

A Continuous Low-Thrust Maneuver Automation System for Electric Propulsion LEO Satellite Operations

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Abstract

Planet operates around 20 high-resolution Earth observation satellites with propulsive capabilities, known as SkySats, Pelicans, and Tanagers. These satellites execute maneuvers for station-keeping, orbit adjustments, and collision avoidance. The newest of these satellites, Pelicans and Tanagers, contain electric propulsion systems to facilitate agile, low-orbit operations. To reduce operator involvement, streamline operations, and improve space situational awareness across the fleet, a ground-based Continuous-thrust Maneuver Automation System (CMAS) was developed. This system builds upon the infrastructure developed for the impulsive maneuvers conducted by the SkySat fleet's chemical propulsion system as defined by our existing Maneuver Automation System (1). The work presented here constitutes a fundamental operational shift from an impulsive to a continuous low-thrust maneuver paradigm.

This conference paper presents the high-level system architecture of CMAS, including algorithm improvements, optimization techniques for maneuver planning, and evaluation logic. Key features of the system will be highlighted, one such example being the minimization of propellant usage through an informed, multi-variable approach which explores a higher fidelity search space while adhering to satellite hardware and mission constraints. Another key feature of CMAS is its ability to consume new telemetry, orbit determinations, and conjunction warnings as they are generated, continuously adapting to an ever-changing feed of new information. As telemetry from executed maneuvers is downlinked, CMAS reconstructs the resulting shift in orbital parameters and re-optimizes all future maneuvers in the campaign. Operational trade-offs that were considered during the development and tuning of this automation system will also be presented, including a novel error function that autonomously prioritizes maneuver targets which are favored by current orbital perturbations.

As part of the optimization strategy, CMAS includes a global Low-thrust Campaign Planner (LCP) to ensure orbital targets are met efficiently and on a timely basis. The LCP can model various campaigns that simultaneously target multiple orbital parameters including semi-major axis, eccentricity, and inclination. These campaigns can be defined as curves through this multi-parameter space. Finally, the various campaigns can be compared by various metrics such as fuel efficiency and total elapsed time. We will discuss a high-level overview of this algorithm and how the LCP can be used both as a standalone R&D tool and as part of the greater CMAS automation.

This paper highlights the design, implementation, and impact of a novel Continuous-thrust Maneuver Automation System, as well as provides insight into the challenges of sustainable operation in the space environment. With its integrated campaign planner, CMAS empowers the long-term operation of a fleet of Earth observation satellites with electric propulsion systems unlike any that Planet has flown before.

Keywords: Maneuver Optimization, Satellite Operations, Conjunction Mitigation, Space Safety, Electric Propulsion

Acronyms/Abbreviations

Application Programming Interface (API)
Campaign Operational Bounds (COBs)
Continuous Maneuver Automation System (CMAS)
Informed Merit Function (IMF)

Keplerian Elements (KEs)
Low-thrust Campaign Planner (LCP)
Maneuver Operational Bounds (MOBs)
Merit Function (MF)
Mission Control (MC)
Operational Bounds (OBs)
Orbit Determination (OD)
Probability of Collision (PoC)
Weighting Factors (WFs)

1. Introduction

Planet Labs PBC is a leading provider of global, daily satellite imagery and geospatial solutions. Founded in 2010 by a team of former NASA scientists, Planet designs, builds, and operates the largest fleet of Earth observation imaging satellites, with a mission to image the entire Earth everyday, and to make global change visible, accessible, and actionable [1]. Planet has launched more than 500 satellites to space, and currently operates a heterogeneous constellation consisting of over 150 medium resolution imagery (3-5 meters per pixel) satellites known as Doves, and around 15 high resolution (enhanced ortho spatial imagery of up to 50 centimeters per pixel) imagery satellites known as SkySats [2]. Planet recently launched 2 new constellations: (1) Pelican, which consists of Planet's next-generation high-resolution tasking satellites; and (2) Tanager, consisting of Planet's hyperspectral imagery satellite. The high-resolution Pelican constellation aims to improve upon SkySats in capacity, speed, and accuracy, whereas the Tanager constellation aims to complement Planet's existing dataset by providing hyperspectral data.

