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Impact of Launch Cadence on the Automation & Economics of Constellation Operations

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Abstract

When designing the operations concept for a satellite constellation a mission owner needs to consider the initial size of the operations team, when and how to ramp up the staffing, and ultimately the steady-state size of that team. In parallel to the routine operations of the existing constellation, the operations preparation and launch and early orbit phase for the next batch of satellites joining the constellation have to be performed, as well as the deorbit of degenerating satellites and the preparation of the constellation's next generation. These factors have to be addressed at the design stage and trying to scale the approach from classical satellite operations to a constellation leads to the conclusion that several hundreds of operators would be required. This is cost ineffective, negatively impacting the ability to close a business case, nor credible because such a number of operators does not exist and cannot be trained up responsibly within the required time. The answer must consequently involve software and automation so that the workload of the operators is reduced.

Several constellations are now operational where, for example, Starlink and OneWeb are already starting to refresh with a second generation. This paper compares the evolution of these constellations and reveals what can benefit those wishing to launch and operate their own constellation in future. We study how the launch cadence impacts the size and growth rate of the constellation and in turn the operations team. We uncover some unexpected trends that are common between operators, such as Planet, Spire, OneWeb and Starlink, and in turn the time and data operators have available for achieving the desired automation. We also discuss when machine learning or digital twins become feasible to employ and the type of mission phase they can help to automate during the lifecycle of the constellation. This also serves as a benchmark, where an assessment as to how much a new technology facilitating automation has to achieve in order for it to be felt in the total lifetime of the constellation. We conclude the paper with lessons that can be learned for upcoming constellations such as LEO-PNT.
Keywords: Satellite Constellation, Launch Cadence, Automation, Operations, LEO-PNT

Acronyms/Abbreviations

AI	Artificial Intelligence
DT	Digital Twins
FTE	Full Time Equivalent
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
ML	Machine Learning
MP	Mission Planning
OA	Orbit Analysis
OPS Team	Satellite operations team
R^2	coefficient of determination
Sat/Op	Number of satellites per operators

1. Introduction

The rapid expansion of satellite constellations, driven by global demands for communication, earth observation, and navigation, has brought new challenges to mission operations. As constellations scale, managing the growing number of satellites, each with its own telemetry and operational requirements, becomes increasingly complex. The approach when operating a single satellite, a handful of satellites or a small fleet is challenging to scale viably for a constellation of hundreds or thousands of satellites. To maintain efficient and cost-effective operations, satellite operators must transition to automation and advanced software solutions, reducing the workload on human operators while ensuring mission success. In recent years, several prominent satellite constellations have become operational, with pioneers such as Starlink and OneWeb being at the forefront. These constellations have pushed the boundaries of what is operationally feasible, requiring new approaches to manage their ever-growing constellations. Furthermore, operators must address not only the routine management of the constellation but also the challenge of preparing for the next generation of satellites and retiring older assets. As Starlink and OneWeb move toward their second-generation constellations, insight can be gained into the cadence with which they and other operators, such as Planet and Spire, deployed the constellations, as well as the level of automation, staffing and operational efficiency they were able to reach. In this paper this comparison is performed with the aim of predicting how future constellations, such as LEO-PNT, could be deployed and what size of operations teams they may need over the lifetime of the constellation.

1.1 Reported Impact of Automation on Manpower Support for Satellite Operations

In a recent study, Ben-Larbi et al. [1] identify seven critical areas of stress encountered by the Operations Team (OPS Team) as the number of satellites having to be operated increases: resource allocation, satellite development, commissioning, nominal operations, software and configuration, orbit management and calibration/validation. This study underscores the need for new operational paradigms to address these challenges. Automation plays a crucial role in improving operational efficiency by reducing operator interaction and increasing task consistency. However, the paper also points out that as constellations grow and data volumes increase, the demand on ground stations and scheduling systems becomes more complex. Advanced automated scheduling and anomaly detection techniques are essential to handle these increased demands and ensure efficient operations. An example of how automation can benefit constellation management and free the operators from some repetitive tasks comes from Planet. Longanback and McGill [2] describe Planet's approach to operating their SkySat, comprised of smallsats, and Dove, consisting of cubesats, constellations. Unlike traditional methods of building manual processes and then automating them, Planet adopted an automation-first strategy, continuously improving their systems over time. Initially, the commissioning process for SkySats was manual and time-consuming but as the constellation grew automation became essential. For launches with multiple satellites (e.g. 4 or 6 SkySats), Planet implemented automated commissioning plans to streamline operations. This optimization led to a reduction in the number of operators per satellite from 8 in 2013 to 0.8 in 2018, while the fleet-wide manual effort was reduced from 16 person-hours per day to 3 person-hours per day. Planet developed several operational tools to achieve these improvements, including a pass planning tool, sequence validator simulation tool, and task alert controller. These automation efforts enabled Planet to maintain health and safety checks without constant human monitoring, relying instead on interrupt-driven alerts for anomalies. This approach demonstrates the effectiveness of proactive automation strategies in managing large satellite constellations, allowing Planet to scale operations efficiently as their fleet grew. The positive impact of automation for Planet is highlighted also in Ahumada et al. [3], which quantifies the impact and improvements of the automation tools developed between launches in terms of commissioning workflow. From the launch of Flock 4a in April 2019 to the launch of Flock 4S in January 2021 the average time between first contact and first light moved from almost 39 days for 20 satellites to little more than 4 days for 48 satellites, while the average time between starting detumble and first light moved from 38 days to 3 days and 15 hours. It is evident that the improved efficiency of routine operation and commissioning tasks has an impact on staffing levels. Howard and Oza [4] depict the evolution of staffing levels as efficiency improvements are implemented, with the result of reducing the need for human intervention over time. The integration of automation occurs in stages, allowing for a controlled decrease in staffing levels as systems become increasingly automated. This trend continues until the constellation reaches maturity, after which routine maintenance and monitoring may necessitate a slight increase in specialized personnel as ageing satellites require more frequent health assessments and repairs. A hypothetical trend of staffing levels is shown in Fig. 1, which is inspired from [4].

