A Survey and 3LE Generation Model of Megaconstellations in the Future LEO Environment

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In May of 2019, SpaceX successfully launched its first batch of Starlink satellites, popularizing the term megaconstellation and marking the dawn of a new space race. As national interests and private corporations alike compete to provide global internet services through their own megaconstellation networks, the International Telecommunication Union (ITU) projects that approximately 100000 satellites will be launched into LEO within the next decade. These massive satellite constellations must be studied, modeled, and simulated in order to determine their effect on conjunctions in LEO and make decisions about future policy with regard to space traffic management. This work seeks to model the future LEO environment by capturing the expected behavior of megaconstellations over the course of the next decade. A sizing classification system and probability score is developed to cross-check the ITU's estimate for the next decade of launches. Currently planned megaconstellations are then surveyed, and those most likely to launch are explored in detail to determine their progress. Case studies are then conducted on Starlink satellites to identify patterns in deployment, station keeping, and deorbit for current megaconstellations. These behaviors are then recreated with a 3LE Generation Model. Such a generator may be adopted by future simulation efforts to improve space domain awareness.

I. Nomenclature

PC	=	probability of conjunction
3LE	=	three-line element

II. Introduction

Formation flying satellites have experienced a tremendous evolution over the past half-century. Communication satellites were first launched as fleets into GEO in the 1960s, and since then, those fleets have evolved into much larger formation flying groups [1]. Iridium, Globalstar, and GLONASS are among the companies that have led the transition from single large satellites to networks of several small satellites. These small satellite networks operate in a constellation, meaning that they function together to provide extensive and near-continuous ground coverage, allowing them to achieve such high resolution that may serve in such applications as Earth observation, wireless telecommunications, defense, research, and positioning, navigation and timing services (PNT) [2,3,4,5].

In the past decade, private corporations and national interests alike have begun the development and launch of megaconstellations, constellation networks consisting of anywhere from a few hundred to several thousand satellites. Operating in LEO, these networks pose substantial benefits to scientists and shareholders alike. Launching several small satellites is significantly more cost-effective than launching individual satellites, and the reconfigurability and replaceability of individual satellites within the constellation network can increase overall system lifespan. These cost savings and configuration flexibility have led to a drastic increase in non-state actors in space in the past three decades [2,6], and China has similarly worked to achieve several notable milestones in the development of its own small satellite economy. Its first launch of a truly commercial satellite mission by a private commercial enterprise was also its first launch of a national commercial aerospace enterprise from a military launch site. Most importantly, this

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unveiling of China's private commercial satellite launch market was the first launch of multiple satellites in a single rocket performed by a private Chinese aerospace company [7].

Unfortunately, these megaconstellations are not without issue. Satellite traffic increased by 3000 units between 2019 and the first half of 2022, and the ITU projects that approximately 100000 satellites will be launched into LEO alone within the next decade [8]. The high competition for space in LEO becomes problematic when it is considered that the orbital regime contains only 0.3% of space below the GEO regime, but already contains approximately 80% of resident space objects [9]. Collision avoidance becomes significantly more complicated in the LEO environment filled with megaconstellations. Conjunctions may arise due to the reconfiguration of a constellation network, the destruction of normal formation geometry from relative navigation failures or control malfunctions, interactions with foreign debris (including satellites from other constellations), and stray drifting satellites [10, 11].

Historical data on conjunctions shows that from 1961 through 2007, there were 200 reported conjunctions involving debris clouds from on-orbit breakups occurred. Today, the 18th SPCS is estimated to send out approximately 35000 Conjunction Data Messages (CDMs) per day, where a warning is issued to satellite operators whenever PC $\geq 10^{-4}$. Megaconstellations have proven their contribution to this sheer volume of CDMs early on in their development. On September 2, 2019, ESA was forced to raise the orbit of their Aeolus spacecraft to narrowly avoid a potential conjunction with Starlink-44, citing an estimated closest distance of approach less than one kilometer in magnitude and a PC greater than 10^{-3} [12, 13, 14].

In such a truly international high-traffic environment, it is difficult to detect orbital maneuvers when their location, timing, direction, and magnitude are unknown. This is particularly true of low-thrust maneuvers and presents a significant challenge with regard to preventing possible conjunctions between satellites [15]. The number of potential conjunctions only increases with the number of satellites, as the total number of error ellipsoids rises. Furthermore, the satellites orbiting in LEO may be subject to higher levels of positioning uncertainty that may increase the size of their error ellipsoids. Variations in the neutral density of the thermosphere create variable drag forces that make satellite motion difficult to predict, and geomagnetic storms may create tracking gaps due to loss of radar instrumentation measurements. Both these variations and issues with tracking complicate orbit propagation due to inadequate modeling and may lead to an increased number of conjunction warnings as a result [13].

While conjunction warnings in and of themselves are not inherently harmful, a satellite that carries out maneuvers for every CDM it receives ultimately suffers a shortened lifespan due to increased fuel consumption. It is difficult, however, to distinguish false alarms from genuine threats more than a few hours in advance. The periodicity of covariance terms in satellite positioning means it is exceptionally difficult to achieve accurate probability calculations far in advance, which can lead to false alarms [11,16,17]. As the threat of increased conjunctions looms over LEO, much research has been conducted on potential collision avoidance maneuvers. Some work suggests the use of demonstrated avoidance strategies that have been proven in flight, such as Hohmann transfers and trace separation methods for short- and mid-term collision avoidance [6]. The majority of literature focuses on algorithms optimized to either fuel consumption or a safety parameter, constrained by the need to remain close enough to its original position to not suffer a loss of signal with the rest of the constellation. Such fuel minimization algorithms seek to carry out avoidance maneuvers as soon as possible in order to lower total fuel consumption [3,12]. Algorithms have been proposed using artificial potential functions [17], linear programming [18], heuristic algorithms, and variations on the Clohessy-Wiltshire-Hill equations [12].

In an effort to better understand megaconstellations and their effects on the future LEO environment, this work seeks to establish a model for megaconstellation maneuvering strategies, including deployment, station keeping, and deorbit practices. A survey of some of the most prevalent proposed LEO constellations is conducted, with each constellation evaluated on its likelihood for full implementation based on the criteria of FCC and ITU regulation, established constellation production and funding infrastructure, constellation concept feasibility, and company history with launching and operating individual satellites and constellations. This information is used to develop a 3LE Generation Model, which is developed using an analysis of maneuvering strategies and behaviors exhibited by Starlink satellites over the course of two years. This model is intended for future use in simulations to model megaconstellations in the LEO environment.

The remainder of this work is divided into four sections. Section III explores the market volatility of megaconstellations and presents a sizing classification system and probability evaluation criteria for future megaconstellations. It proceeds to present a survey of the future megaconstellations deemed most likely to launch within the next decade. Section IV conducts a case study on two years' worth of Starlink Generation 1 satellite launches to identify trends in deployment, station keeping, and deorbit strategies. These maneuvering patterns are then modeled in Section V, where a MATLAB script is developed to function as a 3LE generator for the surveyed megaconstellations. Section VI concludes this work and highlights future simulation work to be performed.

III. Future Megaconstellations

A. Market Volatility and the NewSpace Index

This work is not the first to conduct a survey of potential future megaconstellations. Erik Kulu's NewSpace Index has tracked commercial satellite constellations since 2016, merely one year after the launch of Starlink and OneWeb. The website, as well as its associated literature, highlights a spike in satellite constellation companies founded in 2015 and 2016, rising in an attempt to offer an alternative to the constellations already successfully launched. The sustainability of this business model, however, remains to be proven beyond the first on-orbit technology demonstration in this highly volatile market. Some companies may see initial signs of success, only to collapse the next day. LeoSat is one such case. Founded in 2013, the company raised over $10 million in funding for their own megaconstellation, but after failing to attract further funding were forced to shut down in 2019 [1].

Though the NewSpace Index maintains a relatively updated and comprehensive list of companies and countries planning to develop and launch satellite megaconstellations and their respective applications, it is not a perfect survey. It does not explore the consequences of the increase in LEO traffic in the next decade, nor does it evaluate the probability of the constellation being carried to fruition beyond a single-word description of the project's current status. This section of the work seeks to fill in the gaps left behind by the NewSpace Index by creating a sizing classification system as an alternative to the ill-defined megaconstellation term and developing a probability evaluation scheme to decide which constellations may be expected to successfully launch and operate close to or at their planned number of satellites.

B. Sizing Classifications and the RICH Criteria

Little literature creates a distinction between constellations and megaconstellations. The latter term has only become popularized in the last decade, as companies such as SpaceX and OneWeb announced their plans to launch several thousand satellites into LEO. It has since become a buzzword in the aerospace community, albeit a poorly defined one. Though exact terminology and nomenclature for constellation sizes is not strictly necessary for the evaluation of the future LEO environment, it is important to differentiate between the effects of a constellation with 100 satellites and a constellation with upwards of 50000 satellites. Such distinctions allow scientists and engineers working in space traffic management to evaluate the greatest potential contributors to conjunction notifications. This classification system does not include constellations smaller than 100 satellites as a way to distinguish between constellations and megaconstellations.

Origin-Class encompasses the smallest constellations, with a title that reflects their position as the first true megaconstellations. Advance-Class represents a step forward in satellite network technology, where a company or country is capable of managing several hundred satellites. Mega-Class leverages the popularization of the megaconstellation term to indicate constellations on the order of thousands of satellites. Leviathan-Class consists of only the largest constellations, numbering a minimum of 10000 satellites intended for launch. Each class may be abbreviated by its first letter for compactness (i.e., L-Class, M-Class, A-Class, O-Class). Table 1 summarizes this size classification system. It is important to note that the number of total satellites planned (intended for launch) and the number of satellites from that constellation in LEO at a steady-state condition are not necessarily equivalent, and in fact, rarely are.

Table 1 Constellation size classification system.

Formal Classification	Total Satellites Intended for Launch
Leviathan-Class	$\geq$ 10000
Mega-Class	1000 – 9999
Advance-Class	250 – 999
Origin-Class	100 – 249

An evaluation of constellation size, however, does not contain much meaning without some indication of its likelihood. A company may plan the largest satellite constellation to date, but this plan is meaningless if there is no means by which it may be carried out. An accurate model of the future LEO environment must be able to account for best-, worst-, and predicted-case scenarios. As such, we develop the Regulation-Infrastructure-Concept-History (RICH) criteria to evaluate the likelihood of launch and operations for any satellite constellation. In addition to predicting whether or not a constellation will launch and operate successfully, these criteria may be used to predict the actual size of the constellation in comparison with the planned number of total satellites launched. Such predictive power is a necessity for modeling the interactions of megaconstellations with other satellites in LEO.

As the name suggests, the RICH system is split into four categories: regulation, infrastructure, concept, and history. The regulation criterion encompasses all legal framework, particularly Federal Communications Commission (FCC) and International Telecommunication Union (ITU) applications for new satellite constellations. Modifications to existing constellations fall under this criterion as well. Infrastructure is the broadest of the criteria and includes such elements as funding, facilities, and technical partnerships. This criterion essentially captures the monetary and technical aspects of developing and launching a megaconstellation. The concept criterion is somewhat subjective, as it evaluates the very idea of the constellation itself based on the number of satellites, the proposed launch schedule, and the production timeline. It is included as a metric of reasonableness: a company that claims it intends to launch 100000 satellites in two years has a poor development of concept, whereas a company that plans to launch 2000 satellites within the next five years with detailed information on each orbital plane has an exceptional development of concept. Finally, history is included as an indicator of experience. Companies such as SpaceX have a proven track record with launching and operating satellites and therefore must be differentiated from startups that have launched a single CubeSat.

The probabilistic element of RICH takes the form of a numerical scoring system. Each criterion is evaluated on a scale of 0 to 3 based on available information. When information is not available on a particular criterion, its score is set to 1 by default. The reason for this is twofold. First, the relevant information may be proprietary and thus inaccessible to the public and may indicate a high level of preparedness. The unknown nature of this information mandates a low default score. Second, a score of 0 is reserved only for critical failures that could jeopardize the mission, such as repeated rejections of FCC applications. The scoring metrics for each criterion are found in Table 2.

Table 2 The scoring system used for each RICH criterion.