Planet downlinks more than 300 million km² of imagery daily, the current operational constellation capacity. This is enabled by a highly automated and scalable Mission Control (MC) and operations, as well as by a large network of ground stations. Planet's core offering, however, is accessing both the information gathered from space and the tools necessary to gain valuable insights that allow users to make data-driven, real-time decisions [3].

In order to operate the Pelican and Tanager fleets effectively, we must execute maneuvers for station-keeping, orbit adjustment, collision avoidance, and, initially, orbital insertion. These new fleets aim to be more agile than previous Planet satellites in order to deliver data to customers quicker, hence they are targeting very low Earth orbits. This increases the importance of executing maneuvers regularly and reliably to maintain the orbital health of the fleet, not just on a per-maneuver basis, but on longer mission timelines as well.

A maneuver automation system (MAS) was developed for the SkySat fleet [3], however these Pelicans and Tanagers employ electric propulsion systems which required an overhaul to the underlying maneuver planning architecture. While chemical propulsion burns executed by SkySats can be considered impulsive events, electric propulsion systems deliver much longer finite burns (on the order of tens of minutes) which are required to be modeled as continuous force events. Electric propulsion systems also execute maneuvers with much higher specific impulse and lower overall thrust, thus necessitating the consideration of numerous factors such as the evolving attitude of the satellite and orbital perturbations during each burn.

In order to account for this change in hardware, a novel Continuous Maneuver Automation System (CMAS) was developed to plan optimal maneuvers based on various factors, such as altitude, inclination, propellant usage, available ground station accesses, orbital perturbations, and more. Next to ensure overall mission goals are met, such as operational target orbits and mission lifetime, a Low-thrust Campaign Planner (LCP) was developed to simulate many future maneuvers and feed this information into CMAS to provide single-burn targets. The algorithmic and systemic updates required to address these challenges and implement both maneuver-level and mission-level automation systems will be detailed in the following sections.

2. Low-thrust Campaign Planner and Continuous Maneuver Automation System Architecture

The system architecture, depicted in Figure 1, highlights LCP as the overarching governor of CMAS actions, dynamically aligning operations with a globally optimal campaign strategy. Both the campaign strategy (LCP) and the single maneuver execution (CMAS) are governed by boundary, safety, and legal constraints. These Operational

Bounds (OBs) interact on different levels to achieve the desired final conditions while preserving fuel and extending the SC's operational lifetime.