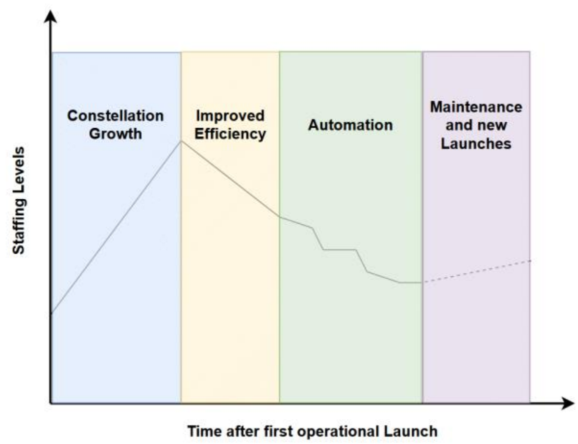

Fig. 1. Evolution of staffing levels across the constellation's lifecycle, encompassing growth, improvements in operational efficiency, automation of tasks and maintenance of aging satellites

The growth of the constellation requires an increment of operators to manage the initial and increasing number of satellites launched. With time the automation of manual tasks allows the efficiency to increase and consequently for staffing levels to steady or to be deployed on to other activities within the business. The maintenance of ageing or deorbit of satellites, as well as the preparation for new launches, will increase the workload for the OPS Team, which will likely require initial manual support that will, just with the routine operations, yield to a further wave of automation and improved efficiency.

1.2 Aims & Objectives

Previous studies have explored satellite operations in traditional contexts, highlighting the need for effective human-machine collaboration to manage mission complexity. Automation, Machine Learning (ML) and Digital Twins (DT) have been proposed as key enablers for future mission operations [5] [6] [7]. This paper takes a higher-level view by examining the operational evolution of a range of large-scale constellations to identify whether common patterns arise that may influence the long-term impact of automation on mission success. The aim of this paper is to study the evolving operational models of satellite constellations and propose a scalable, automation-driven model that can be applied to future constellations. We will assess the feasibility of applying ML and DT to various mission phases, providing guidance for when and how these technologies should be employed. Furthermore, we will use the published data from operators to derive a model on the evolution of the operations team based on launch cadence and efficiency of the automation processes.

1.3 Structure of the Paper

Section 2 presents the results of the deployment rate of LEO constellations, along with their best fitted launch cadence models. Section 3 focusses on the impact of automation on the operations over time. Based on the data from different constellations models, the efficiency increase of the OPS Team is extrapolated by using the Satellites per Operator (Sat/Op) ratio as a metric. These models are compared and an average of all the models is proposed. In Section 4 the previously deduced models for the launch cadence and the Sat/Op evolution is employed to forecast the evolution of the OPS team's size for a future LEO constellation, such as a LEO-PNT constellation. A discussion on the feasibility and timing of introducing automation and technologies like DT based on the average time between launches is included in Section 5. The conclusions and a summary of the results are presented in Section 6.

2. Evolution of operational satellite constellations

For this study, the launch data of several constellation operators are analysed in order to investigate whether there are common trends and to derive a benchmark to be used for future generations of constellations. For each operator, the launch dates with the respective number of satellites launched are retrieved, combining the public information from the various companies' websites and from NewSpace [8] and SkyRocket [9]. By plotting the cumulative number of satellites launched into orbit against the elapsed days since the first launch, it is possible to identify a few correlations between the growth of these constellations, as shown in Fig. 2.

The first striking observation is the growth of the constellation appears to occur linearly. When computing the values for the coefficient of determination (R^2) of the linear regression models, which evaluates the quality of the best fit and where a maximum value of 1 represents a perfect fit, we see in Table 1 that the R^2 values for the launch cadences of the analyzed constellations offers a good linear fit.

