

Enabling Multiple Small Satellite Near-Earth Asteroid Flyby Missions Using Small Solid Rocket Kick Stages with Rideshare Opportunities

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The large number of Near-Earth Asteroids (NEA's) provide almost daily launch opportunities to send small rideshare spacecraft to explore our nearest neighbors. Most asteroid missions require large spacecraft with a dedicated launch service. The large delta-V required for an interplanetary trajectory would typically preclude a NEA flyby rideshare unless it was going to the same target body as the primary mission. In this paper, a low-cost, compact, high energy kick stage with 3-axis steering is proposed that would enable this mission type. This kick stage is compatible with an ESPA ring so that multiple NEA missions can be deployed as rideshares on a single launch.

I. Nomenclature

<i>C3</i>	=	twice the orbit energy
<i>CCSFS</i>	=	Cape Canaveral Space Force Station
<i>COTS</i>	=	commercial, off the shelf
<i>DLA</i>	=	declination of the launch asymptote
<i>DV</i>	=	delta-velocity
<i>EME2000</i>	=	Earth's mean equator and mean equinox at 12:00 Terrestrial Time on 1 January 2000
<i>ESPA</i>	=	evolved expendable launch vehicle secondary payload adapter
<i>GEM</i>	=	generalized energy management
<i>GN2</i>	=	gaseous nitrogen
<i>GPS</i>	=	global positioning system
<i>GTO</i>	=	geosynchronous transfer orbit
<i>IMU</i>	=	inertial measurement unit
<i>Kg</i>	=	kilograms
<i>Km</i>	=	kilometers
<i>LV</i>	=	launch vehicle
<i>NEA</i>	=	near-Earth asteroid
<i>PHA</i>	=	potentially hazardous asteroid
<i>RLA</i>	=	right ascension of the launch asymptote
<i>ROM</i>	=	rough order of magnitude
<i>Sec</i>	=	seconds
<i>SECO1</i>	=	upper stage engine cutoff for park orbit injection
<i>SECO2</i>	=	upper stage engine cutoff for GTO injection
<i>SK</i>	=	Smallsat Kickstage
<i>SRM</i>	=	solid rocket motor
<i>TSRM</i>	=	third stage rocket motor
<i>TVC</i>	=	thrust vector control

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II. Introduction

Our nearest neighbors have potential for in-space resources, are of scientific interest, and sometimes pose a threat of future Earth impact. As of this writing, over 32,000 NEA's have been identified [1] and many more are expected to be discovered once the upcoming Near-Earth Object Surveyor mission is launched in 2028. Only a very small number of these bodies have been imaged by either space or Earth-based telescopes. A larger number of these bodies could be surveyed if low-cost spacecraft could be deployed on flyby missions as rideshares on larger commercial launches.

Rideshare payload orbits are typically limited by the requirements of a primary payload. The large delta-V required for an interplanetary mission would typically preclude flying as a rideshare unless it was going to the same body as the primary. The volume and mass available to a rideshare spacecraft is typically limited to what can fit onto an Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring [2] or similar payload accommodation. An example of such a mission was Janus, a pair of 35 kg spacecraft that would have been co-manifested with the upcoming Psyche mission. Janus would have explored two separate asteroids (1991 VH and 1996 FG3) [3]. Unfortunately, Janus was de-manifested after the Psyche mission was delayed from its original launch date.

A low-cost, compact, high energy propulsion system with 3-axis steering enables rideshare asteroid flyby missions. This technology already exists in the tactical missile systems used for interceptors by the U.S. military. An example of such a system is the Standard Missile Three (SM-3) Third Stage Rocket Motor (TSRM) [4]. A preliminary Smallsat Kickstage (SK) concept was developed based on the TSRM that could deliver up to 1800 m/s of delta-V for a Janus-sized spacecraft. The TSRM comes equipped with a Thrust Vector Control (TVC) system that can be easily interfaced with a flight computer for 2-axis steering during powered flight. A small cold-gas Attitude Control System (ACS) provides roll control during powered flight and 3-axis control during coast phases. A lightweight, tactical grade Inertial Measurement Unit (IMU) is used in conjunction with a Global Positioning System (GPS) receiver to provide navigation. The use of GPS implies that ignition must occur at a relatively low altitude, but that is consistent with the concept of operations since the SK burn will be most effective near periapsis. This paper will demonstrate the feasibility of this concept by providing a description of the integration with the Launch Vehicle (LV), flight sequence, and the detailed trajectory analysis for multiple rideshare spacecraft to conduct flyby's of various NEA's.

III. Smallsat Kickstage Concept

The following section discusses the overall SK concept. The design goal for this configuration is to maximize probability of success and minimize cost by:

1. Providing a simple interface between the spacecraft and the kickstage
2. Providing a simple interface between the kickstage and the launch vehicle.
3. Minimizing flight time by using a high thrust propulsion system.
4. Utilization of existing hardware that is mature and is in a high rate of production.
5. Taking advantage of rideshare opportunities on a year-round basis.
6. Providing a common design that can be mass-produced for a wide range of missions.

A. Hardware Configuration

The Smallsat Kickstage concept shown in Fig. 1 consists of an ASAS-13-30V TSRM mounted to a composite structure that is both an adapter to the ESPA ring and a mounting structure for other system components. Separation from the ESPA ring is accomplished via a RUAG 24" PAS 610 [5]. Separation of the spacecraft from the kickstage is provided by a Motorized Light Band (MLB) [6]. Pitch and yaw attitude control during the SRM burn is provided by the built-in Thrust Vector Control (TVC) on the SRM. Roll control during the SRM burn and 3-axis control during coast phase is provided by a pair of triaxially mounted cold gas thrusters [7] plumbed to a single ACS tank. A blended INS/GPS navigation solution is provided by a HG1900 Honeywell IMU [8] and a GPS receiver. Electrical power is provided by a pair of Lithium-Ion batteries [9]. Vehicle command and data handling is processed by a Space Micro flight computer [10].