Score	Regulation	Infrastructure	Concept	History
0	FCC/ITU application(s) rejected, no new application submitted	Funding continually rejected, no technical partnerships, group currently in Chapter 11 bankruptcy	Group presents no plan for orbital planes, altitude, or number of satellites to be launched	Group has never launched a satellite and has minimal experience with space technology
1	Default when no information is present, no FCC/ITU application(s) found	Default when no information is present, group has begun fundraising, technical partnership details not finalized	Default when no information is present, group presents minimal information such as altitude and number of satellites	Default when no information is present, group has launched and operated a satellite successfully, some experience with space technology
2	FCC/ITU application(s) rejected and new application submitted, or recently unblocked	Group has raised more than half the funds necessary for the project, some technical partnerships finalized	Group presents information on orbital planes, altitude, and number of satellites to be launched; number of satellites or launch schedule more ambitious than other planned constellations	Group has launched and operated several individual satellites, but perhaps not a constellation; experience in developing space technology
3	FCC/ITU application(s) approved, action taken, or accepted for review	Near-full funding achieved for the project, technical partnerships contracted for areas outside of the group's specializations	Group presents detailed information on orbital planes, altitude, and number of satellites to be launched	Group has successfully launched and operated constellation satellites, or otherwise has extensive experience with operating individual satellites

Once all criteria are evaluated, the score is summed to create a RICH score. From this point, scenario generation may be carried out. Each scenario is evaluated by taking a constellation's RICH score, dividing it by 12, and multiplying this value by the number of satellites in each orbital plane. The choice to round up or down depends on the scenario being generated. The worst-case scenario is defined as all planned satellites launching for each planned constellation, regardless of current levels of preparedness. In this case, all RICH scores are automatically set to 12.

The prediction scenario computes the number of satellites per orbital plane without the modification of the RICH score. In such a case, a satellite with a RICH score of 8 would launch two-thirds of its satellite network, with the assumption that these unlaunched satellites are equally subtracted from each orbital plane. In the case of a non-integer number of satellites, the prediction scenario rounds up to the nearest whole satellite. The best-case scenario is somewhat more difficult to define. It is not realistic to claim that no satellites will launch for any constellations, though this might be the most desirable outcome for astronomers, satellite operators, and the 18th SPCS. Instead, this scenario sets modified RICH scores based on their current values. If a constellation has a RICH score less than or equal to 5, it is assumed that the constellation will not launch, and its score is set to 0. A constellation with a score greater than or equal to 10 is ruled highly likely to succeed, but under the best-case scenario, its RICH score is reduced by 2 to account for schedule delays, production issues, and scrubbed launches. All remaining unmodified scores are automatically set to 6, indicating that only half the planned constellation will launch. In the case of a non-integer number of satellites, this scenario rounds down to the nearest whole satellite. The scenario generation process is visualized in Fig. 1.

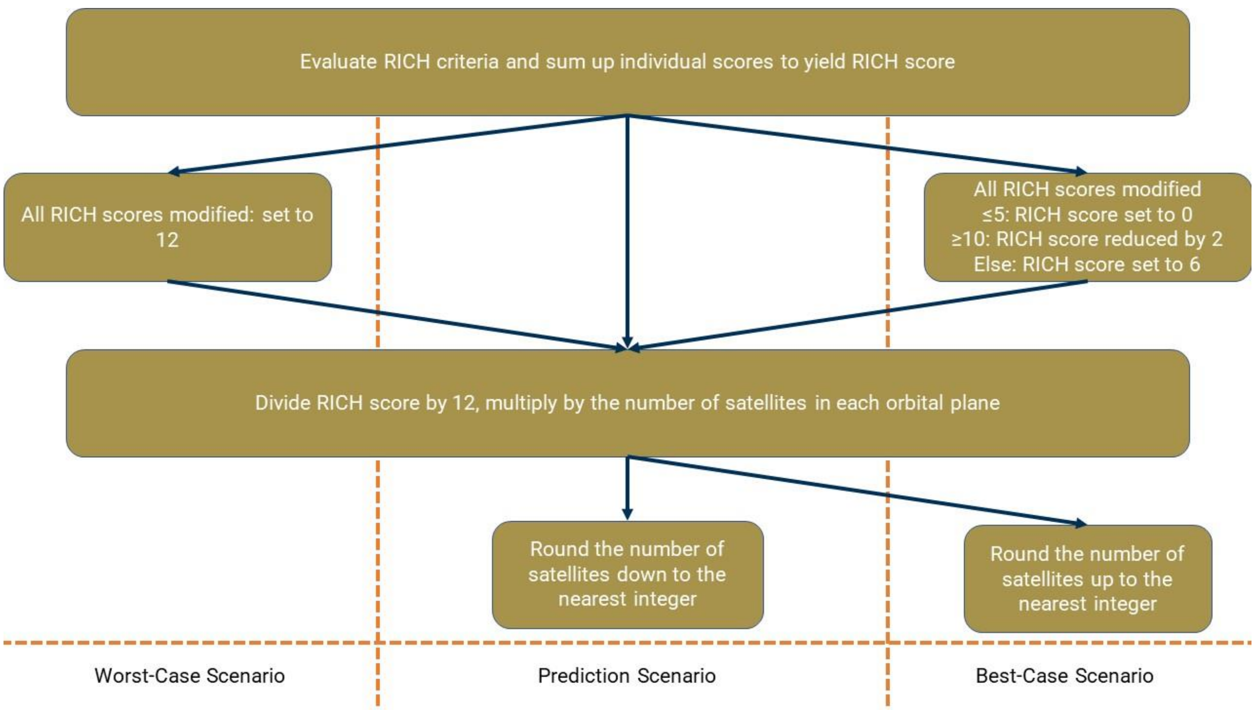

Fig. 1 RICH criteria scenario generation process.

C. Current and Future Megaconstellations

Proper modeling of the future LEO environment requires some knowledge of the constellations planned to launch within the next decade. An updated survey is therefore conducted on existing and upcoming megaconstellations proposed by both private corporations and state powers. This survey is not extensive but rather deals with those constellations with both a sufficient number of satellites to be categorized by our size classification system and a RICH score greater than or equal to 6. This should yield an accurate projection of the upcoming population of LEO and provide an estimate in conjunction with the ITU's projection for the total number of satellites to be launched into this orbital regime within the next decade.

1. Leviathan-Class Constellations

Only three proposed constellations as of this paper's writing are sufficiently large to be considered L-Class: Starlink, GuoWang, and Astra. Since the construction of Starlink Generation 1 is nearing completion, this survey only considers Starlink Generation 2 in depth. These constellations and their respective sizes and RICH scores are listed in Table 3.

The first generation of Starlink consisted of 11927 satellites. Generation 2 seeks to add 29928 satellites to the constellation, bringing the network to a total just under 42000 satellites. No clear distinction exists between the first and second-generation 3LEs. FCC filing for its second generation of constellation satellites and its corresponding modifications were all approved by late 2022, yielding a regulation score of 3 [9,20,21]. SpaceX, the parent company behind Starlink, has made a name for itself in the launch vehicle market as one of the current leaders in the aerospace industry. With facilities already in place from the manufacturing of Starlink Generation 1, it is safe to assume that SpaceX's infrastructure is robust enough to earn an infrastructure score of 3 as well. The company's history also holds up to scrutiny quite well with respect to success in the constellation market. Besides the continued service and operations of Generation 1, Starlink also played a role in supporting Ukraine in its conflict with Russia beginning in April 2022 [9]. On top of the commencement of launch operations for Generation 2, this earns Starlink a score of 3 for its history. The company falls just short of a perfect score in its concept, earning a score of 2. The primary reason for this is that while SpaceX has demonstrated their expertise in launching and operating a constellation network, this new phase of Starlink is over two and a half times the size of the original. With no prior constellation attempting a constellation of this size, the score must be lowered to account for the technological and logistical challenges of hosting a network of this size. Starlink's final RICH score is therefore 11.

China Telecom Satellite Communications has plans in the works for a 12992 satellite constellation, known officially only as GW-2 and GW-A59, but acknowledged by most literature as GuoWang. ITU filings exist for both GW-2 and GW-A59, and while the reason for splitting the constellation into two filings is currently unclear, they provide highly detailed information on the orbital planes, including their altitudes, inclinations, right ascensions of the ascending node, and number of satellites per plane [22,23]. This level of detail earns it a regulation score of 3. Similarly, it earns a score of 3 for history due to the rise of China's public and private aerospace sectors in the past decade, reflected by the recent successes of I-Space and ZeroG Lab [7]. As the largest Chinese constellation to date, with a size exceeding Starlink Generation 1, its concept score is gauged at 2, for similar reasons as the demotion of Starlink's concept from an otherwise perfect score. Unfortunately, little other information exists on the funding and development statuses of GuoWang, yielding a default infrastructure score of 1. This is likely due to national security concerns at a time when the United States, China, and Russia exist in a rather precarious relationship. A similar situation exists with the ROSCOSMOS constellation Sfera, as is discussed later on. GuoWang's final RICH score is therefore 9.

Table 3 Survey of L-Class constellations with total number of satellites planned and evaluated RICH scores. Constellations with no specified project name are listed as the name of their respective company.

Constellation	Company/Country	Total Satellites	RICH Score
Astra	Astra (USA)	13620	6
GuoWang (GW-2/GW-A59)	China Telecom Satellite Communications (China)	12992	9
Starlink (Gen2)	SpaceX (USA)	29988	11

Astra, a proposed 13620 satellite constellation, occupies a unique position among the L-Class constellations in that little information is available about the network besides its FCC filings, submitted in November 2021. Its current status is uncertain, with the most recent update from the FCC being a confirmation of submission [24]. Due to lack of further action on this front, Astra earns a 2 in its regulation score. Detailed orbit information found in the aforementioned filings grants the constellation a 2 on its concept score, for similar sizing reasons as mentioned with Starlink and GuoWang. No information was found on the company's history or infrastructure supports with respect to its constellation project, and as such these scores default to 1. As the filing was submitted within the past two years, it is uncertain whether this project is proceeding as originally planned, though it should be noted that the filings have not been withdrawn, and as such it may be assumed that the constellation is not entirely scrapped. Astra's constellation earns a final RICH score of 6.

2. Mega-Class Constellations

A much larger population of proposed constellations appears when considering M-Class sizing: Kuiper, Lightspeed, ASTE/DASH/RION, STORK, SpinLaunch, Hughes Network Systems, Samsung, OneWeb, and Hanwha Systems. These constellations and their respective sizes and RICH scores are listed in Table 4.

As one of the latest private constellations funded by billionaires, the proposed 3236 satellite Kuiper constellation has garnered significant public attention. Its initial FCC application was granted in July 2020, with an updated orbital debris mitigation plan accepted for filing in May 2022; it is possible that this updated plan was accepted in February 2023 [25,26,27]. Such approval earns a regulation score of 3. Infrastructure and concept scores both come in at 2 due to the detailed nature of the FCC filing and the vast amount of financial resources at Amazon's disposal to fund the project. The history score is reduced to 1. While Amazon is easily the world's premier power in e-commerce, it has yet to make a significant appearance in the space sector. It is therefore somewhat unusual that this constellation is placed under Amazon instead of Blue Origin, despite both companies being owned by Jeff Bezos. Kuiper earns a RICH score of 8.

Lightspeed, produced by Telesat, is a proposed 1671 satellite constellation. Perhaps what makes this satellite system stand out from the rest is its planned implementation. Unlike Starlink and Kuiper, whose plans appear to involve deployments of individual generations, shells, or phases (the terminology is practically equivalent in each case), Lightspeed's implementation plan appears to evolve, with each phase modifying the previous one slightly while building on top of it. The FCC granted the Phase 1 launch plan of 117 satellites in November 2017, but amended filings accepted in July 2022 detail an additional 181 satellites for Phase 1 (298 satellites total) with a 1373 satellite Phase 2 [28,29]. Such detailed plans for continued growth warrant a regulation score of 3. Lightspeed possesses the clearest infrastructure plans of the constellations surveyed thus far and earns a score of 3 in this category. In August 2021, Telesat received a $1.44 billion CAN investment for meeting capital and expenditure requirements. The CEO later claimed arrangements were in place for an additional $4 billion in funding. Both Ontario and Quebec have placed a considerable financial stake in the company as well. Besides funding, Telesat has announced collaboration agreements with NSSLGlobal and Analog Devices for performance validation, testing, and the creation of a beam-forming integrated circuit (BFIC) for the antenna array. The company plans to launch begin launching Phase 1 of Lightspeed in the second half of 2023, with services commencing in the second half of 2024 [30,31,32]. Combined with the detailed orbital information from FCC filings, this constellation earns a concept score of 2. Though it is a telecommunications company, little information was found on the company's history of launching satellite networks, defaulting its history score to 1. Lightspeed earns a RICH score of 9.