Table 1. R^2 values for the Linear Fit of the launches for the analyzed constellation

Constellation	R^2 of Linear Fit
OneWeb	0.9597
Spire	0.9534
Planet	0.9751
Starlink	0.9738
Swarm	0.9151
Iridium	0.9865

Fig. 3 shows the data in greater detail for Starlink and OneWeb. Note, the data for the other considered constellations is presented respectively in Appendix A.

The second observation is that the constellation missions launch a series of test or in-orbit demonstration satellites before ramping up the constellation with their production grade satellites. Table 2 summarizes the duration between the first launch of the test satellite and the commencement of the production grade constellation. For the considered constellations this can range from 0.7 years to a little more than 2.5 years. The single company in our study not to have launched a test satellite is Iridium, who commenced with a production grade satellite with their first launch and proceeded to continue building the constellation. The test campaign allows operators to understand what manual procedures can be automated, which in turn will assist in accelerating the automation of the constellation and a more efficient allocation of staff resources after the first years.

Table 2. Average launch cadence of production series launches and test duration in days of the analyzed constellations

Company	**Average Launch Cadence (Days)**	**Test Duration (Days)**
OneWeb	76	344
Spire	146	466
Planet	263	265
Planet (Doves)	135	265
Starlink	31	456
Swarm	119	965
Iridium	166	0

Note, that our computed best fit models have been derived by excluding the test launches and starting from the first production series launch. It is from this point on that the constellations appear to be established largely in a linear fashion.

Closer inspection of the actual ramp up, as depicted in Fig. 3, reveals that gaps in the launch cadence appear due to unforeseen circumstances. The events, for example, of COVID-19 and the war in the Ukraine had an impact on launch cadence, as well as singular events specific to an individual company, e.g. bankruptcy.

The third observation to be gleaned from the data in Fig. 2 and Table 2 is the average days between launches during the ramp-up phase of the constellation. Note, the average launch cadence derived for Table 2 considers only the ramp-up of the production grade constellations and excludes the unplanned gaps in the launches due to events such as bankruptcy or COVID-19. Starlink leads the way with an average launch every 31 days followed by OneWeb with a launch interval of 76 days. The other constellations in our study are observed to be launching their satellites roughly every 4-6 months.

The fourth and final observation we derive from Fig. 2 is that once the constellation begins to ramp-up none of the operators in our study are able to accelerate the launch cadence or completion of the deployment. Similarly, we also do not observe a tailing off or slowing down of the deployment. Therefore, once a constellation commences its ramp-up it seemingly proves difficult to accelerate this rate.

The data on the whole offers to provide a benchmark for future constellations in terms of launch cadence, deployment and growth rate. In this paper we will make use of these to predict how a future constellation, such as LEO-PNT, can be put into place and made operational. On a more general consideration, Table 3 compares the amount of time in years needed to fill a constellation assuming these observed launch cadences.

As can be seen, Starlink and OneWeb are the companies with the highest launch cadence, and so adopting their model would require significantly less days to fill a constellation than the one required by adopting a Spire or Iridium-like model. An important caveat is the reliability of these linear models is smaller for lower number of satellites, and the number of satellites added to the constellation per launch is not considered, meaning that if a company sends larger batches of satellites, it will have a fewer days to fill the constellation than, for example, a company with the same launch cadence but a smaller number of satellites launched per launch.

An interesting observation derived from Table 3 is if one aims to launch thousands of satellites then only the launch cadence achieved by SpaceX will ensure the envisaged service becomes operational within an acceptable timeframe.

Table 3. Years required to fill a constellation of N satellites by adopting the launch cadence models

No. of Sats	**OneWeb**	**Starlink**	**Iridium**	**Swarm**	**Planet**	**Spire**
100	0.2	0.6	20	1	1	3.7
200	0.7	0.7	22.9	2.7	2.7	8.6
500	2.2	0.9	31.5	7.5	7.7	23.1
1000	4.7	1.3	46	15.7	16.1	47.3
2000	9.7	1.9	74.9	31.9	32.8	95.8
3000	14.7	2.6	103.8	48.2	49.5	144.3

This data, however, does not reveal anything about the efficiency of the operators in terms of their satellite operations. The next chapter captures what operators report on their achieved level of automation over time and our attempts to derive a manpower model that describes the change over time in the ability of a single operator to operate additional satellites by automating the workflow.