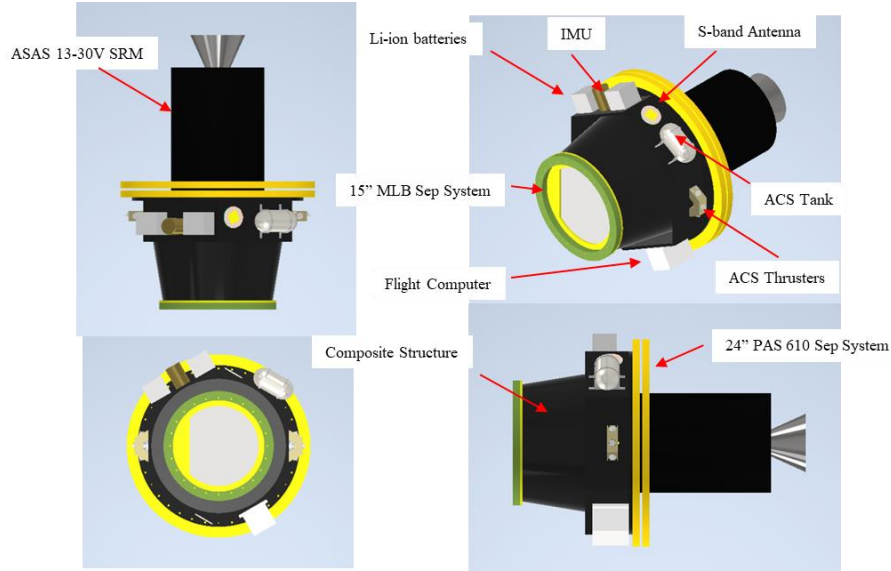


Fig. 1 Smallsat Kickstage Concept

B. Launch Vehicle Integration

The launch vehicle integration concept for two (2) SK's and their associated secondary payload volumes (blue) mounted to an ESPA-Grande adapter [2] within a 5-meter payload fairing envelope (green) is shown below in Fig. 2. This arrangement could accommodate up to four (4) spacecraft and still leave ample volume for a primary GTO payload. Note that a portion of the SK protrudes into the empty volume within the ESPA ring to maximize the available payload volume and to minimize cantilevered loads on the kickstage separation system. The available secondary payload volume in this example is a rectangular box with dimensions of approximately 700 mm x 700 mm x 900 mm.

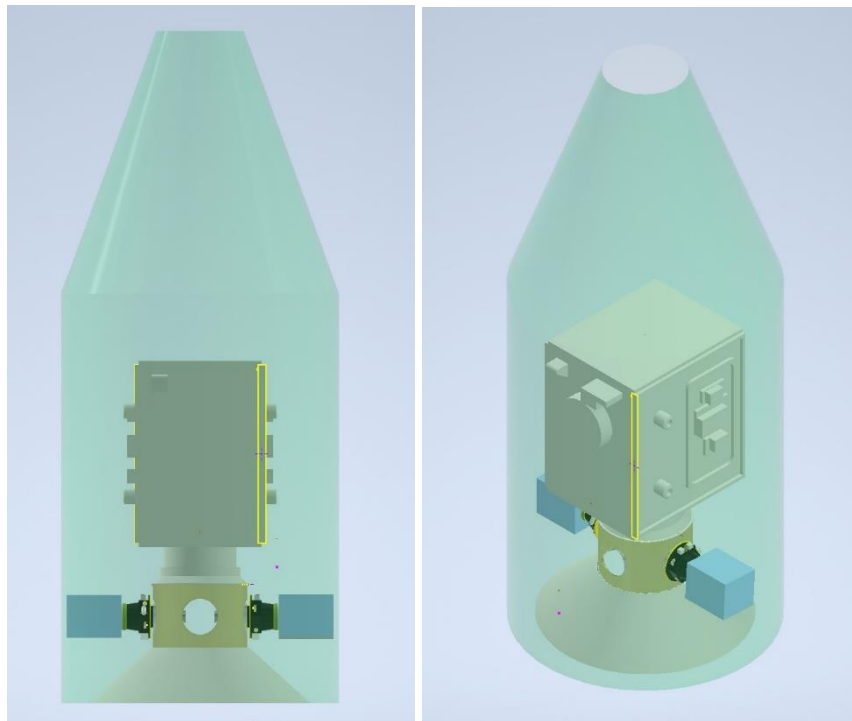


Fig. 2 Secondary Payload Volume with Smallsat Kickstage vs. a 5-meter Diameter Payload Fairing Envelope

C. Delta-V Capability

The delta-V capability of the SK for different spacecraft masses shown in Fig. 3 was determined from an estimate of the total system mass stack-up as shown in Table 1 and the motor parameters listed in Fig. 4. The mass stack-up was determined based on Commercial Off The Shelf (COTS) parts found in various vendor's online open-source catalogs (see Refs. [5] through [10] and Rough Order of Magnitude (ROM) predictions on the composite structure, cabling, GN2 plumbing etc. These masses are intended to be representative, and it is expected that the mass for a detailed design would be somewhat different than the estimates presented here.

Table 1 Kickstage Mass Stack-up

Item (spacecraft not included)	Mass, kg
Motor Total	113.8
Motor Propellant	88.8
Avionics Total	12.6
Proton 2x-Box™ Flight Computer	1.9
2 x SAFT 4S1P VES16 Li-Ion Battery	1.4
Isis S-band Antenna (2)	0.0
Honeywell HG1900 IMU	0.5
Cabling and Brackets (ROM)	8.8
ESPA Sep System Total	5.8
PAS 610 Upper	1.0
PAS 610 Lower (stays w/LV)	4.8
Spacecraft Sep System Total	2.6
15" MLB Upper	0.7
15" MLB Lower	2.0
Attitude Control System Total	3.2
Adelis-Samson ACS Tank	0.4
N2 Propellant	0.5
Latch Valve	0.0
Pressure Regulator (2)	0.2
Fill and vent valve, tubing, brackets, etc. (est)	0.6
Thruster Assy, 3xMOOG 58E163A ea. (2)	1.4
Structure Total	17.5
Composite Adapter + Avionics Module (ROM)	15.3
Joint Fasteners (ROM)	2.1
System Total	155.5
System Flyaway	150.7
System Burnout	61.9