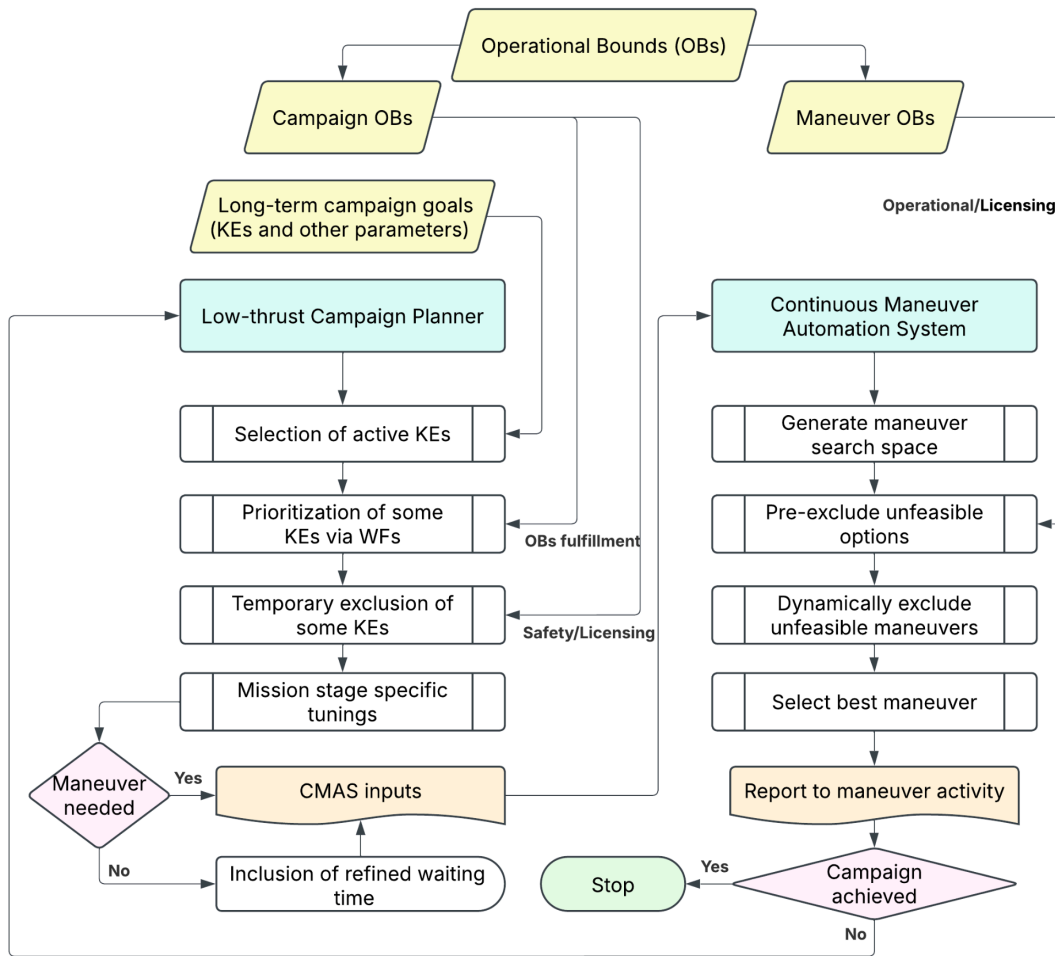


Fig. 1. LCP and CMAS System Architecture

A sample list of the potential COBs and MOBs that might activate or perform checks during each campaign or maneuver planning process is presented in Table 1 below.

Table 1. Examples of Campaign and Maneuver Operational Bounds

Bound	Metric	Description
COB	Eccentricity	If eccentricity is greater than the maximum allowed, restoration WFs are induced, and any potential propellant-saving maneuver wait time is ignored.
	Deviation KE	If a targeted KE is within tolerance, the target is deprioritized to ensure a more robust optimization of the remaining targets.
	Minimum Altitude	Ensures that the orbit's perigee is safely above the licensing/safety limit.
MOB	Duty cycle	Ensures that the search space comprises only maneuvers with specific minimum and maximum burn durations to comply with other requirements.

Burn locations	Verifies that the proposed burn start and end times are within safe and operationally feasible regions.
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Protected windows	Ensures that maneuvers cannot overlap protected windows in line with safety, operational, or strategic constraints.
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OBs are categorized into Campaign Operational Bounds (COBs) and Maneuver Operational Bounds (MOBs). COBs primarily govern broader campaign requirements, managed by LCP, while MOBs focus on individual maneuvers and are enforced within CMAS. Maneuver planning in CMAS targets one or more Keplerian Elements (KEs) or derived perturbative values. LCP assigns weighting factors (WFs) to guide CMAS in prioritizing targets dynamically. For instance, during circularization, WFs may prioritize eccentricity adjustments over semimajor axis changes when the latter is near optimal. If COBs are violated, LCP can impose more aggressive WFs to compel CMAS to prioritize corrective maneuvers. In critical situations, LCP may even ignore specific COBs if respecting them makes it impossible to satisfy other specific COBs that drift too far out-of-bounds.