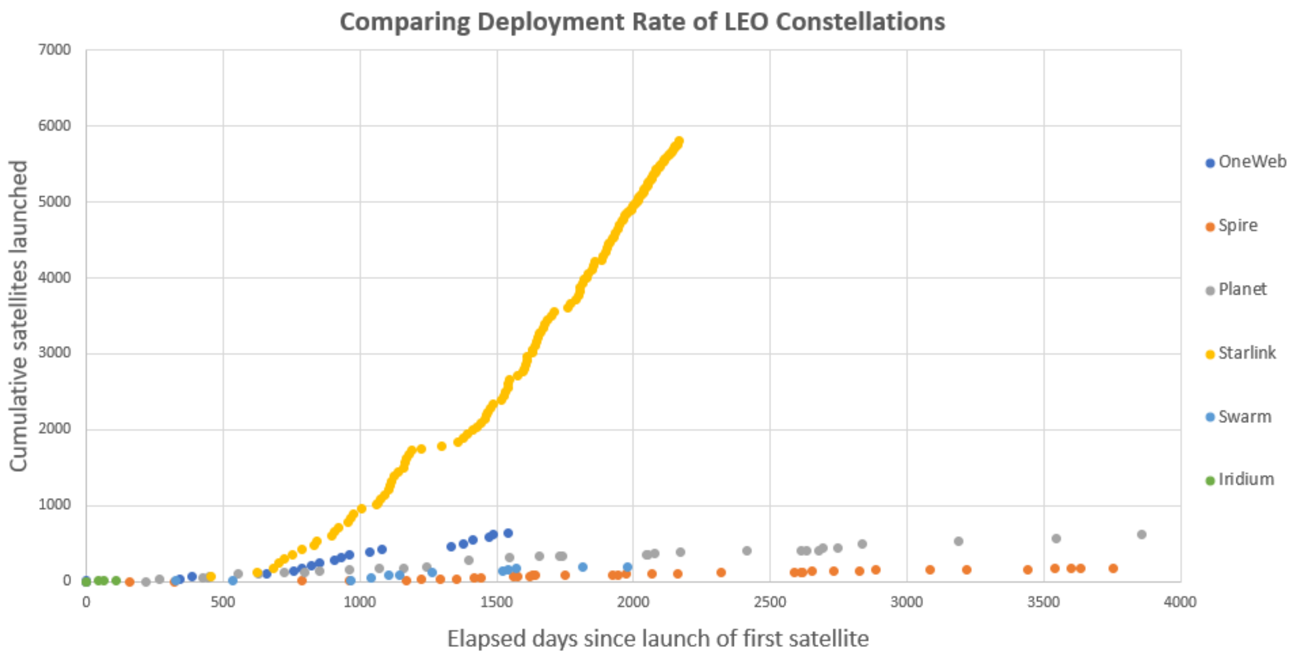

Fig. 2. Comparison of the Deployment Rate of LEO Constellations

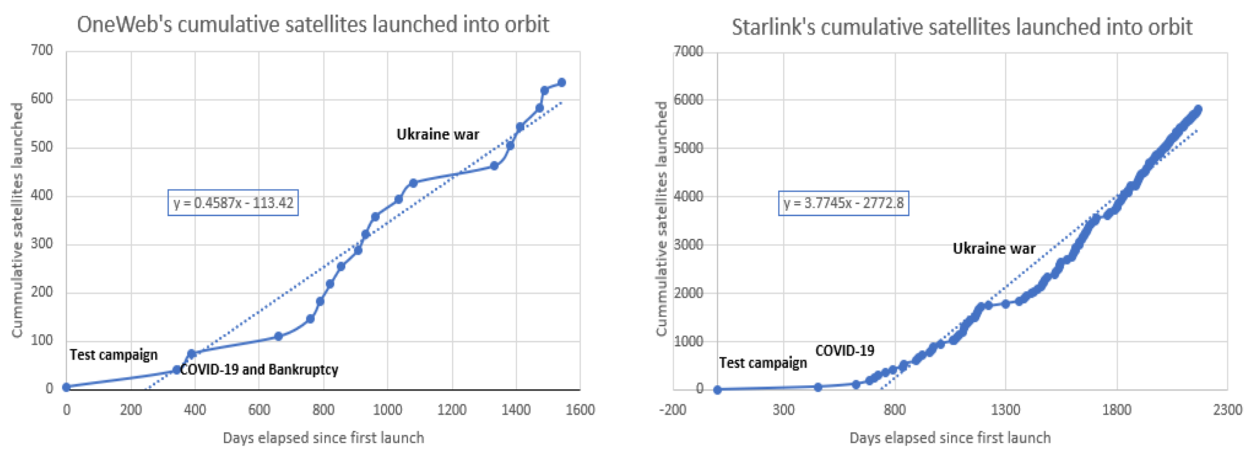

Fig. 3. Cumulative satellites launched into orbit by OneWeb and Starlink with linear best fit models

3. Modelling of the number of satellites operated per operator over time

Several papers report on the impact of automation on the commissioning phase and routine operations. Whilst they reveal some insight, it is understandable in terms of commercial sensitivity and advantage that an explicit operations team size at a given point in time is not necessarily presented, as well as the amount of time or cost it took to automate the processes. Furthermore, the difficulty of retrieving information on the number of active satellites operated at any given time makes the task of deriving a manpower model challenging. Nonetheless, in this paper we attempt to combine multiple sources of information to derive an approximation for a manpower model based on the number of satellites operated per number of operators. This is the efficiency metric and its evolution over time that we focus on in this paper.