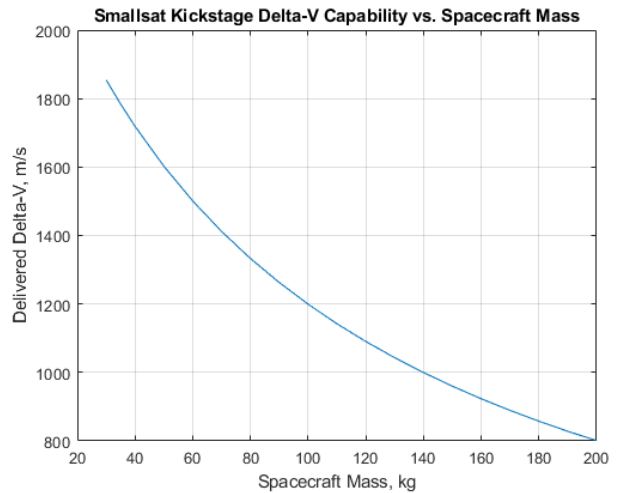


Fig. 3 Smallsat Kickstage Delta-V

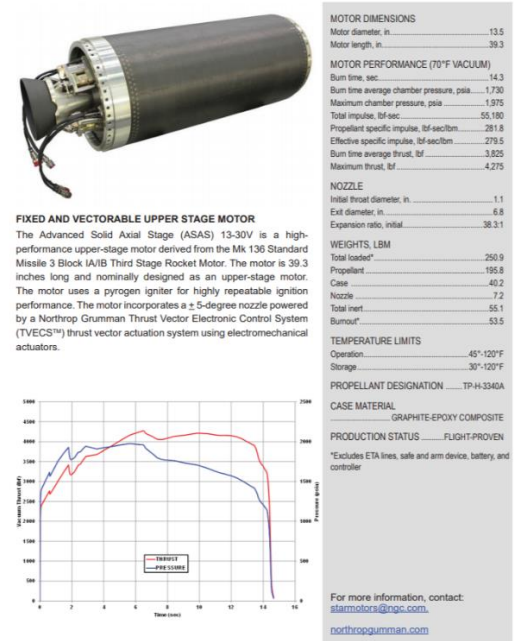


Fig. 4 ASAS 13-30V SRM, Reproduced from Ref. [4]

D. Flight Sequence

Shortly after separation of the primary payload, each SK will receive a command from the launch vehicle indicating that separation is imminent. The onboard GPS receiver is used to determine the calendar day which will be used as the argument to a lookup table of hyperbolic orbit targets within the flight software. Based on these targets as well as the GPS position and velocity state, the SK guidance will determine the commanded ignition attitude. Prior to SK separation, the launch vehicle will inhibit any ACS firings to minimize the probability of recontact during deployment from the ESPA ring. Once the separation command is issued, break wires will indicate to the SK that separation has occurred. Shortly after separation is detected, the SK ACS in 3-axis mode will re-orient the vehicle to the desired ignition attitude while onboard guidance calculates the necessary energy scrubbing maneuver to achieve the desired hyperbolic insertion state. Once the correct conditions have been achieved, ignition is commanded. During the SK motor burn, pitch and yaw steering are accomplished with the TVC system while the ACS maintains roll control. The vehicle energy management guidance algorithm will target the desired insertion state based on a nominal set of motor performance curves. Once burnout is detected by a low threshold on axial acceleration, the ACS system will switch from roll-axis mode to 3-axis mode and slew to the desired separation attitude. After waiting for a period long enough for motor tail off to dissipate, the spacecraft will be separated from the SK. Following spacecraft separation, a collision avoidance maneuver is conducted, followed by blowdown of any remaining ACS propellants. End of mission occurs once batteries have been depleted, rendering the SK passive.

E. SK Burn Environments

The high thrust of the TSRM and the relatively light payloads envisioned in this discussion have the unfortunate result of large quasi-static acceleration environments for the spacecraft. Also of potential concern will be higher vibration loads and thermal soak-back from the TSRM. However, recent advances in guided projectile technology have demonstrated that sophisticated sensors can survive much harsher environments than what is expected from this system [11]. Spacecraft payloads for the SK will need to be designed for the higher environments encountered during the SK burn in addition to that from the primary LV.

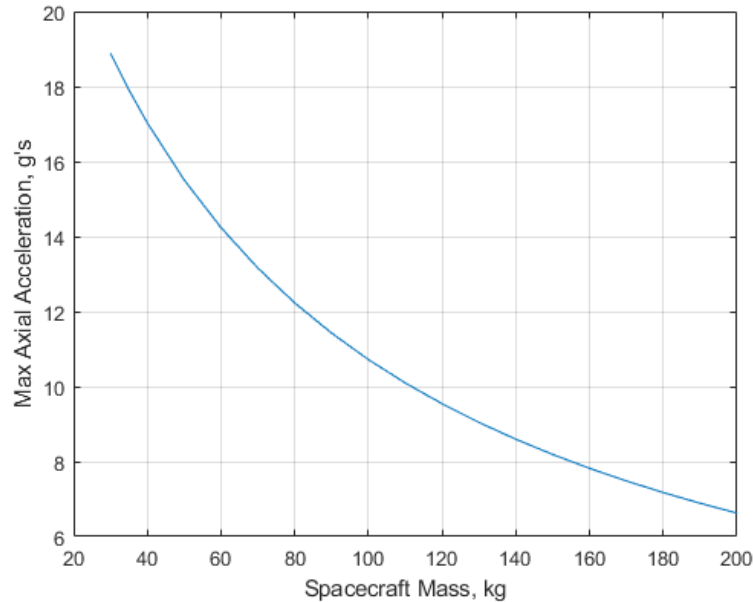


Fig. 5 Maximum Axial Acceleration vs. Spacecraft Mass

IV. Trajectory Analysis Methodology

This section discussed the trajectory analysis methodology used to determine a set of feasible trajectories for a SK with four (4) 35 kg payload from a GTO to their respective NEA targets. This analysis consisted of:

1. A rapid survey of accessible objects using Lambert's method [12]
2. Followed by a detailed analysis assuming a GTO starting point using Copernicus [13] .
3. The resulting targets from the Copernicus analysis were refined using a detailed Launch Vehicle (LV) simulation in POST2 [14]
4. The resulting injection states were confirmed via simple orbit propagation to the targeted body.