LCP and CMAS coordination also involves mission stages, which define distinct operational phases and constraints. Operational mission stages include standard targeting, station-keeping, and orbital plane precession, while simulation strategies add decay mission stages for safety and recovery analyses. These mission stages dynamically adjust OBs to match mission priorities. For instance, a lowering mission stage aims to reach operational altitude quickly, constrained by propulsion, thermal, and electrical limits. In contrast, a station-keeping mission stage prioritizes fuel conservation, executing maneuvers only when strictly necessary.

In this context, LCP ensures MOBs align with COBs while verifying long-term campaign objectives. For example, LCP can delay a maneuver if propagation shows the SC will remain within safety bounds for altitude and eccentricity during station-keeping, postponing action until required.

3. CMAS Maneuver Planning

CMAS evaluates both nominal and critical scenarios, executing maneuvers only when safe and avoiding plans when demonstrably unsafe. Planning a series of low-thrust maneuvers while adhering to all OBs and addressing potential conjunction events requires precision and strict compliance with the SC's force model.

The integration of CMAS with LCP ensures a balance between real-time maneuver planning and long-term simulation. To maintain consistency with other SC trajectories, CMAS employs a high-fidelity n-body dynamical model that includes Earth spherical harmonics, atmospheric drag, third-bodies perturbations, solid tides, and solar radiation pressure. Unlike LCP, which uses a truncated 10x10 harmonic resolution for faster long-term simulations, CMAS employs higher fidelity in both degree and order.

When CMAS receives targets, OBs, and configurations from LCP, its objective is to determine the most efficient, minimum-propellant maneuver to achieve the desired outcomes. The merit function (MF) implemented in CMAS is designed to adapt to various target combinations and external factors. LCP's WFs ensure the MF's normalized formulation prevents one target from disproportionately dominating others, de-emphasizing less critical deviations and treating them as secondary goals. In addition, if a specific action must occur during a planned maneuver, such as avoiding overlap with protected timeframes, the MF incorporates steep penalties to discourage infeasible solutions automatically.

In this context, to optimize maneuver opportunities, LCP informs CMAS about strategies to explore the search space effectively. Each CMAS execution includes three gridded searches: burn start time, burn duration, and burn direction. At each step, an additional metric, the Informed Merit Function (IMF), is computed. The IMF evaluates target metrics as if the potential maneuver did not occur, providing a context-aware comparison which can account for real world factors such as imperfect physical hardware. This approach allows CMAS to consider high-fidelity perturbative effects that may naturally assist some targets, enabling propulsive effort to be redirected to other objectives as needed.

4. Operational Implementation of CMAS

For more detailed information on the architecture Planet has created to enable the successful operation of multiple fleets of satellites, please refer to Section 2 of the paper discussing the SkySat MAS architecture [3] as well as the original paper introducing Planet’s mission operations architecture [4]. Some of the main features are briefly described in Table 2 below.

Table 2. Descriptions of Planet’s Mission Operations Architecture Features [3]

Feature	Description
Mission Control (MC)	A scheduling system which stores all the information about each satellite’s upcoming task queues, ground station passes, telemetry monitoring, and more.
Maneuver Reservations	Reservations are specialized objects inserted into Mission Control to signify the intent to execute a maneuver activity on the satellite and prevent conflicting activities from being scheduled at the same time. These objects capture critical details such as the intended time window and the parameters used to design the maneuver.
Maneuver Activities	Activities are actionable objects created in Mission Control, using the parameters specified in a maneuver reservation, along with other satellite-specific parameters. Maneuver activities detail the exact timeline when the satellite will execute the maneuver commands.
Activity Documents	<p>Activity documents live within Mission Control to capture all required metadata related to satellite activities. Pertaining to maneuver activities, there are three key activity document types: the planned maneuver document, the screening results document, and the reconstructed maneuver document.</p> <p>The planned maneuver document captures all the parameters CMAS used in planning each maneuver as detailed in Section 3 above. The screening results document contains the results of the external maneuver screening analysis, focusing on any close approaches with other objects in orbit, to certify whether the planned maneuver is safe to execute. The reconstructed maneuver document details the results of the post-maneuver analysis of on-orbit execution, capturing if and how the maneuver deviated from the planned parameters.</p>
Maneuver Approver	The maneuver approver is a specialized software component which verifies that a maneuver can transition from the planning to execution state. It does so by analyzing the planned maneuver against a comprehensive set of conditions aimed at ensuring both safety and feasibility.
Maneuver Evaluator	The maneuver evaluator is another specialized software component which classifies the outcome of a maneuver as either “no burn”, “partial burn”, or “full burn”, and then executes a sequence of follow up actions accordingly. Some examples of these actions are cleaning up reservations in the scheduling system corresponding to the maneuver, creating artifacts with telemetry and analysis data that other systems can retrieve and act upon, and initiating orbit determination for the satellite based on the evaluation.