In Ivanov et al. [10] the Iridium case is presented. When the first production launch took place in 1997, the OPS Team consisted of two sub-teams supporting 24/7 operations. The Mission Planning (MP) team was broken down into four shifts including a team supervisor and an Orbit Analysis team (OA), made of a dozen shift workers, several senior engineers and a team leader. Assuming that a full seven days a week shift typically requires a minimum of 5.4 Full Time Equivalents (FTE), we estimate the initial size of the MP team comprising 26 people and the one of the OA team consisting of 17 people. With the help of over 600 Perl and Matlab scripts for MP and OA, a parent process that coordinates tool execution based on operator needs and an automated 24/7 monitoring system was introduced. This allowed the operator to be notified of issues remotely and the staff support hours was gradually reduced from 24/7 to standard business hours. The two separate teams were eventually merged into to a single team and the overall effort associated with the MP and OA routine activities was reduced over time by 90%. Based on the time interval of 6 years reported in the paper and the 66 satellites operated by 2003, we derive an estimate for the operated satellites against the size of the OPS Team over time, which is shown in Fig. 4.

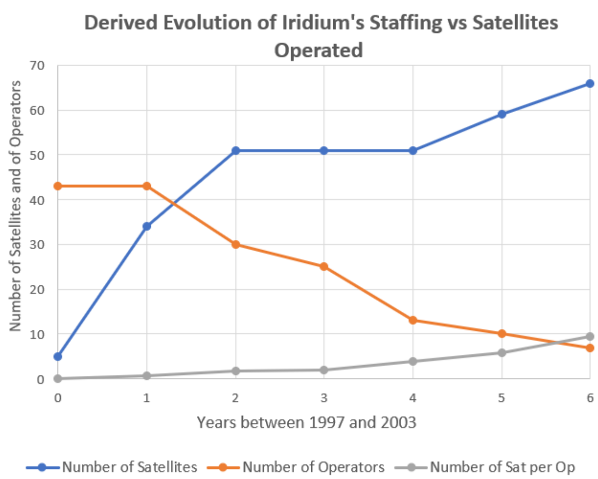

Fig. 4. Iridium's derived evolution of the number of satellites operated and OPS Team size between 1997 and 2003

The introduction of automation allows the hours of operation to be reduced even with a constellation that is growing at a modest pace. Looking at the number of satellites per operators, it is possible to derive a best fit relation that describes the increase in operational efficiency over time for Iridium, which is presented in Fig. 5. Given the small number of data points available, the R^2 value of the linear fit is not high. Moreover, the assumptions needed to allow this data and relation to be derived, means this serves only as a first approximation.

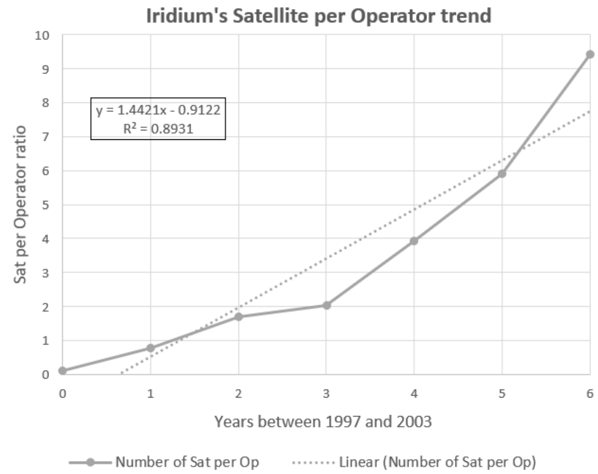

Fig. 5. Iridium's linear best fit approximation of the evolution in the number of satellites operated per operator

Fig. 6 shows the derived evolution of staffing and satellites operated by a large satellite constellation operator, the name of which we wish not to disclose. For this reason, we will refer to this operator simply as a "large constellation", "large fleet" or "large unnamed constellation" throughout this paper. Furthermore, we note the data for this operator are projections prior to deployment rather than based on actual reported operations data. The trend of the satellite per operator evolution is attempted and presented in Fig. 7 along with its best fit curve.

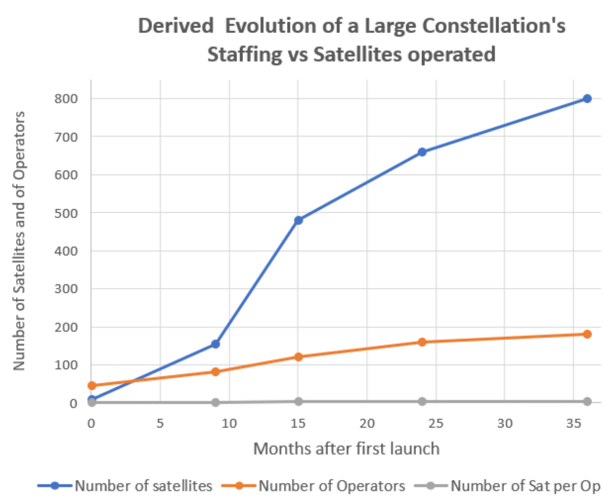

Fig. 6. Evolution of the number of satellites operated and OPS Team size for a large unnamed constellation