Stellar's constellation network appears as three separate ITU filings under the project names ASTE, DASH, and RION. These filings were submitted in December of 2021 and 2022, and present details on orbital planes at a similar level as seen in the GuoWang filings [33,34,35]. As with the previously discussed constellations, this is sufficient for a regulation score of 3 and a concept score of 2. Little more information is found on this constellation network and the company itself, causing the history and infrastructure scores to default to 1. Stellar's constellation series earns a RICH score of 7.

STORK is a proposed 1024 nanosatellite constellation produced by Polish company SatRevolution (SatRev). The company recently signed a 5-year agreement with the Swedish Space Corporation (SSC) to launch from the Esrange launch site in northern Sweden. SSC is a leading provider of advanced space services with over fifty years of experience, making them a worthwhile partnership for SatRev. Additionally, the launch site's proximity to Poland makes transit to and from the site much simpler, and the site's high latitude facilitates insertions into the sun-synchronous orbits where the constellation is supposed to reside [36]. Other technical partnerships include SkyWatch Space Applications, who have signed an agreement to deliver data management services [37], and Virgin Orbit, with whom SatRev entered into a three-year Launch Services Agreement (LSA) [38]. While this would normally merit full points for an infrastructure score, Virgin Orbit announced back in March that it would cease all launch operations effective immediately, filing for Chapter 11 bankruptcy mere weeks later [39]. This downgrades STORK's infrastructure score to 2. No FCC or ITU filings are found for this network, though the extensive infrastructure plans in place, as well as the announced altitude and inclination plans, suggest their existence [40]. STORK is planned to be ready for full deployment by 2026, carried by launch vehicles capable of delivering 500 kg to various orbital planes. With at least four satellites already delivered into LEO, the constellation earns a concept score of 2 [38]. The company's history score defaults to 1. STORK earns a RICH score of 7.

SpinLaunch has captured the attention of the aerospace industry since its inception, presenting an alternative to chemical fuel launch vehicles. Its proposed constellation consists of 1190 satellites with 60 spares, though it has one particularly unique characteristic. Instead of distributing the constellation with several satellites per plane, SpinLaunch proposes a one-satellite-per-plane constellation, under the argument that each satellite occupies effectively the same orbit but offset in time. Such an offset gives the satellites a temporal resolution of approximately 72.4 seconds over any given spot on Earth's surface. This concept, although unique, would practically monopolize the altitude at which the constellation resides with over 1000 nearly identical planes. This downgrades the concept score to 1. The corresponding FCC filing was accepted in July 2022 [41,42] and fosters the regulation score of 3. No information on the supporting infrastructure for the development of this constellation was found, resulting in an infrastructure score of 1. The company's relatively young age and inexperience with launching satellite constellations yields a history score of 2. SpinLaunch earns a total RICH score of 7.

Hughes Network Systems' proposed constellation consists of 1440 satellites. Its FCC filing was unblocked in January 2022, with no apparent updates since then, earning it a regulation score of 2. Detailed information on all orbital planes found in the filing secure a concept score of 2 [43]. A dearth of information exists on the company's planned support infrastructure for the development and operation of the constellation and its historical record of satellite network management, causing both the infrastructure and history scores to default to 1. Hughes earns a RICH score of 6.

Samsung's proposed constellation began as the thought experiment of company president Farooq Khan, who published a paper in 2015 detailing the proposed constellation with extensive information on the company's plans to address the lack of internet accessibility around the world. Though the report contained thorough technical details on the company's data delivery rates and capabilities to meet the growing data demands of an internet-driven world, a clear lack of information on the constellation's orbital elements exists. The constellation is proposed to include 4600 satellites, but besides this, no other information is given [44]. Later reports appear to disagree on the planned altitude of the constellation as well [9,40]. The failure to provide information on the proposed infrastructure network to support the development of the constellation and the company's track record that would foster said development cause infrastructure and history scores to default to 1. No FCC or ITU filings are found for the network, defaulting the regulation score to 1. The company plans to achieve a cellular and Wi-Fi network capable of carrying in excess of 1 zettabyte per month by 2028 [44]. Such a long preparation window, paired with a plan for data delivery, boosts the concept score to 3. Samsung earns a RICH score of 6.

Table 4 Survey of M-Class constellations with total number of satellites planned and evaluated RICH scores. Constellations with no specified project name are listed as the name of their respective company.

Constellation	Company/Country	Total Satellites	RICH Score
ASTE, DASH, RION	Stellar (France)	4843	7
GuoWang (GW-2/GW-A59)	China Telecom Satellite Communications (China)	12992	9
Hanwha	Hanwha (South Korea)	2000	9
Hughes	Hughes Network Systems (USA)	1440	6
Kuiper	Amazon (USA)	3236	8
Lightspeed	Telesat (Canada)	1671	9
OneWeb	OneWeb (UK)	7808	8
Samsung	Samsung (South Korea)	4600	6
SpinLaunch	SpinLaunch (USA)	1190	7
STORK	SatRevolution/SatRev (Poland)	1024	7

Along with Starlink, OneWeb was one of the first constellation networks to be dubbed a megaconstellation. Designed to be the UK counterpart to the US-based Starlink, OneWeb's constellation development has suffered a much more complicated history. The company's founder, Greg Wyler, departed the company in 2017, going on to found two more constellation companies, neither of which have seen significant success [45]. The company initially raised, and then proceeded to spend in entirety, $3 billion. In June 2020, OneWeb filed for Chapter 11 bankruptcy, only returning to the megaconstellation market with an agreement with SpaceX to resume the planned launch schedule [9]. Since then, the original constellation has been downsized to an initial network of 648 satellites. Many proposed expansions have been made, the vast majority of which quickly turn into reductions as the company struggles to determine the ideal sustainable constellation size for their company [19]. As of October 2022, the company is set to merge with GEO operator Eutelsat [46]. This results in concept and history scores of 1, though a high infrastructure score of 3 due to fundraising capabilities and partnerships. The current constellation is set to implement in 2 phases. The original Phase 1 was granted by the FCC in June 2017, with an amended filing proposing the expanded Phase 1 granted in August 2020. A later filing, however, proposed a significant reduction of approximately 90% to the original Phase 2 plan. The resulting number of total planned satellites is 7808 [47,48,49]. The consistency of OneWeb applications earns a regulation score of 3. OneWeb earns a RICH score of 8.

Hanwha Systems earns a regulation score of 1 due to an apparent absence of FCC/ITU filings but makes up for its score in the other categories, particularly its infrastructure and history. The company has plans in place to invest $420 million into their constellation, and in April 2021 announced a capital increase of 1.2 trillion won, or approximately $1 billion through new shares. This capital will go towards technology asset acquisition, the development of innovative satellite communications technology, launches, and production facilities. Their acquisition of the UK aviation satellite antenna company Phasor, now Hanwha Phasor, as well as their investments in the Kymeta Corporation, a mobile antenna company, sets Hanwha up for success in terms of their technical partnerships. Further negotiations are currently underway between Hanwha and leading companies outside of South Korea to discuss cooperation for the development of satellite control and operations technology, though the company has not disclosed these partners by name. This earns Hanwha an infrastructure score of 3. They similarly receive a history score of 3 for over twenty years of experience in the military satellite communications business. The company plans to pilot their services beginning in 2023, with half of their 2000 satellite network beginning service in 2025. Their ultimate goal is to take their initial land and maritime applications and expand these to aircraft and urban air mobility vehicles. The company hopes to realize a 6G service by 2030 [50]. However, no detailed orbital plans are found, and for this Hanwha earns a concept score of 2. Hanwha Systems earns a RICH score of 9.

3. *Advance-Class Constellations*

Few A-Class megaconstellations appear to exist; discussion of this is deferred to the survey of O-Class constellations. A-Class constellations include Mangata Networks, Dove and Super Flocks, and Sfera. These constellations and their respective sizes and RICH scores are listed in Table 5.

Mangata Networks stands apart from the rest of the crowd as one of the only megaconstellations poised to leverage the orbital regimes of MEO and HEO. Founded by OneWeb's former VP of Space Systems, the company has already reserved nearly the entire capacity of its initial launch group. Such confidence and background earn a history score of 2. The company plans to begin the constellation with a smaller initial launch of 8 HEO and 24 MEO satellites, incrementally building out from this point. This business model allows the company to generate real revenue from the initial deployment prior to sinking a significant portion of their financial assets in the production of the remaining satellites. With planned launches and services beginning in 2024 and full deployment beginning in late 2025, Mangata receives a concept score of 3. Similar to Lightspeed, Mangata boasts heavy financial investment in its constellation, with $33 million raised in Series A financing with intercontinental representation from the US, Singapore, South Korea, and the UK. An additional $36 million was invested by the South Ayrshire Council, with £3.6 million put towards research and development grant funding. They would later go on to achieve a $100 million financing deal for a manufacturing facility in Scotland, where expected production capacity outputs up to 24 satellites every three months [51,52,53]. As for technical partnerships, Honeywell IACS was brought on in October 2022 for their experience with navigation, data handling, and momentum control products [54]. Such extensive financing and technical partnerships yield an infrastructure score of 3. Action was taken on their FCC filing in January 2021, leading to a regulation score of 3, though no further updates appear to exist [55]. Mangata Networks earns a RICH score of 11.

Planet's Dove and Super Flocks did not receive nearly as much media attention as Starlink and Kuiper when they first launched due to their significantly smaller size. This constellation, however, has experienced a great degree of success. Action was taken on their FCC application in March 2021, granting a modification such that up to 544 technically identical satellites could be launched into non-GEO orbits for the flocks. With approximately 475 satellites already launched, this yields regulation and history scores of 3 [1,56]. The high number of prior launches indicates infrastructure already exists for the production of further satellites, though the company has not announced any new investments or technical partnerships to further progress their constellation. This yields an infrastructure score of 2. Planet earns a history score of 3 for similar reasons as its history, in that they have launched a majority of their constellation already, with no signs of any interruption to servicing. The Planet Flocks earn a RICH score of 11.

ROSCOSMOS' Sfera (Sphere) program, formerly Efir (Ether), bears similar traits to the GuoWang megaconstellation with respect to its secrecy. Little information exists publicly on this constellation, to the extent that even the number of satellites to be launched remains questionable. Current estimates size the constellation at 640 satellites [1], though there are reports that this size has been downsized to an O-Class constellation [57]. This uncertainty penalizes the concept score, though the decision to downsize a satellite network prior to any possible financial troubles indicates some foresight, leading to a concept score of 2. No FCC or ITU filings were found to support or refute these claims, defaulting the regulation score to 1. Supporting infrastructure, however, appears to be in full swing. Gazprom Space Systems recently began construction of a spacecraft assembly production facility, SPKA. Upon completion, it will be the first full-cycle satellite assembly and testing facility in modern Russia, with a predicted production of up to 100 small satellites per year. As of November 2019, the facility was planned to begin commissioning in 2022 with a business model founded in partnerships between public and private enterprises [58]. This leads to an infrastructure score of 3. Historically, Russia exists as one of two powers that were involved in the 20^{th}-century space race. In this new space race, Russia is attempting to reprise this role and has successfully launched its first satellite of the constellation [57]. Sfera earns a history score of 3, totaling to a RICH score of 9.

Table 5 Survey of A-Class constellations with total number of satellites planned and evaluated RICH scores. Constellations with no specified project name are listed as the name of their respective company.

Constellation	Company/Country	Total Satellites	RICH Score
Dove Flock, Super Flock	Planet Labs (USA)	544	11
Mangata Networks	Mangata Networks (USA)	791	11
Sfera	ROSCOSMOS (Russia)	640	9

4. Origin-Class Constellations

The large number of O-Class satellite constellations proposed seems to suggest a preference in sizing for both private companies and state powers. Both L- and A-Class satellites sport a relatively small number of constellations, seeming to suggest that groups developing constellations choose one of two paths: either they choose to develop a small megaconstellation, possibly as an experiment or technology demonstration for a larger network, or they opt for a large network while remaining wary of the high costs and logistical coordination required for operating a multi-thousand-satellite network. Companies choosing the prior of these situations have proposed and developed constellations including Boeing, BeetleSat, Spaceloop, Sateliot, SpaceMobile, Jilin-1, Spire Global, and SpaceNet. These constellations and their respective sizes and RICH scores are listed in Table 6.