The ensuing sub-sections will detail how CMAS is operationally implemented using the above-listed mission operations infrastructure to achieve its mission of optimized fleet maneuver automation.

4.1 Integration of CMAS with Conjunction Risk Mitigation

Due to the mission requirements of lower altitude and constraints imposed by low-thrust electric propulsion systems, CMAS must plan and execute maneuvers frequently, reliably, and with short lead-time. Therefore, CMAS

necessitates tighter integration than was required by the SkySat MAS with internal OD and external close approach screening systems.

While both MAS and CMAS screen planned maneuvers using external screening services, their reactions in the case of a predicted close approach differ. MAS would simply pause maneuvering until the identified high-risk TCA had passed, but CMAS cannot fulfil mission requirements if maneuvering is blocked for an extended period of time. Therefore, if the ideal planned maneuver as determined by the MF is projected to cause a close approach that exceeds configured risk tolerance (i.e. PoC and/or miss distance), CMAS runs again and incorporates the identified close approach risks into the MF so that any feasible maneuver not only progresses towards target constraints, but also aims to decrease the risk of collision and increase expected miss distance. As described in Figure 2, if an orbit raising maneuver would lead to an increased conjunction risk, that information is fed back into CMAS so that it targets a different part of the merit function, such as inclination or eccentricity, on the next planned burn. This allows the satellite to avoid increasing an external conjunction risk while continually working towards its mission goals.