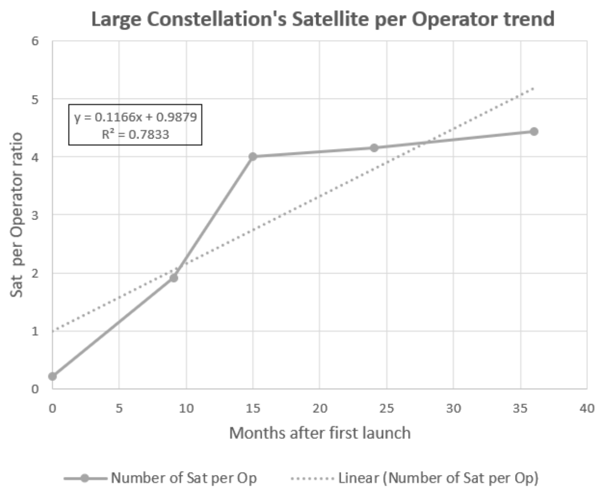

Fig. 7. Linear fit of the evolution in the number of satellites operated per operator for a large unnamed constellation

We see that the R^2 value of this linear fit at 0.7833 is rather poor and worse than the one derived for Iridium. This is due to the smaller number of data points available over a time interval of three years.

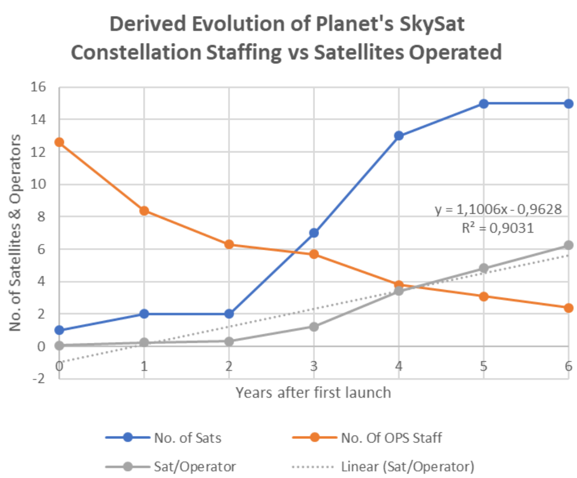

Fig. 8. Linear fit of the evolution in the number of satellites operated per operator for Planet's SkySat constellation

Planet operates a constellation of smallsats, called SkySat, where in [12] a manning profile over 7 years was published. The paper discusses in detail what aspects of the operations were automated and how the required amount of manpower support could consequently be reduced in accordance with their operational philosophy and their confidence in the achieved automation. Following the above approach for Iridium and the large unnamed constellation we present in Fig. 8 the derived results for the SkySats based on [12]. The R^2 value for the linear best fit is 0.9031.

3.1 Derivation of the satellites per operator metric for a constellation of CubeSats

The previous three cases considered data from smallsat constellations. However, companies, such as Planet, have launched constellations consisting of cubesats. Planet started to launch its first Doves production series in 2015 and in batches called 'Flocks'. At the time of writing, Planet's constellation, called PlanetScope, has approximately 130 Earth observation cubesats. Zimmerman et al. [11] provides an overview on Planet's historical launches, with a focus on the automation processes to manage nominal operations for the PlanetScope constellation. The OPS Team at Planet is mostly responsible for commissioning new satellites, detecting and solving on-orbit issues and maintaining the health of the production fleet. Starting from a small team of two operators for Flock 1, the constellation grew and so did the challenges and the tasks. This led to the expansion of the team, which in 2017 consisted of three satellite operators in San Francisco and a team in Berlin, who were also responsible for RapidEye's constellation operations. Based on this information, it is possible to track the growth of the PlanetScope constellation and to infer a possible growth of the OPS team over the time, as well as derive the satellites per operator metric for a cubesat constellation. Our estimate for the cubesats per operator over time based on [11] are shown in Fig. 9.