Boeing's ventures into the constellation industry have experienced a rather turbulent history. Their original FCC application for a large (M-Class) constellation appears to have been withdrawn, while the new application granted in November 2021 calls for a constellation of only 147 satellites. That same month, the company filed a new proposal for an M-Class expansion on their approved constellation, though no action appears to have been taken on this front [40,59,60]. This yields a regulation score of 3 but drops the history score to 1 due to the apparent issues in choosing a constellation size. As a leading aerospace company in the US, Boeing has a well-established network of resources at its disposal, yielding an infrastructure score of 3. The constellation concept granted calls for a small constellation perfect for a technology demonstration, seeming to suggest that the company's initial withdrawal from a large constellation plan was performed strategically in an effort to prove performance and troubleshoot technology prior to investing in an M-Class constellation. This earns a concept score of 2. Boeing earns a RICH score of 9.

BeetleSat, formerly NSLComm, is the only constellation surveyed in this work with its origins in the Middle East. The Israeli company has made plans for a 240 satellite constellation, but an ITU filing suggests possible plans for expansion beyond this into a larger class of constellations [61,62]. The lack of agreement between the filing and the company's website decreases the regulation score to 2. The history score defaults to 1, as little information is present on the company's development of the network besides the confidence to rebrand the company after the constellation itself. Infrastructure earns a score of 3 due to a partnership with Arquimea, a Spanish global technology company with 15 years of experience in developing space-qualified components and systems and contracts that have led to the manufacture of over 30000 components for ESA and NASA. Additionally, the company boasts a new disruptive large aperture deployable antenna for its satellites, claiming that they are capable of maintaining ten times the bandwidth of traditional rigid antennas while simultaneously being cheaper. The constellation's deployment into a sun-synchronous orbit has been successfully demonstrated twice as of January 2023. BeetleSat is planned to begin services in 2026, earning it a concept score of 3 due to successful demonstrations and an achievable launch schedule [63,64]. BeetleSat earns a RICH score of 9.

Spaceloop is the 126 satellite constellation planned by Orbitare, a company of shared ownership between Switzerland and Luxembourg. Its ITU filing from May 2022 provides extensive details on its orbit, earning regulation and concept scores of 3 [65]. It achieves a history score of 2, as its founding is the direct product of an ESA contract with the Luxembourgish government. The company has a deal established with Spire Global, discussed later, to deploy Spaceloop through the Spire nanosatellite constellation for two on-orbit demonstrations, earning it an infrastructure score of 2 [66]. Spaceloop earns a RICH score of 10.

Established in 2018, Sateliot is the smallest of the proposed constellations surveyed in this work, proposing a network of only 100 satellites. The ITU filing for the constellation was approved back in December 2020, earning a regulation score of 3 [67,68]. The Spanish company has developed a solid foundation of resources, both financial and technical. The first three rounds of investment for the constellation yielded 16.5 million Euros, with the last round netting 10 million Euros alone. Partnerships with Telespazio and Thales Alenia Space meet the company's demands for customer needs and technical assessment. Further financing is underway, and with a planned turnover of approximately 236 Euros, the company earns an infrastructure score of 3 [69,70]. Sateliot has successfully launched two satellites of its network, with four more planned by the end of 2023. The company plans to launch the other 96 satellites by the end of 2025 [71]. This produces concept and history scores of 2. Sateliot earns a RICH score of 10.

SpaceMobile is AST & Science's planned 243 satellite constellation. Their FCC filings, including detailed orbital plans, were accepted in April 2020, producing a regulation score of 3 [72,73]. Concept and history scores of 2 are given for the planning of a smaller constellation and the successful launch of the constellation's first satellite in August 2021 [1]. An infrastructure score of 1 is given by default due to the lack of information found on the network. SpaceMobile earns a RICH score of 8.

Jilin-1 is one of many small Chinese constellations planned within the next decade, and similar to GuoWang, reflects China's growing influence in the private aerospace sector. No ITU filings are found for this network, defaulting the regulation score to 1. The concept and history scores, on the other hand, yield perfect scores. Chang Guang, the company responsible for Jilin-1 [74], announced the successful deployment of its first 10 satellites in

January 2018, and in November 2022 announced that 68 out of the planned 138 satellites were already in orbit. The company plans a full implementation of the constellation by 2030, a highly achievable goal with the current launch rate. Jilin-1 is China's first self-developed remote sensing satellite marketed for commercial use, and due to this gradual rise in power in the space industry, the constellation earns an infrastructure score of 2 [75,76]. Jilin-1 earns a RICH score of 9.

Spire Global's Lemur constellation has already launched at least 140 of its planned 175 satellites, earning it a history score of 3 [1]. Similarly, it earns a regulation score of 3, with an FCC filing from May 2021 granting the deployment of up to 175 satellites at an altitude of 650 km [77]. As a smaller constellation with proven launches constructing the majority of the constellation already, Lemur earns a concept score of 2. The infrastructure score is defaulted to 1 due to a lack of information on the funding and continued operations of the constellation. Spire earns a RICH score of 9.

Table 6 Survey of O-Class constellations with total number of satellites planned and evaluated RICH scores. Constellations with no specified project name are listed as the name of their respective company.

Constellation	Company/Country	Total Satellites	RICH Score
BeetleSat	BeetleSat, formerly NSLComm (Israel)	240	9
Boeing	Boeing (USA)	147	9
Jilin-1	Chang-Guang (China)	138	9
Sateliot	Sateliot (Spain)	100	10
Spaceloop	Orbitare (Luxembourg/Switzerland)	126	10
SpaceMobile	AST & Science	243	8
SpaceNet	Astrome Technologies (India)	198	7
Lemur	Spire Global (USA)	175	9

SpaceNet, Astrome Technologies' planned 198-satellite constellation, stands apart from all other constellations surveyed in this work for its infrastructure planning. The space startup has been pre-selling its internet services under French jurisdiction since August 2019 but has made an unusual choice in its financing. SpaceNet's financial foundation lies in blockchain and has an initial coin offering (ICO) with its French subsidiary to create the SpaceWave (SPW) token. Though innovative, Astrome is the only company to have attempted such a financing campaign, and the lack of a proven track record of such efforts combined with the volatility of cryptocurrency reduces the concept and history scores to 2. The company boasts patented millimeter wave wireless technology [1,78] but otherwise demonstrates few plans for technologically supporting the development of its constellation. This results in an infrastructure score of 2. The regulation score defaults to 1 due to the absence of ITU filings. SpaceNet earns a RICH score of 7.

D. The Projected LEO Population

With RICH scores established, it is of great interest to determine the projected number of satellites that may be launched in the next decade, particularly with regard to the ITU's estimate of 100000 satellites launched within the next decade. Table 7 shows the projected scenarios based on the RICH scoring system.

Immediately, it is noticed that the ITUs projection most likely assumes a worst-case scenario. This scenario yields nearly 88% of the ITU's estimate and is well within the bounds of their approximation, especially once all other constellations not surveyed here for reasons either size or low RICH score are included. Our predicted scenario yields a significantly lower margin, at only 64% of the ITU's projection and 73% of the worst-case scenario. This data point is still within the ballpark range of the ITU's projection but indicates a potentially overly cautious approach by the union. The best-case scenario predicts a total satellite launch count of only 52% of the ITU's projection, or 59% of the worst-case scenario. Such a scenario would likely be the consequence of many companies failing to implement their constellations to any degree and seems much more unlikely than the predicted scenario. Though our predicted figure appears to disagree with the ITU significantly, it is not an indicator of errors in calculations so much as a cautious viewpoint to prepare for any scenario.

Table 7 Projected worst-case, predicted-case, and best-case scenarios of upcoming launches into LEO within the next decade based on RICH scoring.

Constellation	Worst-Case Scenario	Predicted-Case Scenario	Best-Case Scenario
ASTE, DASH, RION	4843	2825	2422
Astra	13620	6810	6810
BeetleSat	240	180	120
Boeing	147	110	74
Dove Flock, Super Flock	544	498	408
GuoWang (GW-2/GW-A59)	12992	9744	6496
Hanwha	2000	1500	1000
Hughes	1440	720	720
Jilin-1	138	103	69
Kuiper	3236	2157	1618
Lightspeed	1671	1253	836
Mangata Networks	791	725	594
OneWeb	7808	5205	3904
Samsung	4600	2300	2300
Sateliot	100	83	67
Sfera	640	480	320
Spaceloop	126	105	84
SpaceMobile	243	162	122
SpaceNet	198	115	99
SpinLaunch	1190	694	595
Lemur	175	131	88
Starlink (Gen2)	29988	27489	22491
STORK	1024	597	512
Total	87754	63986	51749

IV. Deployment, Station Keeping, and Deorbit Strategies

We now turn our attention to their projected behavior. As the current largest and most well-known megaconstellation in LEO, Starlink acts as the industry standard for new constellations and a metric for success by which many companies shall be judged in the future. Starlink is taken to be a representative model of how we might expect the proposed constellations mentioned in the previous section to behave, partially due to the limited number of megaconstellations larger than O-Class currently in operation. In order to successfully model the maneuvering operations and strategies of these constellations, we must isolate and identify certain features of the operational envelope. In particular, there are three broad categories of satellite constellation operations in which we are interested: deployment, station keeping, and deorbit. Transits, phasing, and maintenance orbits are explored as subdivisions of these larger behaviors.

This case study explores the operations of every Starlink satellite launched between 2019 and 2020, studying their altitude and other orbital elements as a function of time from cradle to grave. Data is retrieved in the form of 3LEs from space-track.org and proceeds all the way until April 1, 2023. The 3LEs are grouped together such that one dataset exists for each satellite, and the orbital elements are retrieved through MATLAB.

Some new terminology is introduced in order to identify certain features of the satellite's orbital behavior. First, the altitude at which the satellite resides for an extended period of time, or its steady-state orbit, is referred to as its permanent orbit. In addition to this orbit, a phasing orbit may be defined as an orbit in which a satellite may temporarily reside in close proximity to its permanent orbit, most likely for the purposes of phasing during initial deployment. These orbits are grouped together by an orbit window, or the neighborhood in which a given satellite resides, encompassing the permanent orbit plus or minus the difference between the permanent orbit and the highest (or lowest) phasing orbit. Zooming into the satellite's permanent orbit, a control box may be identified, defined as the local neighborhood in which the satellite resides. Station keeping maneuvers are executed to keep the satellite within this control box in an effort to prevent stray drift or any other constellation formation anomalies which could result in possible conjunctions. Station keeping frequency (SKF) is introduced as a means to provide a rough estimate of how frequently a satellite performs station keeping maneuvers. Finally, the idea of a maintenance, staging, or salvage orbit is introduced (each term may be used interchangeably depending on the context) to refer to any orbit in which a satellite resides outside of its orbit window during a non-transitory period. Fig. 2 visualizes some of these terms. Data on the SKF, orbit window, control box, and remaining proportion of living satellites is shown in Table 8 for each launch group. Note that some launch groups contain two launches due to the way data from space-track.org was split.

Table 8 Starlink orbit and station keeping properties per launch group.

Launch Date(s)	SKF (days)	Orbit Window (km)	Control Box (m)	Remaining Living Satellites (% of launch group)
24 May 2019	13	±10	±100	0%
11 Nov 2019	7 – 14	±20	±40	84.75%
7 Jan 2020	7	±5	±55	81.36%
29 Jan 2020	12 – 14	±5	±75	86.44%
17 Feb 2020	6 – 9	±15	±55	86.44%
18 Mar 2020	4 – 6	±20	±45	94.92%
22 Apr 2020	7 – 14	±10	±75	89.47%
4 & 13 Jun 2020	6 – 11	±15	±50	90.99%
7 Aug 2020	5	±5	±65	94.64%
18 Aug 2020	6	±5	±55	92.98%
3 Sep 2020	4	±5	±75	86.44%
6 Oct 2020	9 – 12	±10	±75	83.05%
18 & 24 Oct 2020	4 – 6	±10	±75	76.27%
25 Nov 2020	6	±10	±75	69.49%

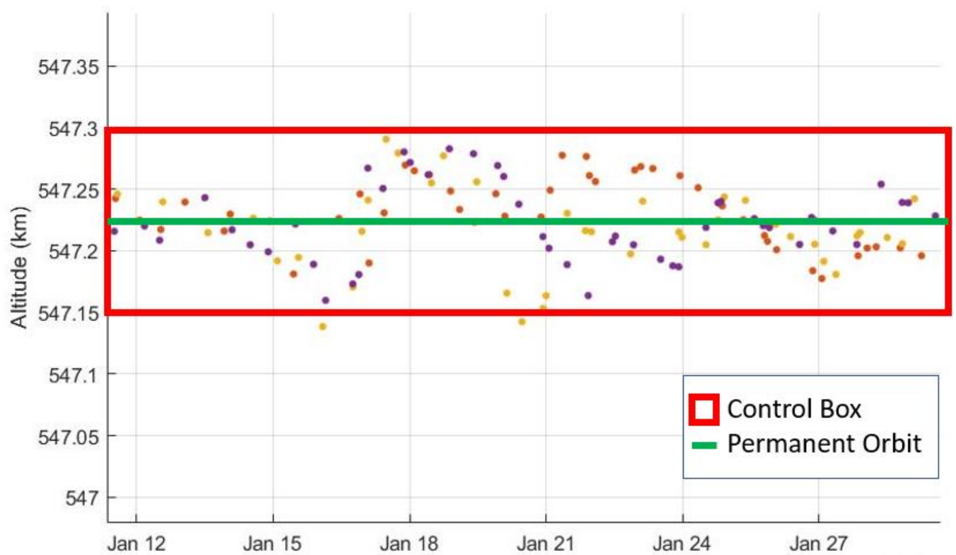

Fig. 2 Visualization of the relationship between the permanent orbit and the control box. The SKF for this set of satellites is approximately seven days.