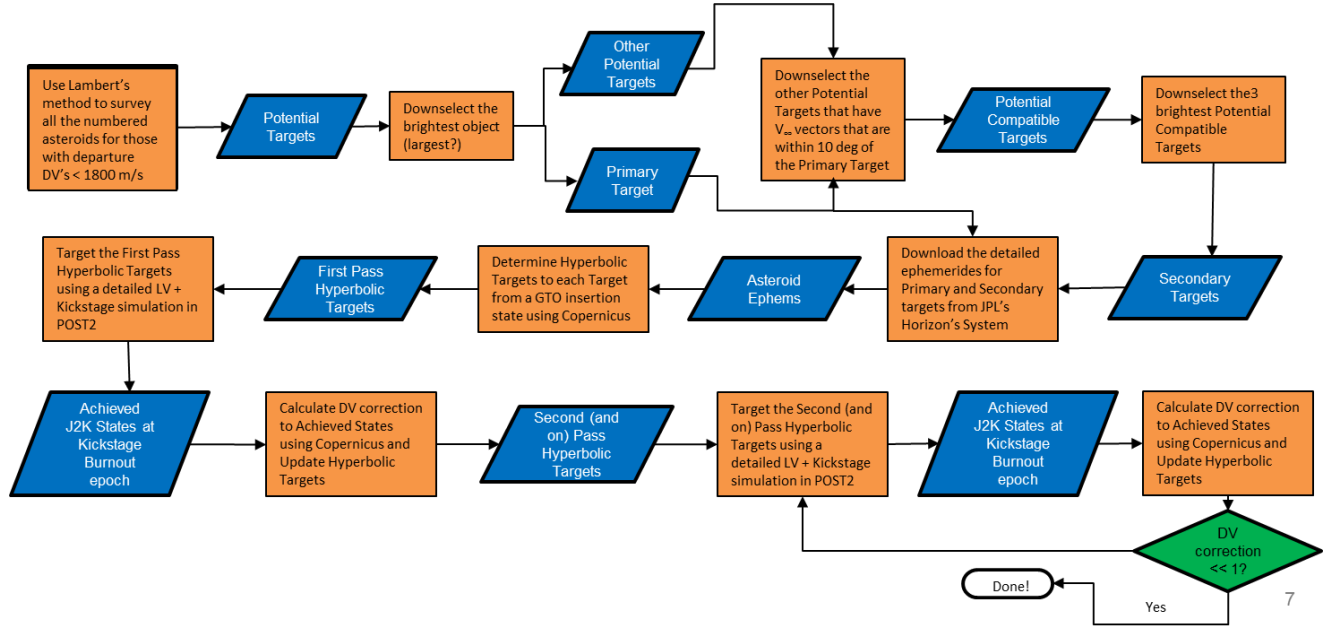


Fig. 6 Trajectory Analysis Methodology Process

A. Lambert Survey

A low-fidelity survey of the entire catalog of numbered asteroids (620,108 objects, not just NEA's) [15] was conducted using for a launch opportunity spanning the 2028 calendar year. The survey was conducted as follows:

1. The departure delta-V's for all the asteroids in the catalog based on their two-body orbital elements were determined for a given launch date using Lambert's method.
2. The asteroids the departure delta-V's within the capability of the kickstage were identified as **Potential Targets** for a flyby mission.
3. These **Potential Targets** were then sorted by apparent magnitude with the brightest automatically selected as the **Primary Target**. Note that this selection criterion was somewhat arbitrary, but since there is a correlation between apparent magnitude and size, this was used in order to skew the results towards larger objects.
4. The **Potential Compatible Targets** were identified by comparing their departure V_{∞} vectors of the other **Potential Targets** against that of the **Primary Target** with the retention criteria being that they be within 10 deg of each other.
5. The **Secondary Targets** were selected from the three brightest of the **Potential Compatible Targets** for further analysis.

A **Primary Target** and three (3) **Secondary Targets** were identified for each day in the opportunity.

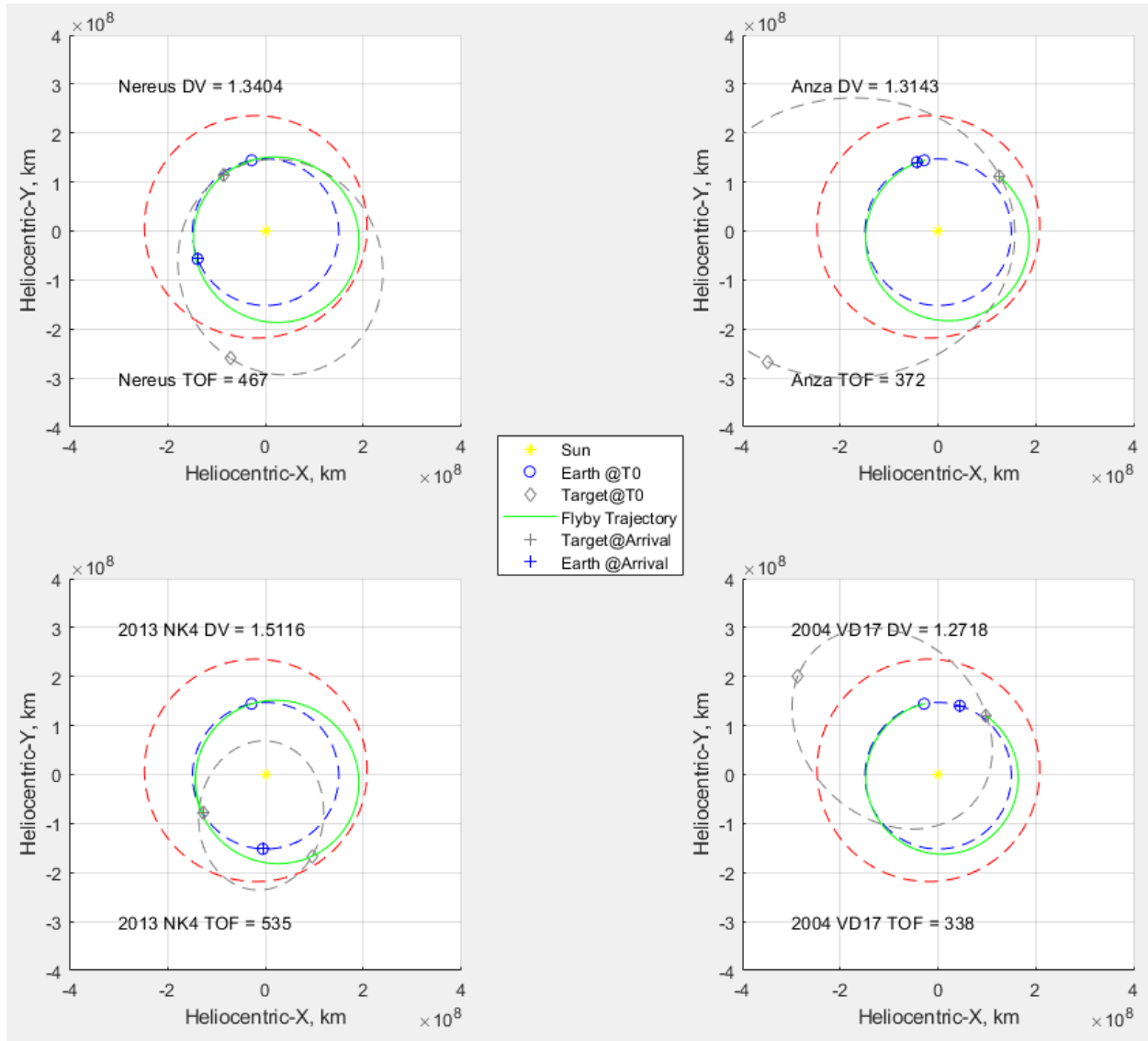


Fig. 7 NEA Flyby Opportunities Launched as Secondaries on a Single GTO Mission on January 1, 2028

B. Development of Hyperbolic Targets from GTO

A subset of these launch opportunities was analyzed using detailed asteroid ephemerides and the industry standard Copernicus mission analysis software. The initial state assumed that the NEA rideshare missions were co-manifested on a single Geo-Synchronous Transfer Orbit (GTO) launch from the Cape Canaveral Space Force Station (CCSFS), but the Right Ascension of the Ascending Node (RAAN) was free to be optimized for the NEA rideshare missions.