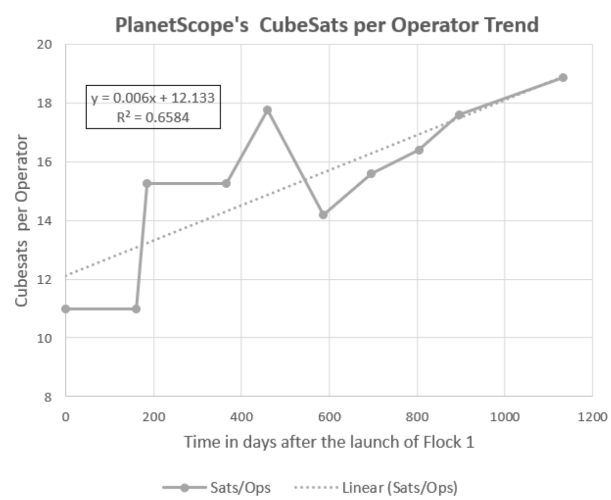

Fig. 9. Linear fit of the estimated evolution in the number of cubesats operated per operator for Planet's PlanetScope constellation

Despite the low R^2 value of 0.6584, the linear fit is the best approximation for this dataset. However, we found conflicting information and data between the two conference papers Planet published on their cubesat operations and one can speculate as to what might be contributing to fluctuation in the satellites per operator efficiency. Due to the low reliability of this result and the fact we could not find additional data on cubesat constellations operations in the literature, we decided not to use this derived estimate in the further analysis of this paper.

3.2 Comparison of the different efficiency models

Fig. 10 shows the comparison between the derived Sat/Op metric evolution coming from three different sources. The first source is Iridium’s data, the second is the data for a large unnamed constellation operator and the third is Planet’s SkySat data.

The data from these sources covers only a limited timeframe, so the subsequent points are projections of the linear models. For example, Iridium’s data covered 5 years after the first launch, so the subsequent 7 years are projections based on Iridium’s efficiency model. We must note that this modelling is an estimate and approximation that disregards the complexity and number of telemetry points, say, associated with each specific satellite. The large unnamed constellation operator has the highest sat/op ratio but it is impossible to judge whether this is because they have achieved higher automation, the satellites have greater onboard autonomy or whether their mission and satellites are simpler than Planet’s SkySats, say. Nonetheless, it is interesting that the evolution of manpower support for operations and its evolution over time are somewhat similar between the three operators. The average of the three models is computed and shown in black in Fig. 10, along with its linear best fit. This average offers a first approximation of a benchmark for how the satellite operations of a constellation can be optimized and automated over time. It can also be used to estimate the size of an operations team for a constellation and how it may evolve as the automation becomes implemented. In the next chapter we demonstrate this for a LEO-PNT constellation.

4. Estimating the sizing and evolution of an operations team for a LEO-PNT constellation

In this chapter we combine the models derived in Section 2 and 3, to explore the deployment of a LEO-PNT constellation consisting of 330 satellites. By combining the achieved launch cadence so far within the sector and the impact of automation over time on the required manpower support needed to operate the constellation, we can begin to understand how long it may take for the constellation to become operational, as well as how many FTEs are required to operate such a constellation. For example, considering a OneWeb-like launch cadence and the average Sat/Op metric derived in Section 3, Fig. 11 summarizes the growth of the constellation and OPS team over a time span of 12 years. We see how, due to the intense launch campaign, the number of operators is significantly higher than the number of satellites for the first two years. Then, as the constellation reaches its final size, the continuously improving automation of the routine operations leads to a decrease in the required number of operators. Figures for different launch cadences and automation efficiencies are shown in the Appendix B.

Adopting different launch and automation models of the operation team will impact the growth of the OPS team differently. In Table 4 the growth of the OPS team size for different combinations of launch cadence and efficiency models is presented. Given the same efficiency model and a higher launce cadence implies a larger initial OPS ream is required to keep pace with the upcoming LEOPs whilst performing the routine operations and trying to introduce the automation. The higher launch cadence also results in less time being available for implementing the automation, which means the OPS team cannot be ramped down as quickly. A higher launch cadence of course also means that the operational service is achieved sooner.

Table 4. Evolution of the OPS Team for a LEO-PNT constellation of 330 satellites as a function of the years after first production launch, comparing different launch cadence and manpower efficiency models

Launch Cadence	OneWeb	OneWeb	Iridium	Starlink	Planet
Manpower Evolution Years after first launch	Large Fleet	Derived Average	Derived Average	Derived Average	Derived Average
1	113	284	63	350	108
2	88	146	46	146	72
3	64	92	42	92	63
4	51	68	40	68	58
5	42	53	39	53	53
6	36	44	38	44	44
7	31	38	37	38	38
8	28	33	33	33	33
9	25	29	29	29	29
10	23	26	26	26	26
Years to complete the LEO-PNT fleet	2	2	7	1	5

For the deployment of a constellation one may therefore voluntarily opt to select a slower launch cadence in order to initially have a smaller OPS team and to give the operators time to implement the automation. This represents a trade-off during the initial design phase of the mission, as well as of course the actual availability of the commercial launchers. In Fig. 12 we compare the impact of completing the LEO-PNT constellation within two and three years, assuming a first batch of 15 satellites is launched, on the initial sizing and evolution of the OPS team for all manpower evolution models. The result demonstrates how the more aggressive launch cadence requires a larger initial

OPS team that must be sustained longer before the automation has its desired impact. Over time the sizing of the OPS team converges once the constellation has reached its final size.