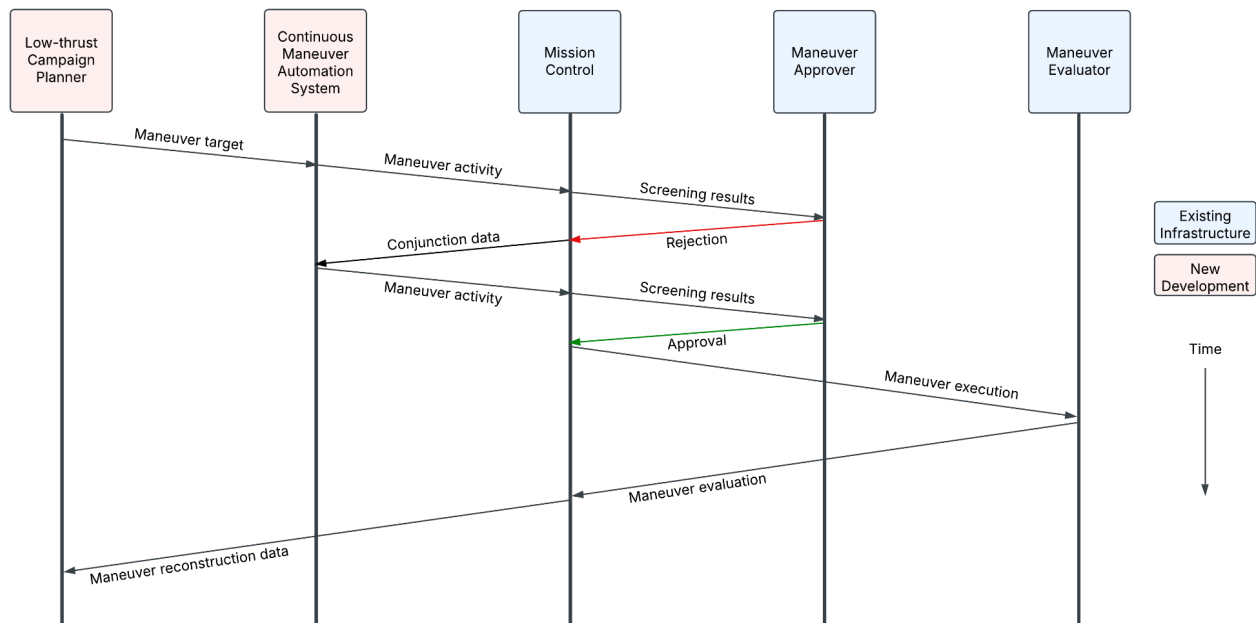


Fig. 2. Integration of LCP and CMAS with Existing Operational Architecture

In order to facilitate the nuanced navigation of many identified close approaches, Mission Control was extended to represent each Conjunction as a dynamic, persisted, and queryable object with its own lifecycle and documents using similar API semantics as the other objects in the MC satellite timeline (e.g. Activities or Reservations).

4.2 Integration of CMAS with Satellite Mission Requirements

CMAS is also able to incorporate a dynamic stream of imaging tasks interleaved with station keeping maneuvers. Unlike previous versions of MAS, Planet customers can continuously task SmallSats with new imaging targets to be captured at specific times and CMAS responsively adjusts the planning of maneuvers to avoid conflicts with imaging activities. Furthermore, because each maneuver affects the optimal timing and pointing for already-planned imaging activities that are scheduled to execute after maneuvering, CMAS automatically "refreshes" upcoming imaging tasks after each maneuver is planned, executed, or cancelled.

Another key strength of the CMAS is its contribution to system-wide resiliency as a result of unsuccessful maneuvers. Maneuvers may not execute as planned for a number of reasons, such as unsafe conjunction screening results or a failed ignition. In these scenarios, there is a clear sequence of events that are executed by the CMAS architecture to minimize the impact of an off-nominal maneuver on the production imaging targets. Once Maneuver Evaluator classifies a maneuver activity as a no burn or partial burn, the reconstructed maneuver activity document is updated in MC to include the reconstruction analysis of actual satellite discretized accelerations, burn duration, achieved delta-v, and more. The OD service then incorporates this evaluation to update the positioning estimation

and state propagation of the spacecraft based on the maneuver result as well as downlinked GPS telemetry. Upon completion of the updated OD analysis, upcoming imaging activities are refreshed as needed to optimally capture already-tasked customer targets, even if the resulting orbit diverges from what was originally anticipated by CMAS.

5. Lessons Learned and Next Steps

As we worked on developing and implementing this novel maneuver automation architecture, we faced numerous challenges and unexpected complexities. From this experience, we have gathered a range of key takeaways and lessons that we consider important to record. Additionally, we have identified several next steps to enhance the architecture and prepare it for the anticipated growth of the Pelican and Tanager satellite constellations.

5.1 Failure Recovery and Risk Resiliency

Maneuvers do not always go as planned, whether due to hardware failures, system faults, safety risks, or other unexpected events. The system had to be resilient, with a predefined process to minimize the impact of failed maneuvers. The ability to update satellite positioning and refresh imaging tasks after a failure was crucial for ensuring operational continuity and minimizing disruption to revenue-generating activities. The dynamic nature of this scheduling highlighted the importance of a flexible and adaptive Mission Control.

The integration of CMAS with conjunction risk mitigation strategies was challenging. Unlike the previous MAS, where maneuvers would simply be paused if there was a close approach risk, CMAS had to dynamically adjust planned maneuvers to reduce conjunction risk while still working towards mission goals. This balancing act was a crucial design feature but also added complexity to the real-time decision-making process.