A. Deployment

The deployment strategies among the 14 data sets are all relatively similar and can be visualized in Fig. 3. Upon successful launch, the constellation satellites rise to a staging orbit. Note that 3LE data may not be available much longer before this orbit due to some ground stations being unable to identify and track satellites at extremely low altitudes. This orbit, as the name suggests, appears to act as a staging ground, a sort of low-altitude parking orbit to perform final systems checks. At this altitude, some satellites may be deorbited with little consequence, as they are typically at or below 400 km in altitude, and therefore have minimal risk of entering a conjunction with another satellite. In some cases, a second staging orbit may be identified, rising some tens of kilometers above the original, perhaps for further systems checks on the way up to the permanent orbit.

All the studied launch groups embrace the same three-pronged deployment strategy. The constellation satellites all launch together, and upon reaching their staging orbit appear to diverge paths as they split into three ascension groups. The first group rises almost immediately after reaching the staging orbit, the second group rises approximately 1.5 months after the first, and the third group rises approximately 2 months after the second. Such sequential deployment allows for greater sustainability, as any satellites displaying performance issues in the staging orbit can be deorbited with little danger to other satellites. Each launch group has exceptions to this rule, where individuals or smaller clusters of satellites may rise by themselves, though these are taken to be anomalies from normal behavior due to an apparent lack of repeated patterns between launch groups regarding these stragglers.

Upon reaching their permanent orbit, satellites may enter phasing maneuvers, described by the orbit window. Many launch groups perform these maneuvers, but not all do, suggesting that they are not strictly necessary, though instead may be highly desirable to achieve the proper spacing between satellites. Such phasing orbits are typically raised 5 to 15 km from the permanent orbit, and while phasing orbits below the permanent orbit are found to exist, they are far less common. One possible reason for this is that a raised phasing altitude reduces the drag force acting on the satellite, allowing for greater certainty on the satellite's position while lowering fuel consumption. Satellites may remain at this altitude for up to three months before they descend back into the permanent. There may be many reasons for this particular timing, though two strong candidates involve the allocation of orbits by regulatory authorities such as the FCC and ITU. These orbits may be allocated directly to the constellation for the purposes of phasing, or the more likely alternative is that these altitudes are reserved for future launches of the constellation and may thus be leveraged for phasing while they are empty. In either case, the frequency with which this maneuver occurs between launch groups suggests it may be considered common practice for the Starlink constellation.

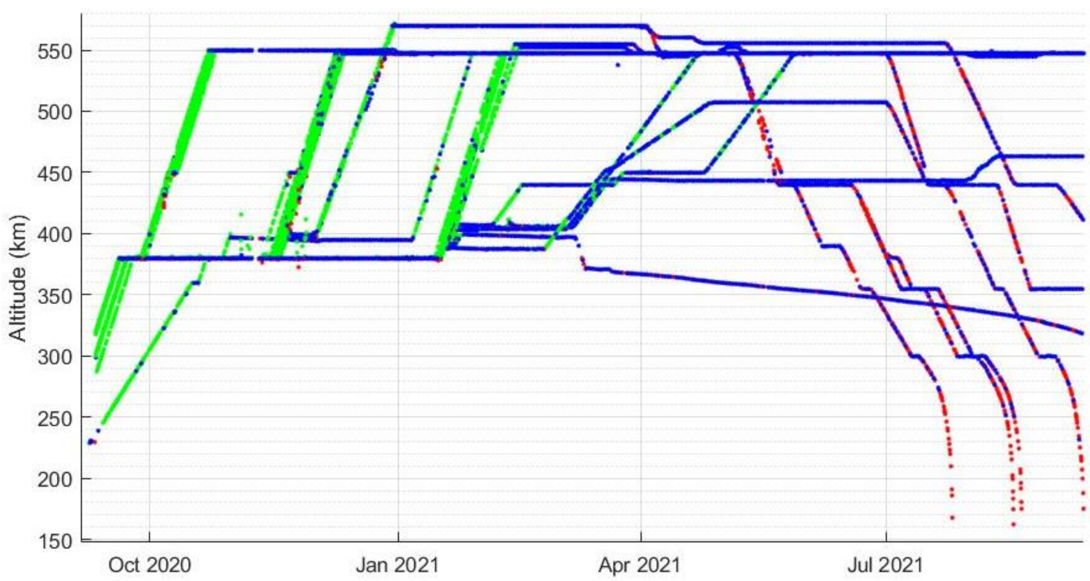

Fig. 3 Starlink three-pronged ascension groups deployment strategy.

Finally, it is highly desirable to understand how the ascending transit from the staging orbit to the permanent orbit is performed. Transits between orbits can often be the most dangerous periods for satellites as they transect the orbital planes of other spacecraft, heightening the risk of a conjunction. Understanding how these maneuvers are performed is therefore critical to achieving better space domain awareness. Fig. 4 plots altitude and eccentricity as a function of time, allowing us to glean some relationship between the two. Two features of the eccentricity plot are immediately noteworthy. First, all eccentricity values remain on the order of $1\text{x}10^{-3}$ upon arrival at their staging orbit. The eccentricities before this are typically higher due to the extreme conditions of launch.

The satellites rise at a rate of approximately 200 km per month, which equates to approximately 7 km per day. This slow rate of ascent is reflected by the second notable feature of the eccentricity plot, in that all eccentricities appear to vary periodically around some value on the order of 10^{-3} during their ascending transit. Upon arrival to the permanent orbit, however, these eccentricity values reduce significantly. Once each deployment group has reached its final destination, the eccentricity plot drops off, and the values oscillate around a much lower steady-state. It is therefore clear that the satellites enter higher-eccentricity orbits during transits between orbits. This pattern is similar for both ascending and descending transits. Such higher eccentricities may indicate characteristics similar to a Hohmann transfer, however, the long period between the transition's departure and arrival, coupled with the near-circular transit orbit, distinguishes this from a perfect Hohmann transfer. This distinction is likely due to Starlink satellites employing low-thrust instead of impulsive maneuvers, a characteristic which is reflected in station keeping as well.

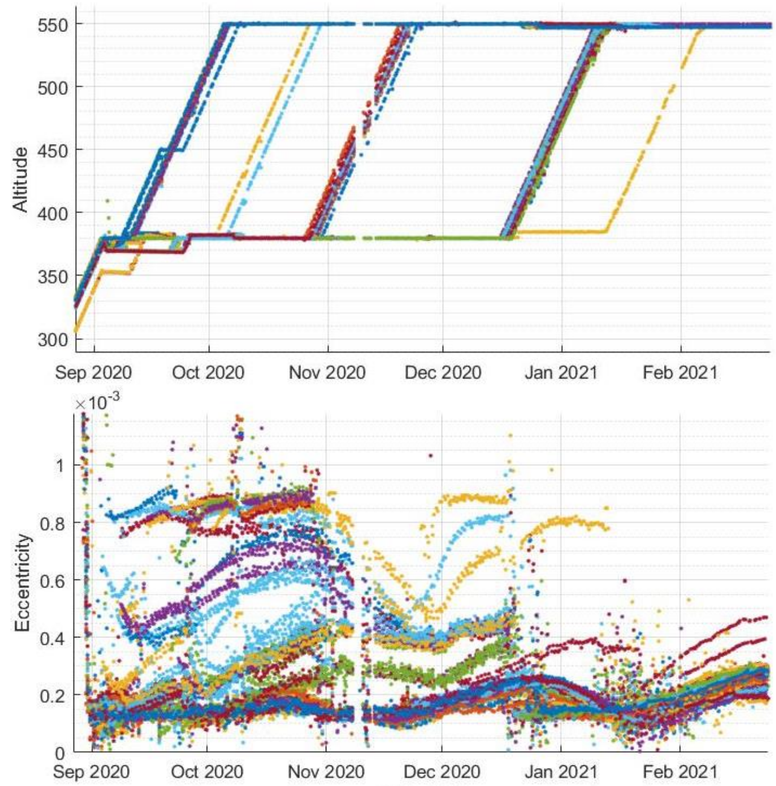

Fig. 4 Starlink eccentricities during transits between staging and permanent orbits.

B. Station Keeping

The drag forces present in the LEO environment mandate that station keeping maneuvers be performed with higher frequency than may be seen in higher-altitude satellites. Failure to perform such maneuvers may result in a satellite falling outside of its control box, heightening the risk of conjunction. Starlink's station keeping maneuvers initially do not appear to be captured in 3LE data through cursory glances at Fig. 4. Zooming into the permanent orbit, however, patterns emerge, as shown in Fig. 5. The station keeping maneuvers are in fact present in 3LE data, and the reason for their initial apparent absence is that the satellites' control boxes are significantly smaller than initially expected. The majority of satellites hold within a control box of ±75 m, with the average control box for the launch groups studied computed to be approximately ±65m. It is unlikely that satellite operators would approach the edge of their control box intentionally, as any failure in control would cause the satellite to exit the box. It is therefore proposed that the Starlink control box is roughly ±100m to account for measurement and operator error. Such a tight control box paired with the slow rates of ascension from staging to permanent orbits reflect the low-thrust maneuvering practices of the constellation.

Station keeping maneuvers are performed every 4 to 14 days in these launch groups, with a group average of approximately 8 days. In other words, each satellite must perform a station keeping maneuver at about once a week. This is of great interest to space traffic management with respect to conjunction prevention and developing collision avoidance maneuvers. If leveraged properly, satellite operators may be able to perform collision avoidance maneuvers in conjunction with their predetermined station keeping maneuvers, saving fuel and boosting efficiency. This requires a relatively high SKF, as satellites that do not carry out these maneuvers for several weeks may have finite windows of opportunity that do not coincide with conjunction warnings. Starlink's SKF of approximately one maneuver per week should be adequately high such that they may employ collision avoidance maneuvers during their normal station keeping.

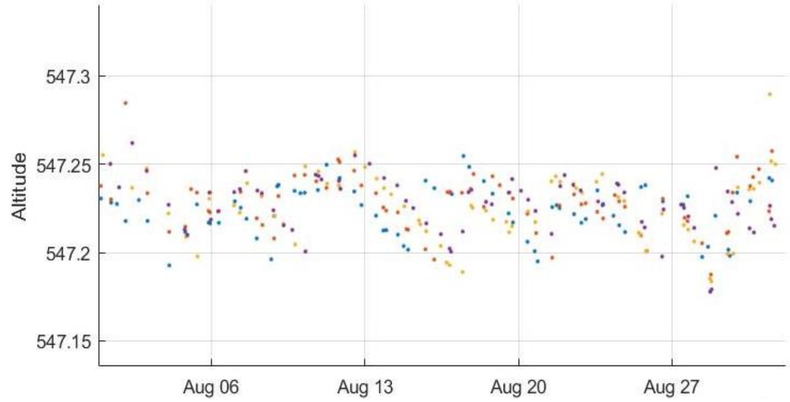

Fig. 5 Altitudes of four Starlink satellites engaging in periodic station keeping maneuvers.

C. Deorbit

Despite being nearly identical in their characteristics (in accordance with the earlier definition of a satellite constellation), two different deorbit schemes may be identified for Starlink satellites, as shown in Fig. 6. The first scheme, which we shall call a rapid deorbit, appears highly controlled. The satellite descends at a rate nearly equivalent to the rate of ascent performed during deployment, allowing the satellite to fully deorbit over the course of 1 month, during which time it may stop at a maintenance orbit. This brief stop in a maintenance orbit may be used to perform system failure diagnostics, download any remaining data from the satellite, or even attempt to repair software. The second scheme, which we shall call a slow deorbit, appears to be slightly more uncontrolled. This deorbit process stretches over significantly longer periods of time, with the most rapid descent happening in the last 6 months of the satellite's life. Though the shape of the curve seems to suggest an uncontrolled drag-based descent, the longevity of this maneuver suggests that some propulsive control is used to slow descent. A purely uncontrolled drag-based descent would occur much more rapidly; discussion of the degree of control of this deorbit scheme lies outside the scope of this work.