Table 2 GTO States Common to all Launch Dates (Earth-Centered-Earth-Fixed Coordinates)

Orbit Parameter	Value
X (km)	6563.090
Y (km)	24.840
Z (km)	0.013
VX (km/s)	-0.033
VY (km/s)	8.656
VZ (km/s)	-4.654

While the initial RAAN of the GTO injection state is common for all four spacecraft initial states, the true anomaly at SK ignition was allowed to vary from 10 deg to 180 deg for each NEA mission since that parameter can be targeted by delaying the kickstage ignition time. The lower true anomaly threshold of 10-deg was implemented to ensure adequate time for the primary spacecraft to be deployed near periapse. The use of 3-axis steering on the SK permits a variable delta-V to be applied to each spacecraft for a fixed spacecraft mass of 35 kg. This is accomplished via an energy scrubbing maneuver such as the Generalized Energy Management (GEM) algorithm [16] . An example for a January 1, 2028 launch date is shown below in Fig. 8 and Table 3.

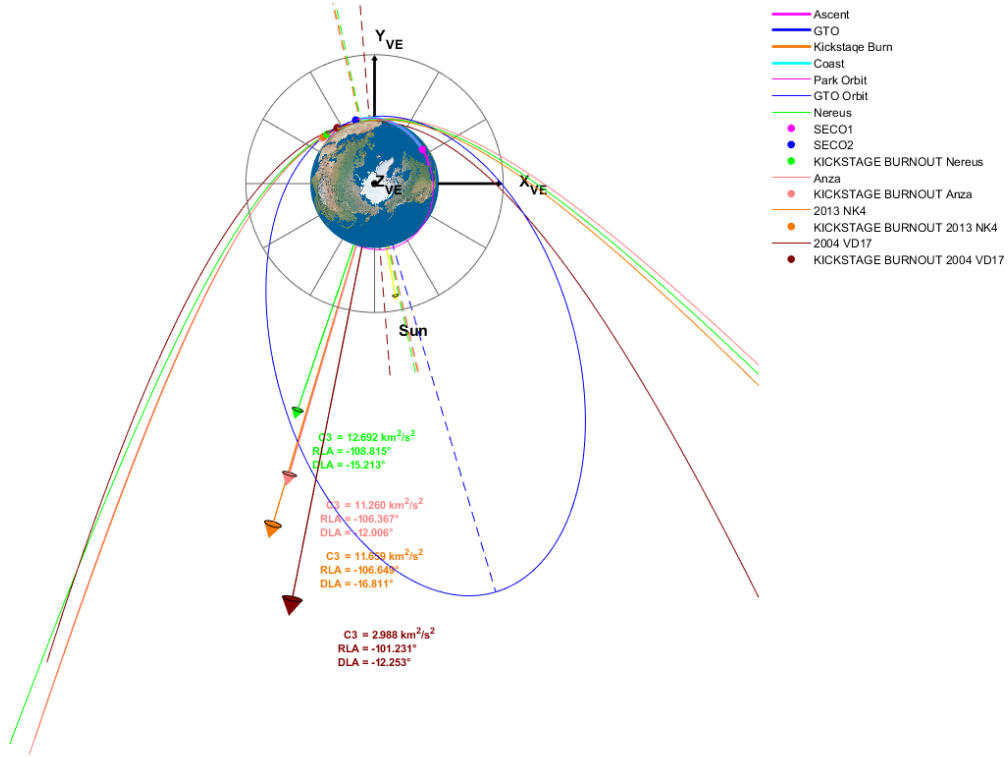


Fig. 8 Rideshare NEA Flyby Trajectories Achieved from a Single GTO Launch from CCSFS using SKs

Table 3 Rideshare NEA Hyperbolic Orbit Targets for the January 1, 2028 Launch Date Co-Manifested with a GTO Launch in EME2000 Coordinates

Target Asteroid	GTO RAAN (deg)	Time of Flight (days)	C3 (km ² /sec ²)	RLA (deg)	DLA (deg)	Geocentric Altitude at Ignition (km)	DV from GTO (km/s)
Nereus	-73.367	467	12.692	-108.815	-15.213	596	1.340
Anza	-73.367	372	11.260	-106.367	-12.006	753	1.314
2013 NK4	-73.367	535	11.659	-106.649	-16.811	690	1.512
2004 VD17	-73.367	338	2.988	-101.232	-12.253	352	1.272

C. Refinement of Hyperbolic Targets using a Detailed LV Simulation

To check the validity of the hyperbolic targets generated by Copernicus, a launch vehicle trajectory simulation was run in POST2 [14] with 4 separate kickstage branch trajectories targeting one of the four asteroids flown from the common GTO orbit. As can be seen in Fig. 9 and Table 4, the SK burn events occur over Southern Africa and within a time span of a few minutes of primary spacecraft separation. This is advantageous from a telemetry ground station standpoint. However, further analysis will be necessary to ensure that there is an acceptably low risk of collision and/or contamination between the SK's and the primary GTO spacecraft.