5.2 Complexity of Transitioning to Low-Thrust Systems

The shift from chemically-propelled impulsive maneuvers to electrically-propelled continuous thrust maneuvers introduced significant complexity, particularly around the modeling of orbital perturbations and real-time maneuver planning. The continuous nature of electric propulsion requires a detailed understanding of multiple dynamic factors that affect satellite orbits. It also necessitated that CMAS be able to continuously adapt to real-time telemetry. This means the system must constantly adjust its maneuver strategies to incorporate evolving data, which requires sophisticated algorithms for rapid optimization. The ability to re-optimize maneuvers based on new information proved vital for the sustainability of operations.

5.3 Expanding the Low-Thrust Maneuver Campaign Planner Capabilities

To further improve mission planning, the LCP could be enhanced to handle more complex mission stages and incorporate more granular parameters for each maneuver, improving the efficiency of orbit optimization over longer campaign durations. Specifically, an ongoing improvement in both LCP and CMAS focuses on the exploitation of short-term targets, such as semi-major axis, eccentricity, and inclination, to induce some desired long-term evolution of slow-changing KEs without direct targeting. This approach will improve the overall long-term constellation sustainability and stability, particularly for orbits which are heavily influenced by RAAN and periapsis drifts.

5.4 Scalability for Larger Constellations

As Planet expands its satellite constellations via the Pelican and Tanager fleets, scaling CMAS and LCP to handle an increased number of satellites and maneuvers will be a key focus. CMAS handles individual maneuver-level targets and LCP currently handles the mission-level requirements of a single satellite, so a natural next step is to develop an agent that exists one level above LCP which acts as a constellation-level manager. This new agent would ensure all satellites in a particular fleet are phased optimally to maximize imaging windows and ensure safe operational distances are maintained across all internal spacecraft.

Relatedly, as Planet's constellations scale, the maneuver cadence requirements make it harder to coordinate with other satellite operators. A future improvement will be to extend CMAS to screen and deliver multiple future maneuvers simultaneously. In doing so, external screening services will have a better-informed expectation of the satellite state propagation in burn or no-burn scenarios with accompanying likelihoods. This may involve optimizing parallel processing and increasing automation across all levels of fleet management to handle higher operational demands.

References

- [1] McGill, L., Beukelaers, V., Faler, A., Lewis, B., Mueting, J., and Shah, V., SkySat Block 3 Launch Campaign, Proceedings of the AIAA/USU Conference on Small Satellites, Year in Review, SSC21-III-06, 2021, 7 - 12 August. <https://digitalcommons.usu.edu/smallsat/2021/all2021/152/>
- [2] Mallik, V., Mueting, J., Reuter, A., Paul, A., McGill, L., Jagatia, B., and Shah, V., An Automated Approach to Maneuver Campaign Management for SkySats, Proceedings of the AIAA/USU Conference on Small Satellites, Advanced Technologies II, SSC22-VI-03, Logan, Utah, USA, 2022, 6 - 11 August. <https://digitalcommons.usu.edu/smallsat/2022/all2022/171/>
- [3] Aurich, J., Clark, J., Thawer, Z., Mallik, V., Johl, S., A Novel Ground-Based Maneuver Automation System for Low Earth Orbit Satellite Operations, IEEE Aerospace Conference, Yellowstone Conference Center, Big Sky, Montana, 2024, 2 - 9 March. <https://ieeexplore.ieee.org/document/10521007>
- [4] Boshuizen, C., Mason, J., Klupar, P., & Spanhake, S., Results From The Planet Labs Flock Constellation, Proceedings of the AIAA/USU Conference on Small Satellites, Private Endeavors, Logan, Utah, USA, 2014, 2 - 7 August. <https://digitalcommons.usu.edu/smallsat/2014/PrivEnd/1/>