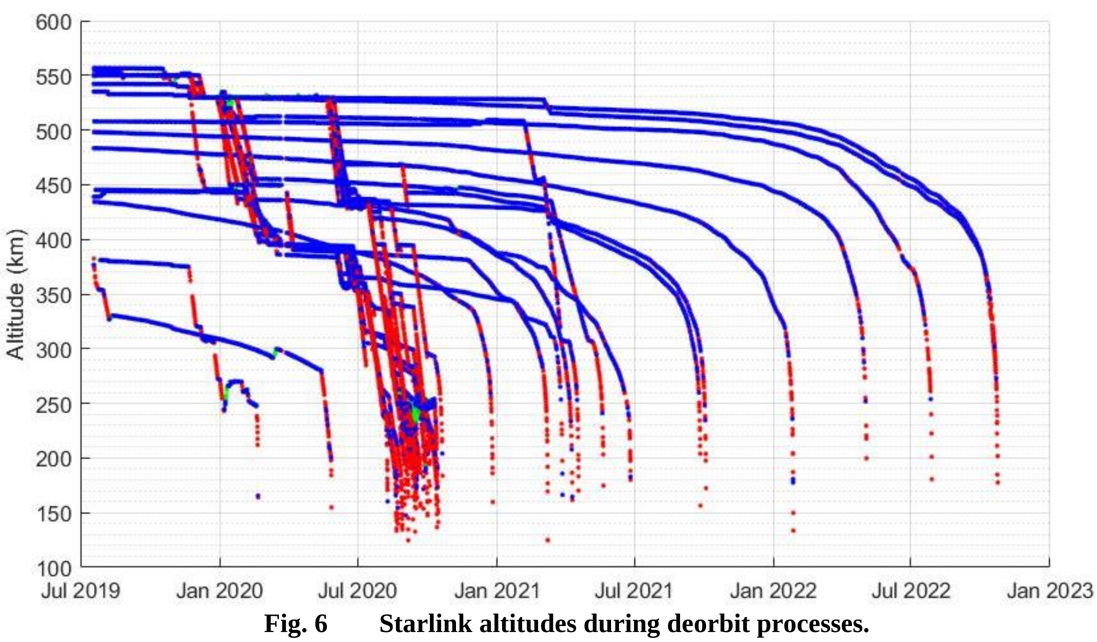

Fig. 6 Starlink altitudes during deorbit processes.

V. Modeling the Future LEO Environment

Now that we possess an understanding of the megaconstellations expected to be launched in the next decade and their potential deployment, station keeping, and deorbit strategies, we may set out to model megaconstellation behavior in the LEO environment. This work is part of a larger effort to model and simulate the future LEO environment and the effects of megaconstellations on space traffic management and space domain awareness in this orbital regime. Successful modeling of constellation behavior allows multiple scenarios to be simulated, including the best-case, worst-case, and prediction scenarios. This is a critical ability given the volatility of megaconstellation projects; though the RICH scores proposed in Section III may be representative of the future LEO environment as of this paper's writing, these scores may change significantly as companies find further financing, file for Chapter 11 bankruptcy, launch satellites, and more. Furthermore, as more companies and countries propose their own megaconstellations, a model allows us to incorporate these new satellites into a quantitative model with relative ease. The culmination of this work is the development of a 3LE Generation Model to accurately reflect megaconstellation behavior.

A. Model Assumptions and Methodology

The model incorporates the deployment, station keeping, and deorbit strategies mentioned in the previous section. It is important to note that it cannot model every piece of megaconstellation behavior perfectly. Though the previous section yields significant insight for modeling megaconstellation behaviors, there are still some parameters that cannot be determined from the data without further information. Some of this data may be publicly available and may be pursued by future works to improve the performance of this 3LE Generation Model. Much of the necessary data, however, likely remains proprietary, particularly due to rising competition in the LEO market. As such, some assumptions must be made regarding the behavior and distribution of megaconstellation satellites based on the information at our disposal.

Given the near-circular nature of the orbits, the eccentricity of each satellite is deemed negligible and is set to 0 as a default. Similarly, as the argument of the perigee is a nonsensical measurement for a circular orbit, it is set to 0 as a default unless otherwise specified by detailed orbital information contained in FCC and ITU filings. Many constellations provide information on the number of satellites per plane, the altitude, and inclination, but not how these planes are separated. The initial assumption is that orbital planes with identical altitudes and inclinations are separated through differences in their right ascensions of the ascending node (RAAN). Starlink is used as an example once again in Fig. 7, which shows the validity of this assumption through groupings of satellites occupying different RAAN values. The drift in RAAN matches our expectations for RAAN drift due to J2 effects as well. Within each orbital plane, it is reasonably assumed that the constellation satellites are evenly distributed by their true anomalies, such that the distance between any two satellites is nearly uniform.

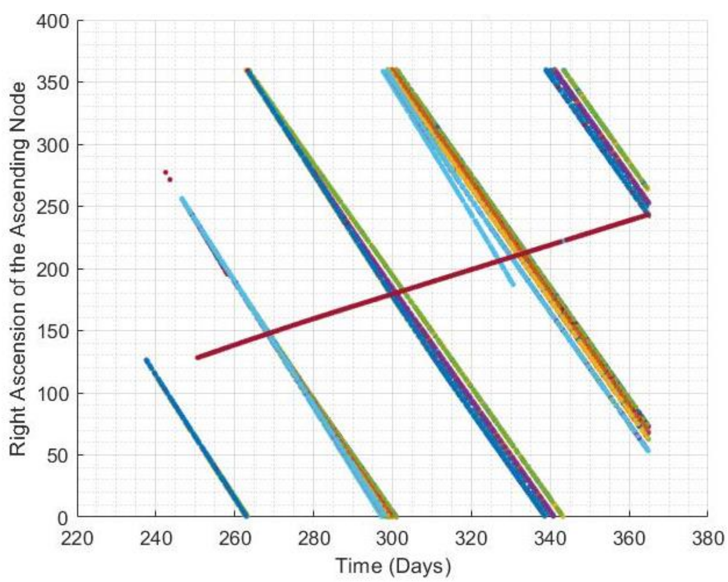

Fig. 7 Right ascension of the ascending node values with respect to time for a group of Starlink satellites.

Additional assumptions for 3LE generation include setting the first and second derivatives of mean motion to 0, setting the element set to 999, and setting the revolution number to 10000. Mean motion is calculated based on the expected altitude of a satellite and assumes a fixed Earth radius and standard gravitational parameter. Perhaps the loosest of all assumptions made is the decision to set the B* term to a constant value of $5x10^{-4}$, represented in 3LE form as 50000-3. The B* term is primarily a drag term but can also act as a catch-all for miscellaneous unmodeled forces, which may include solar radiation pressure. It is a function of the satellite's ballistic coefficient, which is not necessarily known for each constellation surveyed in this work, though it should be pointed out that various estimation schemes may be employed to yield a reasonably accurate value of this coefficient [79]. In LEO, we assume that the drag portion of the B* term dominates all other terms due to large differences in magnitude, meaning the term effectively measures the extent to which a satellite is affected by the variable drag forces of LEO [13]. Further work is recommended to achieve a better model for the B* parameter in 3LE Generation Modeling.

This model is created for a larger simulation effort, and therefore its operation must be constrained by the capabilities of the simulation software. The simulation is not equipped to handle frequent 3LE updates, and therefore 3LEs must be provided for crucial moments where changes in satellite motion occur, including deployment, station keeping, and deorbit. From these requirements, it is concluded that 3LEs are required for satellites at the following stages:

- Initial arrival at staging orbit
- Departure from staging orbit
- Arrival at permanent orbit
- Start and end of phasing orbit maneuvers
- Station keeping
- Initial satellite deorbit
- Maintenance orbits

The 3LEs corresponding to these points are referred to as junction 3LEs since they indicate crucial changes in the satellite's motion. Each 3LE's epoch is updated to reflect the time at which the satellite enters the given state. Using this information, the simulation may compute the necessary ΔV to transfer from one junction 3LE to another.

The model requires 10 input parameters for the constellation itself, as well as 4 additional user inputs which are not inherent to the constellation's orbital parameters. The ten inputs include three slots for the year, month, and day of arrival at the staging orbit (launch date is assumed to happen shortly before and is therefore ignored). The fourth slot lists the number of satellites in the orbital plane. The next two slots ask for the staging and permanent altitude; the staging altitude is not listed in FCC or ITU filings, and therefore an estimate must be made based on existing data. Slots 7-9 include the orbital plane's inclination, starting RAAN, and argument of the perigee, the last of which is set to 0 unless specified otherwise, as previously described in the assumptions. The final slot is reserved for the expected lifespan of an individual satellite. The four additional inputs include the constellation name, used for generating line 0 of the 3LE; a count offset, used to indicate the satellite's number within the constellation if the orbital plane is not the first; a catalog number start, used to specify the starting catalog number where it is assumed that the catalog number of each individual satellite increases sequentially; and a phasing vector, which specifies which ascending groups enter phasing maneuvers and which do not.

The initial arrival at staging orbit is identical for all satellites in a given launch group. Departure from the staging orbit and arrival at the permanent orbit is split into three groups to reflect the three-pronged deployment approach adopted by Starlink. The first ascending group shall rise one day after its initial arrival at the staging orbit, with the second and third groups ascending 1.5 and 3.5 months afterward, respectively (45 and 105 days). Arrival at the permanent orbit is set for 1 month (30 days) after departure from the staging orbit for all groups. At this point, an optional phasing maneuver may be implemented at user discretion, where one-third of the satellites are sent to up to a phasing orbit for three months after their arrival at the permanent orbit. This rise to and fall from a phasing orbit occurs over the course of 1 day for each direction, though this parameter may be modified. 3LEs are generated for the start and end of the maneuver at the phase orbit altitude. Station keeping at the staging, phasing, maintenance, and permanent altitudes is modeled using a series of constant altitude 3LEs, each separated by 1 week (7 days). Simulation propagating these 3LEs will reflect the reduction in altitude between station keeping maneuvers through the implementation of drag modeling.

Based on user input regarding the expected lifespan of the satellites, the model will randomly select approximately 15% of satellites to deorbit at some point prior to the end of their expected lifespans, rounded down to the nearest whole satellite. The deorbit date is randomly selected. This metric is based on the longevity observed of Starlink satellites shown in Table 8 in the previous section. Each satellite selected for deorbit will be randomly assigned a slow or rapid deorbit scheme, with approximately a 50% split between the two. Satellites assigned a rapid deorbit also have a 3LE generated for their arrival to and departure from a maintenance orbit, set to coincide with the staging orbit's altitude. Any satellite that is not marked for deorbit by this random process is automatically set to deorbit at the end of the satellite's lifespan. All modeling is carried out in MATLAB.

The 3LE Generation Model is implemented on a select set of megaconstellations surveyed earlier in this work, using their RICH score to demonstrate the predicted scenario. A minimum of one constellation per size class is selected for modeling, and one orbital plane is modeled from each of these constellations for the sake of brevity. Starlink Gen2 is used as the control case since data already exists for this constellation, and all other constellations have yet to deploy a significant portion of their constellation. GuoWang is taken to represent L-Class constellations, Kuiper represents M-Class constellations, Mangata Networks represents A-Class constellations, and Sateliot represents O-Class constellations. The class variety is chosen such that the effect of different sizes on the model may be identified. Each satellite network is assumed to arrive at its staging orbit on April 25, 2028. Table 9 shows the 10 orbit input parameters for each constellation, where all data except the staging altitude, argument of the perigee, and lifespan are taken from FCC or ITU filings. The staging altitude and lifespan are based on the Starlink parameters observed in the previous section, and the argument of the perigee is assumed to be 0 due to the near-circular nature of each orbit. A variety of input phasing vectors are used. For simplicity, zero offset is assumed and the starting catalog number is set at 30000. Once 3LEs are generated, the altitude of the corresponding satellite at a given point in time is computed from the mean motion entry of each 3LE and plotted for model validation.

Table 9 Orbital planes modeled using the 3LE Generation Model.