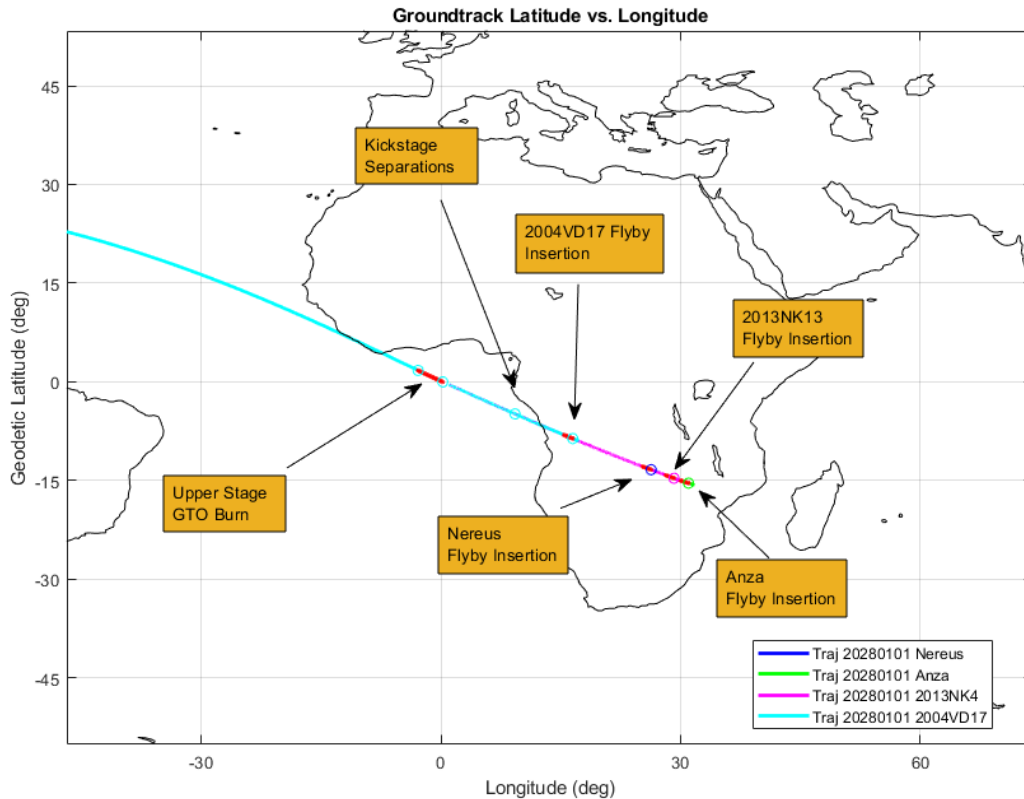


Fig. 9 Geographical Location of Kickstage Events for the January 1, 2028 Launch Date

Table 4 Sequence of Events for the January 1, 2028 Launch Date

Event	Time Since SECO-2, sec
SECO-2	0.0
Primary Spacecraft Separation	60.0
Kickstage Separations	120.0
2004 VD17 Flyby Insertion	216.8
Nereus Flyby Insertion	744.2
2013 NK13 Flyby Insertion	770.4
Anza Flyby Insertion	788.3

D. Final Cleanup of POST Injection States vs. Propagation to Asteroid Flyby

The insertion states at kickstage burnout from the POST2 runs were then ingested back into Copernicus and a DV cleanup maneuver was implemented to correct any differences between the expected asteroid close approach conditions and the propagated flyby trajectories. Due to differences in the achieved GTO from POST and the assumed GTO orbit used in Copernicus, some cases initially required DV cleanup maneuvers of approximately 10's m/s. The hyperbolic orbit targets were updated based on this first pass DV cleanup maneuver and the POST2 trajectories were re-run in a second pass. The achieved second pass insertion states were passed to the Copernicus DV cleanup and the magnitude was reduced to be < 1 m/s.

V. Analysis Results

In order to demonstrate that this type of mission is feasible over an extended launch period, a month-long set of targets was analyzed for a 30-day launch period starting on 1 January 2028 through 30 January 2028. Efforts were made to maintain a common set of targets over a period of several days with minimal changes from day to day for operational simplicity. It was found that a launch near UTC midnight was generally the most favorable for a secondary mission to an interplanetary object because it places the vehicle inertial velocity vector close to the Earth's heliocentric inertial velocity vector when the AoP is 180-deg.

A. Asteroid Targets Identified for a January 2028 Launch Opportunity

A total of eight (8) different asteroids were identified as shown in Fig. 10. With the exception of Toutatis, which was imaged by the Chang'E 2 spacecraft in 2012 [17], these objects have not visited by a spacecraft. This is by no means an exhaustive list, and many other asteroids were identified that would also be within reach of a system with these capabilities. As noted earlier, these targets were selected to minimize changes across the various launch dates.

Further details on these targets is listed in Table 5. These objects belong to three different asteroid categories (Apollo, Aten, and Amor) and with the exception of Anza are in the Potentially Hazardous Asteroid (PHA) category. Note that Nereus is an object of particular interest because of the fact that it has regular close approaches to Earth and has an overall round trip DV requirement for a crewed rendezvous and return mission that is comparable to the Moon [18]. Target sizes range from a few 100 m to several km in diameter.

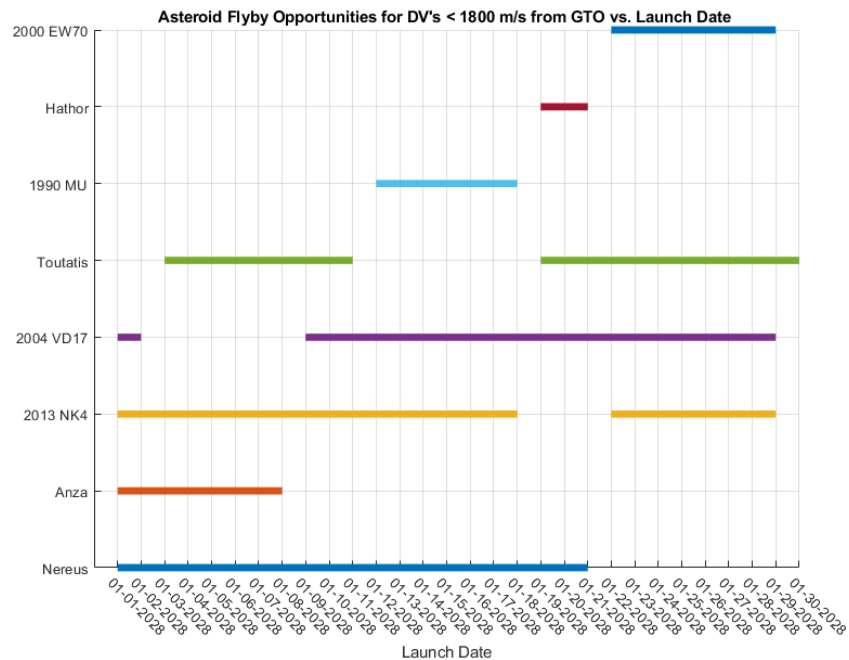


Fig. 10 Possible Flyby Targets for each Launch Date in the January 2028 Opportunity

Table 5 Asteroid Target Sizes and Classifications

Asteroid Name	Catalog Number	Diameter, km	Type	Potentially Hazardous?	Image
Anza	2061	2.6	Amor	No	None
2013 NK4	439437	0.6	Apollo	Yes	None
2004 VD17	144898	0.5 – 1.0	Apollo	Yes	None
Nereus	4660	0.5	Apollo	Yes	Yes [18]
Toutatis	4179	2.5	Apollo	Yes	Yes [17]
1990 MU	4953	2.8	Apollo	Yes	None
Hathor	2340	0.2	Aten	Yes	None
2000 EW70	234145	0.3	Aten	Yes	None

B. Delta-V Requirements

The Delta-V from GTO to each asteroid target is shown in Fig. 11. Note that the maximum Delta-V is approximately 1800 m/s for a spacecraft mass of 35 kg. Note also that the Delta-V curve is not necessarily smooth for each target. This is due to the fact that the optimizer in POST-2 is only looking for a feasible rather than an optimal solution to the equivalent hyperbolic targets.

