:** To accurately model the behavior of the NEA Scout under the multiple gravitational and non-gravitational forces, a high fidelity dynamical model was developed. The system model is formulated in the international celestial reference frame (ICRF) and employs ephemeris data for the inertial time-dependent position history for all bodies under mutual gravitational influence. Additionally, a non-ideal square sail model, which accounts for the optical properties associated with the NEA Scout solar sail are incorporated to appropriately simulate the thrust generated by solar radiation.

**Launch Date Analysis:** A multiple near Earth asteroid flyby tour was considered as a possible contingency trajectory option in the event of the failure of the initial trim maneuver and a lunar flyby. This particular scenario was analyzed for EM-1 projected launch in December of 2019. Transformation of the contingency scenario to variable launch dates throughout the month of December 2019 resulted in a wide range of possible departure trajectories. Due to the large number of candidate asteroids heading towards the $L_5$ Lagrange point, launch dates that result in departure trajectories in the same direction (Dec 1$^{st}$ – Dec 31$^{st}$) were selected for further analysis. After the launch, the simulated trim maneuver failure and failed lunar flyby result in a range of states past the Moon's orbit at which point the sail is fully deployed and can be leveraged to perform adequate attitude maneuvers. Trajectories corresponding to possible initial position states are spread between December 17, 2019 and January 16, 2020 as illustrated in Figure 1.

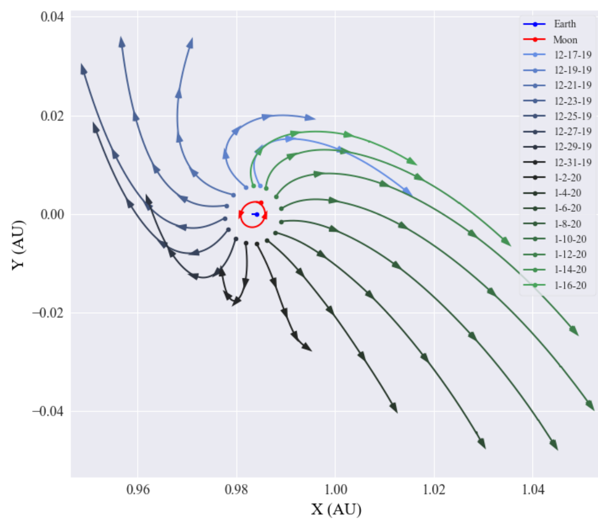

Figure 1: Initial corrective state (ICS) modified for the proposed launch in the month of December 2019. The ICSs are propagated for 75 days as viewed in the Ephemeris Sun – Earth rotating frame (Moon's trajectory is shown in red).

Note that the simulation assumes that the spacecraft launch window ranges from December 1, 2019 to December 31, 2019 [2]. Figure 1 makes it evident that the possibilities range in direction that the NEA Scout sail may be heading based on the selected launch date and the subsequent state when corrective maneuvers can be made. After one complete lunar orbit (shown in red), the trajectories propagate in the same general direction, i.e., the states propagated for 12-17-19 and 1-16-20 show directional similarities.

**Multiple Targets Selection Criteria:** A range of potential target asteroids exist that warrant further feasibility investigation. Primarily, based on the current technology onboard the existing NEA Scout spacecraft, potential targets were down-selected to meet the communication range barrier of 1 AU at the time of NEA Scout's asteroid flybys. Candidate asteroids for rendezvous were identified based on an analytical estimate for the time necessary for the NEA Scout to leverage the sail, thus, the solar radiation pressure, to match the orbital plane of the target asteroid [3]. Furthermore, the tour order was constructed from the targets that meet the communication barrier, the orbital plane change time, and exhibited small relative phase angles between the spacecraft and target asteroids, thus allowing fast and efficient transfers between subsequent targets.

**Multiple Flybys and Rendezvous:** A simulated tour is generated based on the criteria outlined above. As a test case, a low speed flyby of one asteroid is performed, following which, NEA Scout continues on its trajectory to perform a high speed flyby with the final target. In this example, asteroids 2008 EA9 and 2007 UN 12 were selected for low and high speed flyby, respectively. Owing to the small initial phase angle relative to Earth and the orbit being at a low inclination, asteroid 2008 EA 9 was chosen as the initial target. Whereas, asteroid 2007 UN 12 was selected as the follow-up target due to its small negative phase angle with respect to the potential flyby location of the first leg along the trajectory. The X-Y view of the converged NEA Scout flybys of the two asteroids is shown in Figure 2 as seen in the Sun-Earth rotating frame.

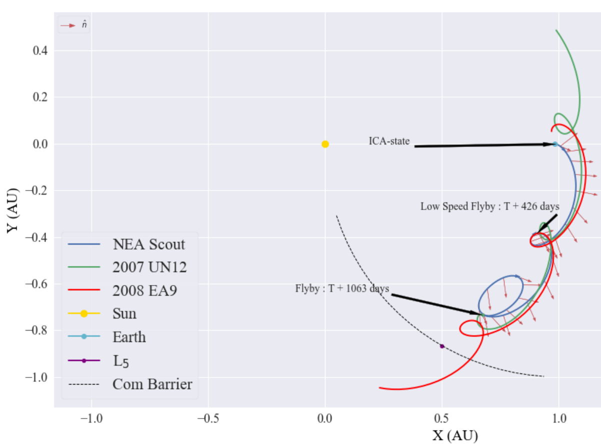


Figure 2: NEA Scout (blue) encounter with asteroid 2008 EA9 (red) at T + 465 days and a follow-up flyby of asteroid 2007 UN12 (green) as viewed in the Sun-Earth rotating frame. Where T is the initial launch date. The arrows along the blue trajectory represent the sail unit normal vector. The dotted arc marks the 1 AU communication barrier relative to Earth.

The initial leg fulfills NEA Scout's primary mission objectives of performing a low speed flyby with 2008 EA9 with TOF of 426 days (flyby distance: 130 m; flyby speed: 8 m/s). The spacecraft then departs towards 2007 UN12 and performs a high-speed flyby at 2.3 km/s from an altitude of 1.9 km.

**Conclusions:** Solar radiation pressure from the Sun can potentially offer unique maneuvering capabilities to a spacecraft equipped with a solar sail. In case of NEA Scout X, CubeSat technology, in conjunction with a sail, can be leveraged to perform close flybys and encounters with multiple near Earth asteroids, thus, preserving the cost-effective nature of the technology. In this work, high fidelity analysis of multiple asteroids flyby is carried out. The investigation also revealed that the NEA Scout spacecraft is capable of making low speed encounters with asteroids by leveraging the dynamics associated with the sail. The spacecraft was able to successfully demonstrate the potential of employing a sail to maneuver the CubeSat, adjusting the energy associated with the spacecraft, to perform close flybys of near Earth asteroids 2008 EA9 and 2007 UN 12 that are of significant interest to the scientific community. Additional mission scenarios are further investigated to generate tours with multiple NEAs.

**References:** [1] Johnson, L., McNutt, L., and Castillo-Rogez, J., *Near Earth Asteroid (NEA) Scout Mission* (2017); [2] Pezent, J. Sood, R., Heaton, A., *Near Earth Asteroid (NEA) Scout Solar Sail Contingency Trajectory Design and Analysis* (2018); [3] Macdonald, M. and McInnes, C. R., *Analytical control laws for planet-centered solar sailing* (2005).