Constellation	Starlink	GuoWang	Kuiper	Mangata	Sateliot
Satellite Count	120	60	36	21	4
Staging Altitude (km)	350	300	380	450	350
Permanent Altitude (km)	535	508	610	6400	550
Inclination (˚)	33	55	42	50	97.6
RAAN (˚)	180	90	240	120	144
Argument of the perigee (˚)	0	0	0	0	0
Lifespan (years)	4	4	4	5	4

B. Modeling Results

The plots created from the 3LE Generation Model are incapable of showing behavioral patterns without some modification to the color and sizing of each 3LE junction. As such, each 3LE junction in the proceeding plots is marked as follows:

- Initial arrivals to the staging orbit are called out by green points at standard size
- Departures from the staging orbit to the permanent orbit are marked by black circles at standard size
- Arrivals to the permanent orbit are marked by gold points at standard size
- Arrivals to and departures from the phasing orbit are marked by teal points at standard size
- Station keeping operations are marked by blue dots at reduced size
- Initial deorbits, both controlled and uncontrolled, are marked by red dots at standard size
- Arrival at the maintenance orbit for controlled deorbiting satellites are marked by pink dots at standard size

We first turn our attention to Starlink, the most well-developed megaconstellation to date. Verification of the functionality of our 3LE Generation Model requires that the model capture the overarching behaviors of the real data, a sample of which is shown in Fig. 8. The modeled behavior is shown for scenarios where only the first ascension group enter phasing maneuvers and where both the first and third ascension groups enter a phasing maneuver, displayed in Figs. 9 and 10, respectively.

The most important behaviors to capture in the model are the deployment of the satellites from their staging orbit in three groups, the phasing maneuvers, and the two types of deorbit scenarios. Certain anomalies from the real data are not captured, including individual straggling satellites ascending to their permanent orbit by themselves or phasing at a staging orbit altitude. These behaviors appear on a case-by-case basis in the Starlink analysis from the previous section and therefore no conclusive patterns can be deduced. These deviations from standard behavior are therefore ignored in the modeling process.

The models generated for both phasing scenarios successfully capture the three-pronged deployment from the staging orbit to the permanent orbit, as highlighted by the black circles on their corresponding gold points. Each phasing maneuver achieves its three-month duration and appears exactly where it is expected with respect to the input phasing maneuver commands. In both cases, roughly 15% of the satellites are successfully marked for deorbit prior to reaching the end of their lifespan, with an even split between those marked for controlled deorbits and those marked for uncontrolled deorbits. The scenario with both ascension groups 1 and 3 phasing even captures a satellite deorbit soon after its arrival to its permanent orbit, an important behavior to capture that can indicate a critical system failure. All satellites that are not marked for deorbit prior to the end of their lifespan are successfully marked for deorbit at the end of the input lifespan. The successful capture of each of these behaviors, therefore, validates this as a successful modeling of real-world megaconstellation behavior.

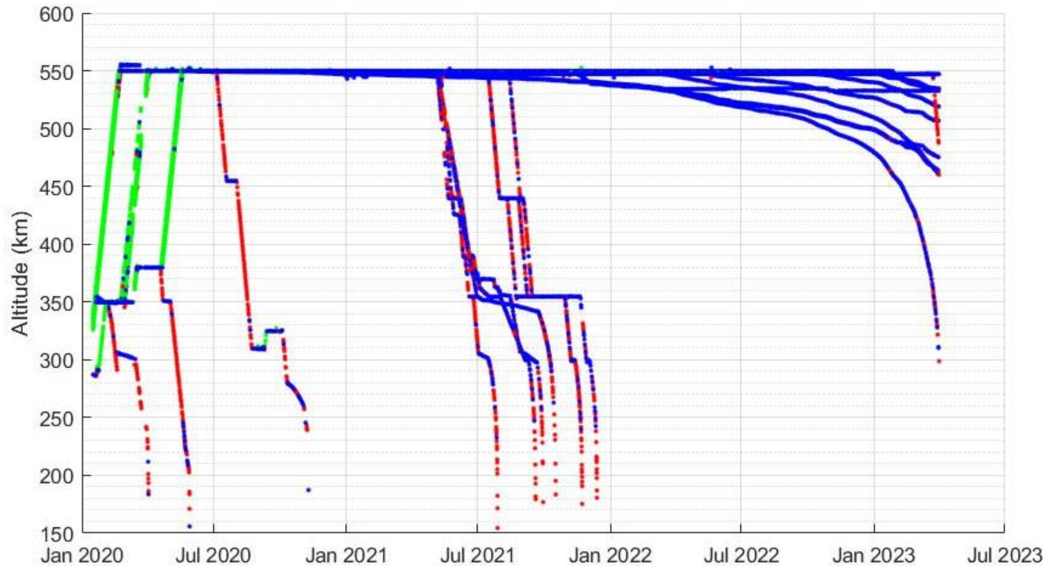

Fig. 8 Actual maneuvering behavior of a single Starlink Gen1 launch group, used to verify the model of the 3LE Generation Model's performance.

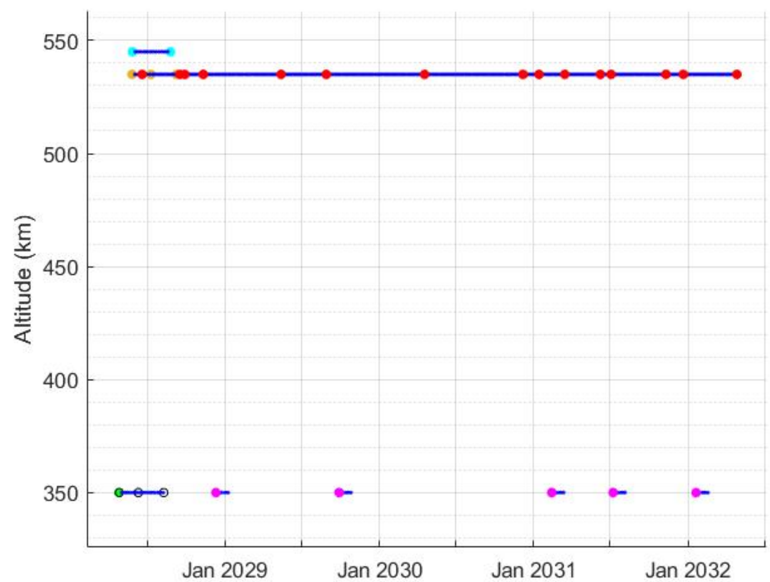

Fig. 9 3LE Generation Model of a single Starlink Gen2 constellation orbital plane with phasing maneuvers implemented for ascension group 1 only.

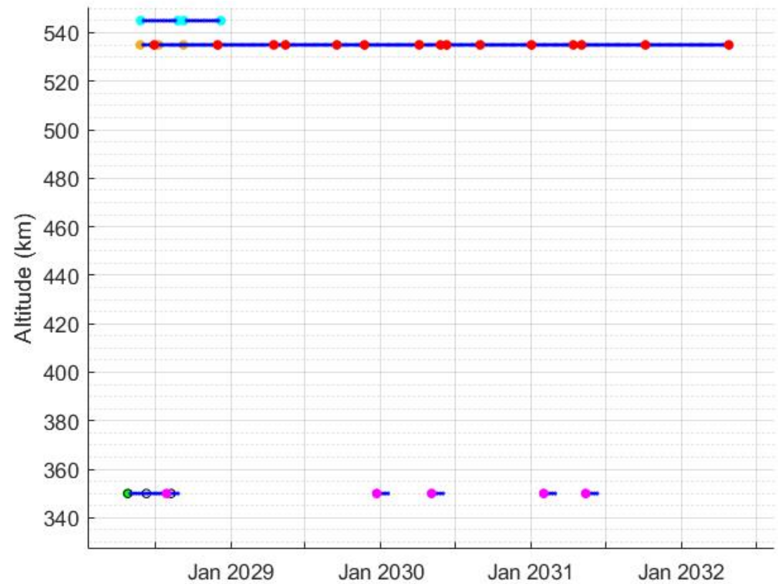

Fig. 10 3LE Generation Model of a single Starlink Gen2 constellation orbital plane with phasing maneuvers implemented for ascension groups 1 and 3.

The successful verification of Starlink's behavior allows us to demonstrate how this model is implemented for constellations of various sizes. Beginning with L-Class constellations, we consider an orbital plane of GuoWang (GW-A59). The generated models with phasing maneuvers for only ascension group 1 and both ascension groups 1 and 3 are shown in Figs. 11 and 12, respectively. Once again, the departure from the staging orbit and arrival at the permanent orbit are successfully marked, as is the phasing of each ascension group. Compared to the Starlink case, the GuoWang case with two phasing maneuvers displays no commands to deorbit satellites until after all phasing is complete. This is a consequence of the way in which deorbit commands are randomly assigned and reflects the success of the model in capturing the unknown behavior of deorbit timing. It should therefore be noted that if a constellation's expected rate of satellite deorbit prior to the end of its lifespan differs from 15%, or if more uncontrolled deorbits occur than controlled deorbits or vice versa, then these parameters may be modified through the addition of further inputs. This is discussed further with the other cases below.

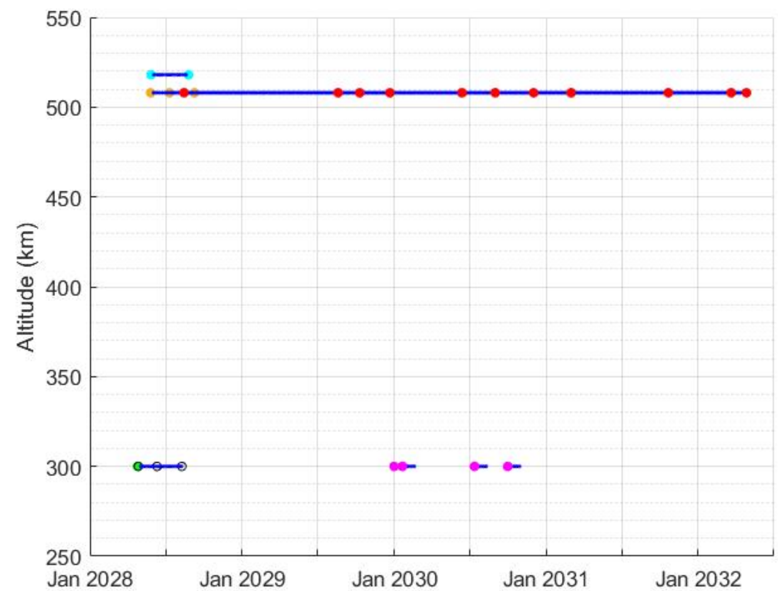

Fig. 11 3LE Generation Model of a single GuoWang constellation orbital plane with phasing maneuvers implemented for ascension group 1 only.

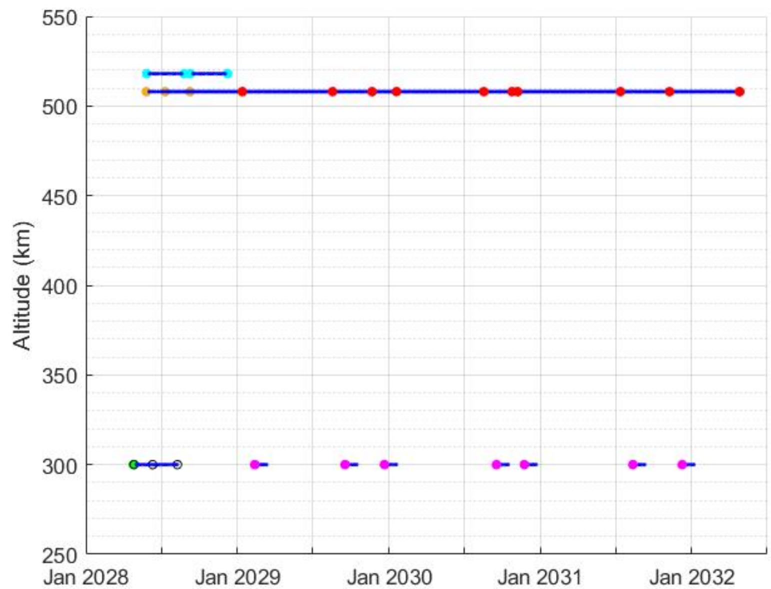

Fig. 12 3LE Generation Model of a single GuoWang constellation orbital plane with phasing maneuvers implemented for ascension groups 1 and 3.

Moving onto M-Class constellations, Figures 13 and 14 show the modeled behavior of Kuiper satellites for phasing commands of only ascension group 1 and both ascension groups 1 and 3. The first noticeable difference from the previous plots is that the deorbit rate for the case of a single phasing group appears much lower. This is a consequence of sample size: the smaller a constellation network is, the less representative it will be of the overall statistics due to an inherent inability to accurately capture fine changes in said statistics. This orbital plane contains only 36 satellites, meaning that a 15% deorbit rate would consist of 5-6 satellites. The single phasing group model only shows two deorbited satellites, both of which enter a controlled deorbit. This seeming anomaly actually further enhances the model and highlights the unpredictable behavior of satellite deorbits.