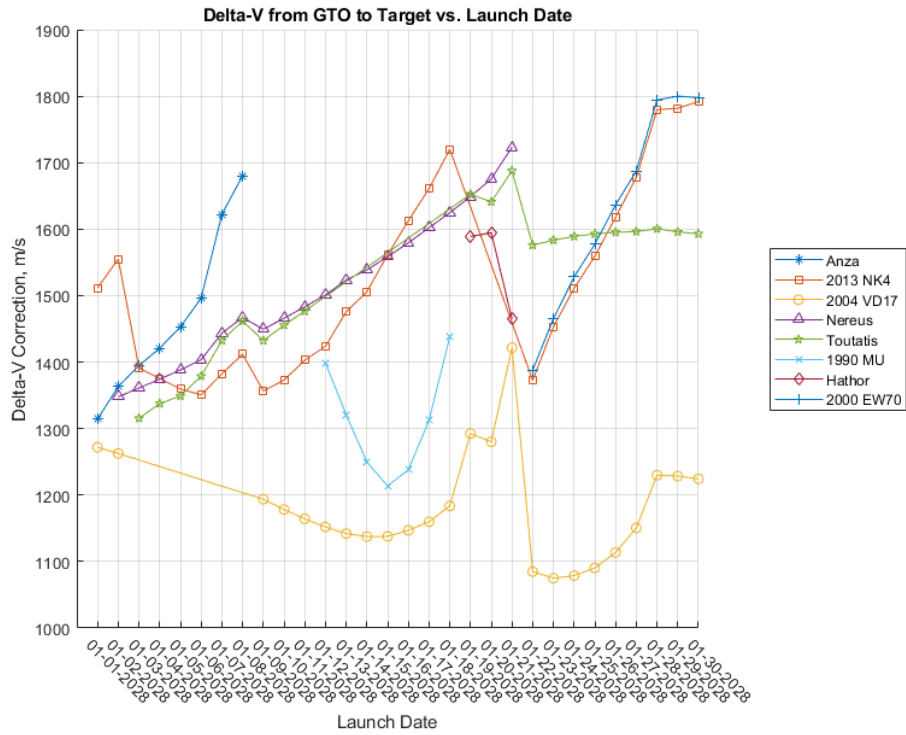


Fig. 11 Delta-V from GTO to Various Asteroids vs. Launch Date

C. Kickstage Departure Hyperbola and Conditions at Ignition

The hyperbolic orbit targets for each kickstage mission opportunity is shown in terms of orbit escape energy (C3), Right Ascension of the Launch Asymptote (RLA) and Declination of the Launch Asymptote (DLA) in Fig. 12 through Fig. 14 respectively. The targets for a given asteroid target generally follow a similar trend across the launch opportunity. The injection altitude for the SK is shown in Fig. 15 and demonstrates that insertion is well below the GPS constellation altitude, which should allow GPS to augment the IMU navigation solution throughout the kickstage burn.

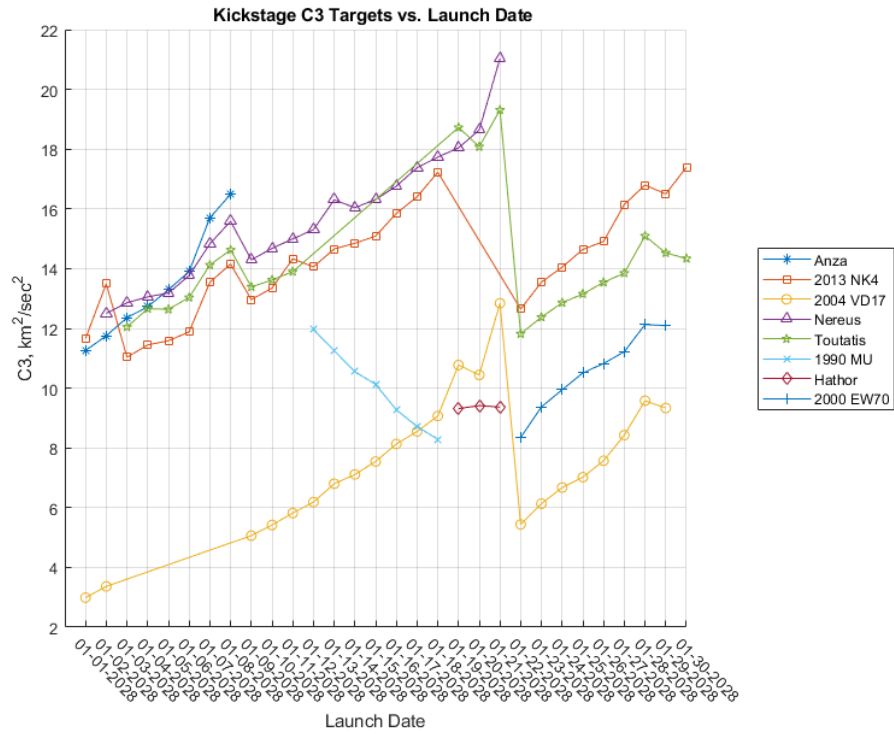


Fig. 12 Kickstage C3 Target vs. Launch Date for the January 2028 Opportunity

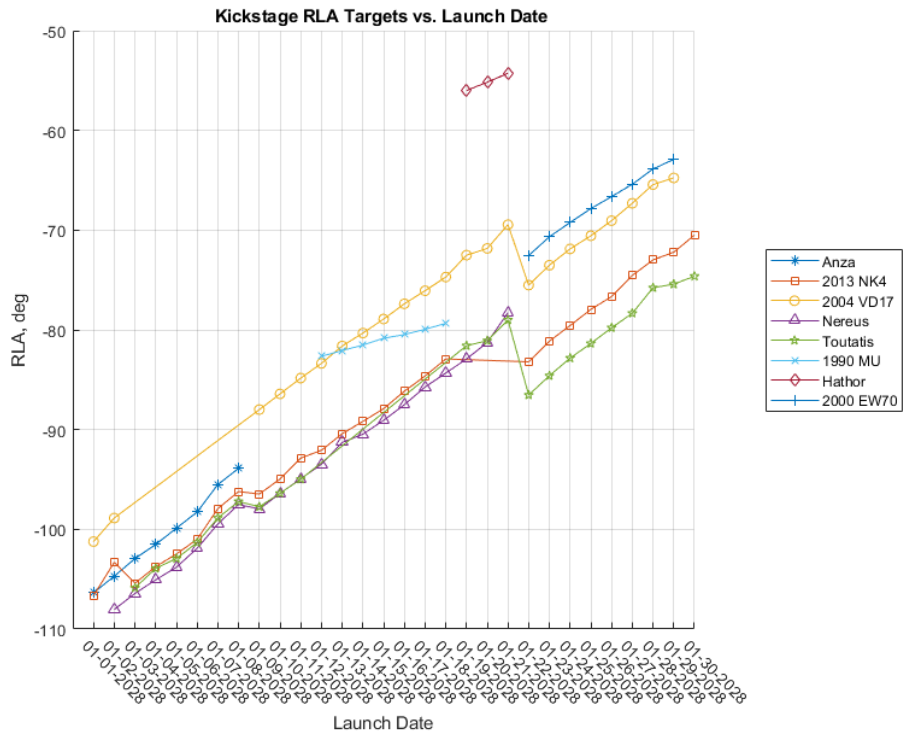


Fig. 13 Kickstage RLA Target vs. Launch Date for the January 2028 Opportunity

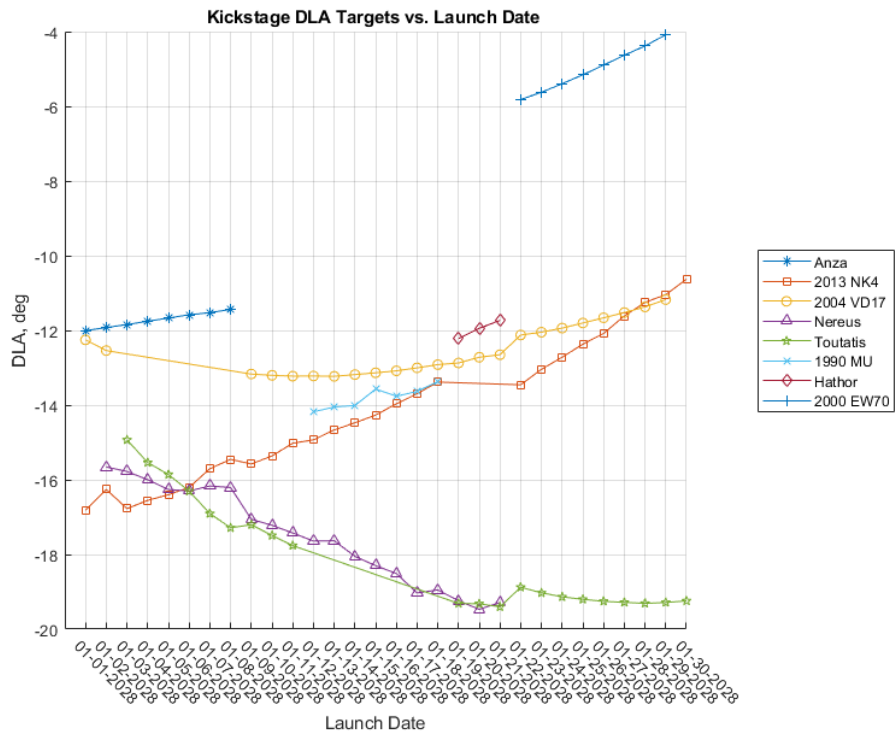


Fig. 14 Kickstage DLA Target vs. Launch Date for the January 2028 Opportunity

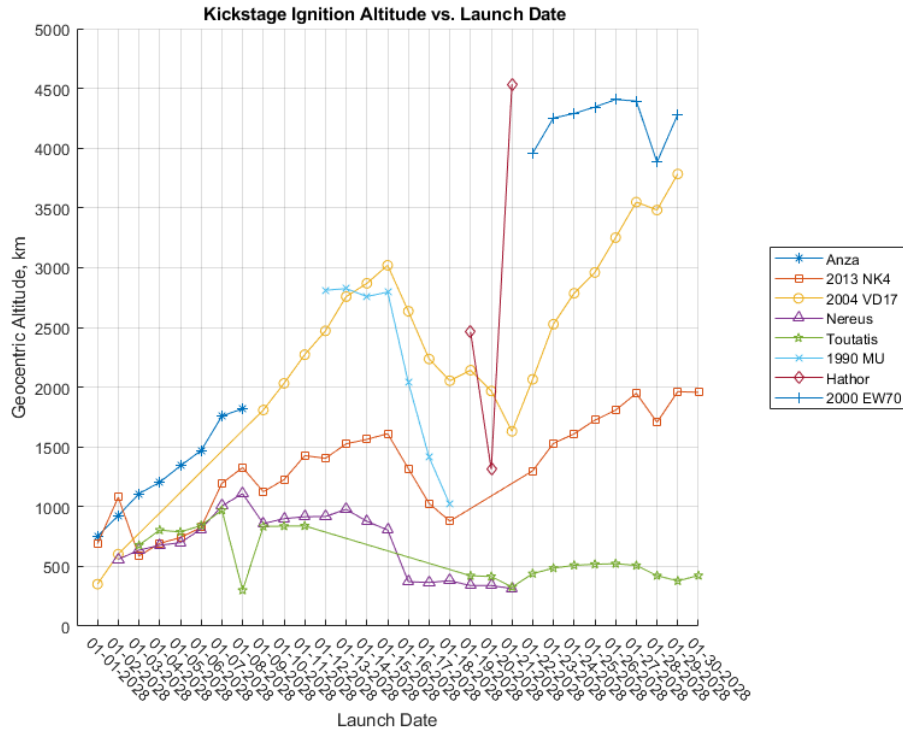


Fig. 15 Geocentric Altitude at Kickstage Ignition

VI. Conclusions and Future Work

Multiple secondary missions to different NEA's using small solid rocket motor stages mounted on an ESPA ring on a single GTO launch has been shown to be feasible. This concept allows flyby missions to be conducted at lower cost due to the re-use of military grade hardware that has already been qualified to a rigorous set of environments and the through the use of cost-sharing on the launch service with up to three (3) other NEA missions and a primary payload customer. Due to the commonality of these types of flyby missions, a single spacecraft design could be capable of servicing a wide variety of asteroid targets, allowing cost-reduction through economies of scale.

Future work to develop this concept further is as follows:

1. Conduct an insertion accuracy analysis of the SK that accounts for motor impulse uncertainties, navigation errors and other dispersions. Due to the fact that kickstage ignition can occur at altitudes up to 5000 km, a detailed analysis of GPS performance will be necessary.
2. Investigate the appropriate flight sequence groundrules to avoid contamination and collision between the kickstages and the primary spacecraft.
3. Engage the spacecraft community to determine the appropriate spacecraft configurations for NEA flyby missions with a mass of 35 kg.
4. Examine the necessary contractual mechanisms and agreements that would allow a transfer of excess TRSM's as Government Furnished Equipment (GFE) to NASA and/or its contractors for integration into a SK.
5. Determine a set of requirements for a SK service.

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