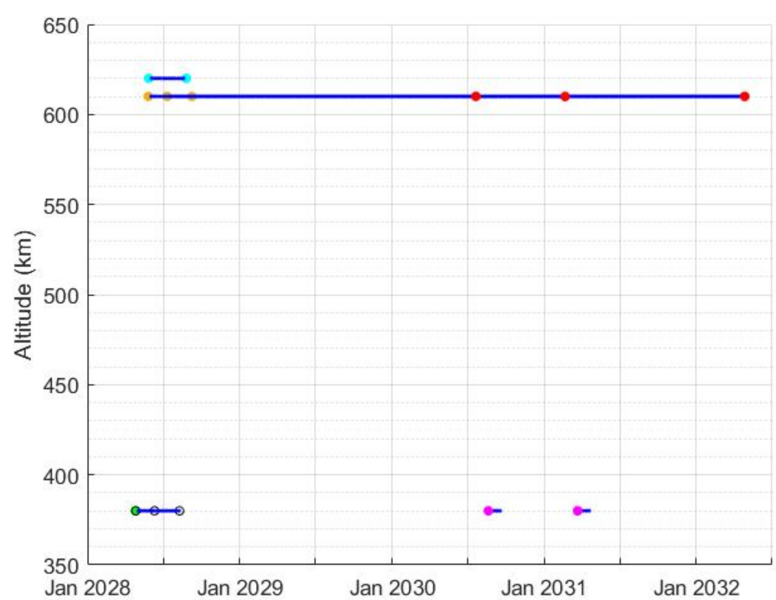

Fig. 13 3LE Generation Model of a single Kuiper constellation orbital plane with phasing maneuvers implemented for ascension group 1 only.

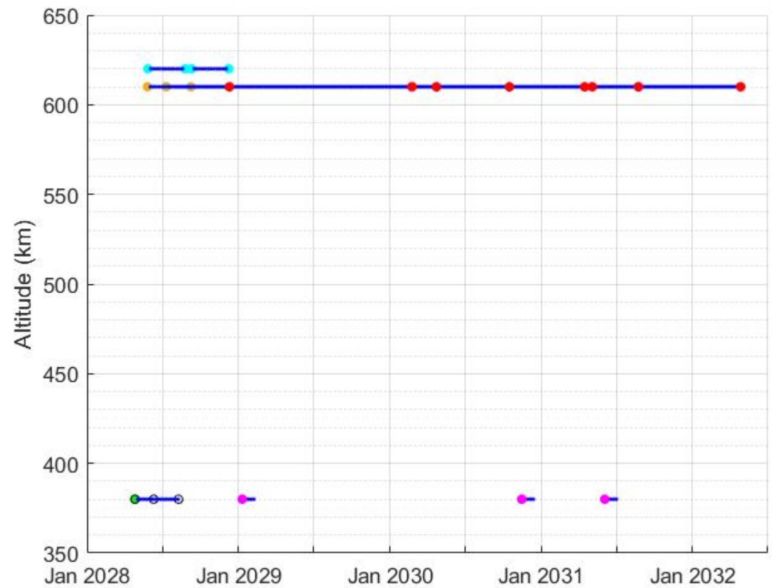

Fig. 14 3LE Generation Model of a single Kuiper constellation orbital plane with phasing maneuvers implemented for ascension groups 1 and 3.

Mangata Networks represents the A-Class constellations due to the relatively high level of knowledge about its orbital planes in comparison to Sfera. Though the Dove and Super Flocks better represent a LEO case, it is important to be able to capture constellations in MEO and HEO as well, since their transitions from staging to permanent orbits as well as their deorbit processes must inevitably pass through LEO. Fig. 15 captures the modeled behavior for Mangata with a phase command issued for only ascension group 1. Due to the significantly large altitude difference, Fig. 16 zooms into the phasing maneuver to demonstrate separation from the permanent orbit. This also allows for an enhanced perspective of the station keeping maneuvers, demonstrating the imperfect overlap of the maneuvers between different ascension groups. As with the previous cases, all behaviors are successfully captured, indicating that should the deployment, station keeping, and deorbit strategies remain the same between different orbital regimes, the model can be successfully implemented for all of them. A difference in these behaviors would require the readjustment of certain model parameters, but the structure of the model as a whole still works.

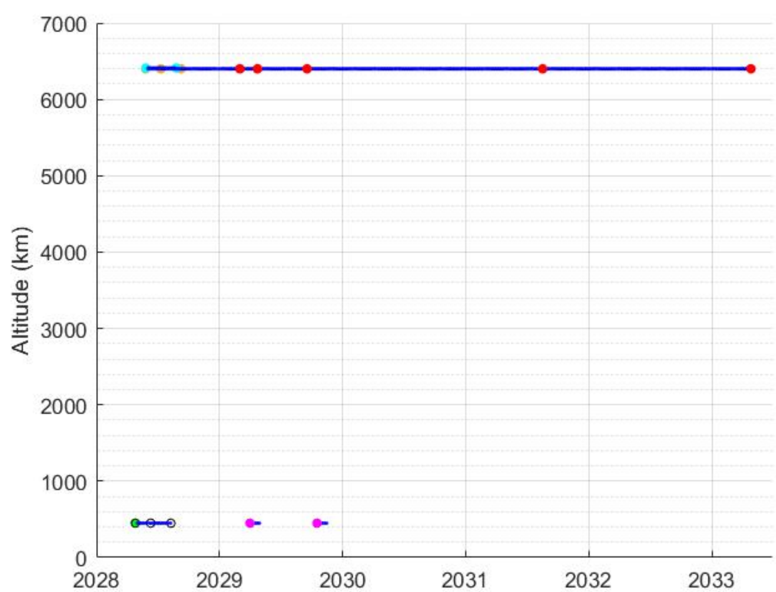

Fig. 15 3LE Generation Model of a single Mangata Networks constellation orbital plane with phasing maneuvers implemented for ascension group 1 only.

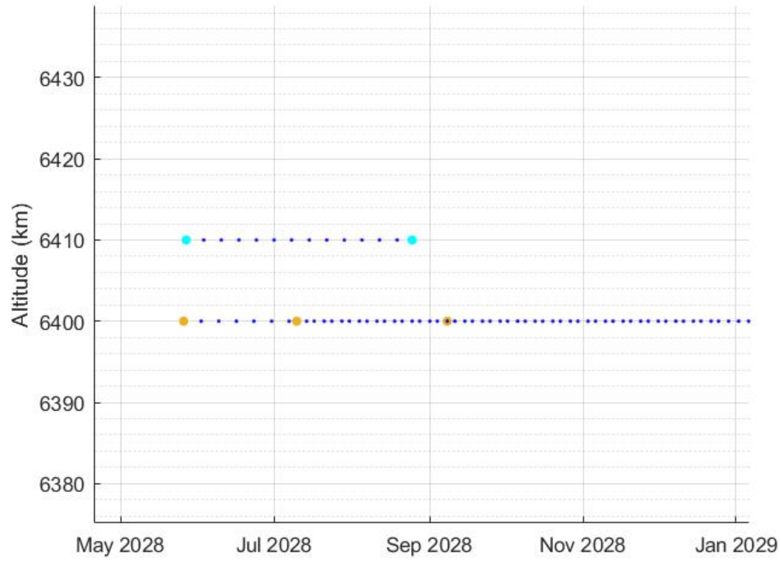

Fig. 16 3LE Generation Model of a single Mangata Networks constellation orbital plane zoomed in on the phasing maneuver implemented for ascension group 1.

Finally, Sateliot represents the O-Class constellations as the smallest network surveyed in this work. Fig. 17 looks at this modeled behavior with a phasing command entered for only ascension group 1. The small size of this constellation is truly highlighted here by some simplified plot characteristics which may also point out potential sources for improvement in the model. First, no satellite deorbits occur before the end of the projected lifespan. With only 4 satellites in this orbital plane, it is expected that a maximum of 1 satellite would deorbit, so this behavior is no anomaly. Additionally, no satellites appear to enter a phasing maneuver, despite such a maneuver being planned for the first ascension group. This is once again a consequence of the small number of satellites in the orbital plane. The model implements a phasing maneuver for only one-third of satellites in an ascension group, a statistic estimated based on Starlink behavior analyzed in the previous section. Each ascension group in this case would only consist of 1-2 satellites, meaning that no satellites would be sent into a phasing maneuver.

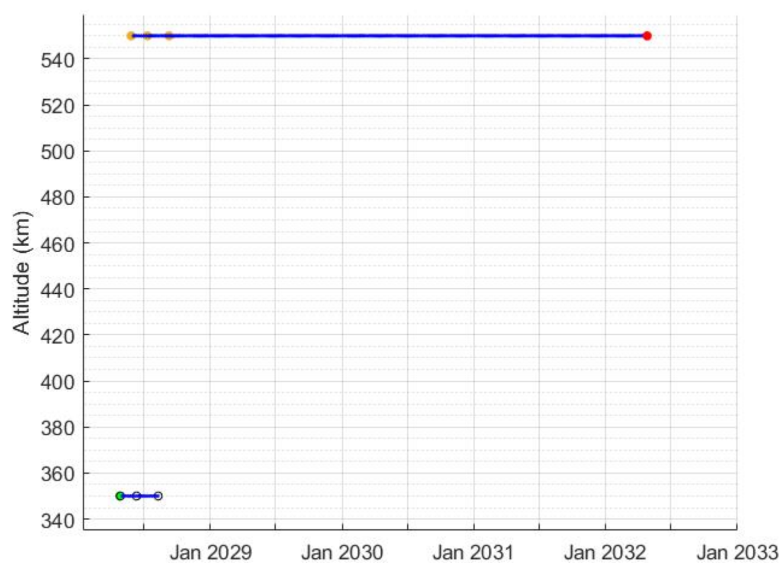

Fig. 17 3LE Generation Model of a single Sateliot constellation orbital plane with phasing maneuvers planned for ascension group 1 only.

From the five constellations modeled above, it may be concluded that the 3LE Generation Model is able to effectively capture the most important behaviors of megaconstellations, though this behavior potentially degrades for orbital planes with fewer than 20 satellites. Further modifications to the model may be carried out as desired to introduce inputs to account for differences in phasing orbit altitude, deorbit rate, and similar adjustable factors.

VI. Conclusion

The rise of megaconstellations in the past decade has led to a rapid increase in the rate of satellite population growth in the LEO environment. Occupying only a small portion of near-Earth orbital space, the orbital regime is set to become much more crowded than ever before within the next decade as more private companies and state powers alike launch their own megaconstellations.

Understanding the future LEO environment is critical for a multitude of reasons. Improved space domain awareness allows for better modeling and tracking of debris, helping to combat the Kessler syndrome. The ability to simulate this environment allows us to determine the effect of megaconstellations on the number and frequency of conjunctions in LEO, and with proper simulation tools can even aid in the development of improved collision avoidance maneuvers and algorithms. This may ultimately lead to the development of improved space traffic management policy in the long term.

Our efforts conducted a survey of future megaconstellations currently planned around the world, including an evaluation of their likelihood based on their current status. This information, however, is insufficient for proper modeling due to the volatile nature of megaconstellation projects. Two years of Starlink launches are therefore analyzed as a means to determine current industry standards for the deployment, station keeping, and deorbit practices of megaconstellation satellites. These strategies are much less subject to change than individual constellation projects. Using this information, a 3LE Generation Model is created to represent critical points in satellite lifetimes. This model will be used by currently active efforts to perform simulations on the future status of the LEO environment with the hopes of analyzing the effects megaconstellations may have on conjunctions and the environment as a whole.

It is possible that megaconstellation maneuvering strategies may evolve in the coming years as more satellites are launched by various groups. As these groups learn from mistakes and alter maneuvering strategies, the model must be updated. Additionally, continued launches may allow for the refinement of certain assumptions made in the current 3LE Generation Model, creating a higher-fidelity model that more accurately reflects the behavior of these satellites. The ability the generate 3LEs as a model for future megaconstellations represents a step forward in space domain awareness and space traffic management, and as the model evolves with maneuvering strategies, simulation efforts may be able to portray the LEO environment further in advance with increasing accuracy. Such simulation capabilities hold incredible potential for the reduction of conjunctions and the ultimate ability to monitor and regulate traffic in LEO.

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