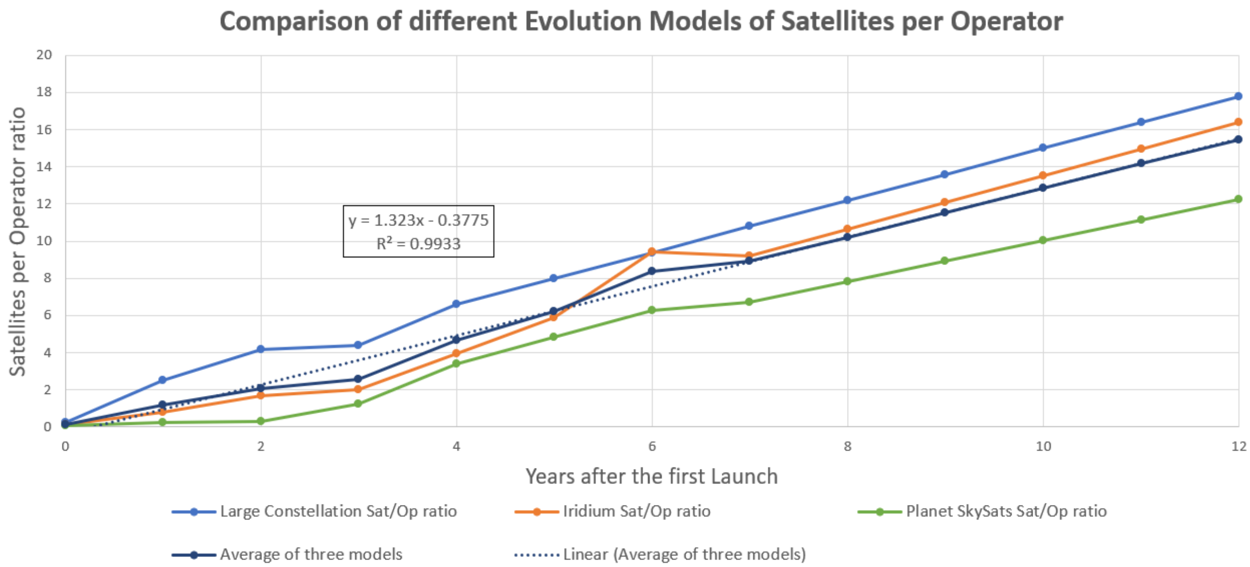

Fig. 10. Comparison of different automation efficiency models using the Sat/Op metric

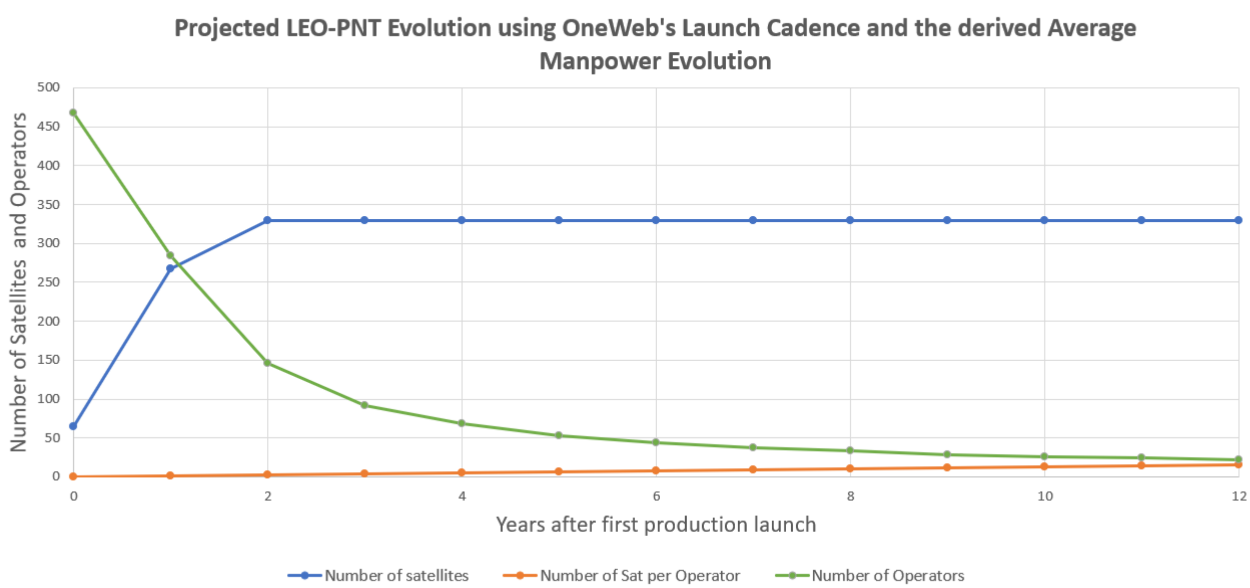

Fig. 11. Projected Evolution of LEO-PNT considering the launch cadence model of OneWeb and the average automation efficiency model to describe the Sat/Op ratio

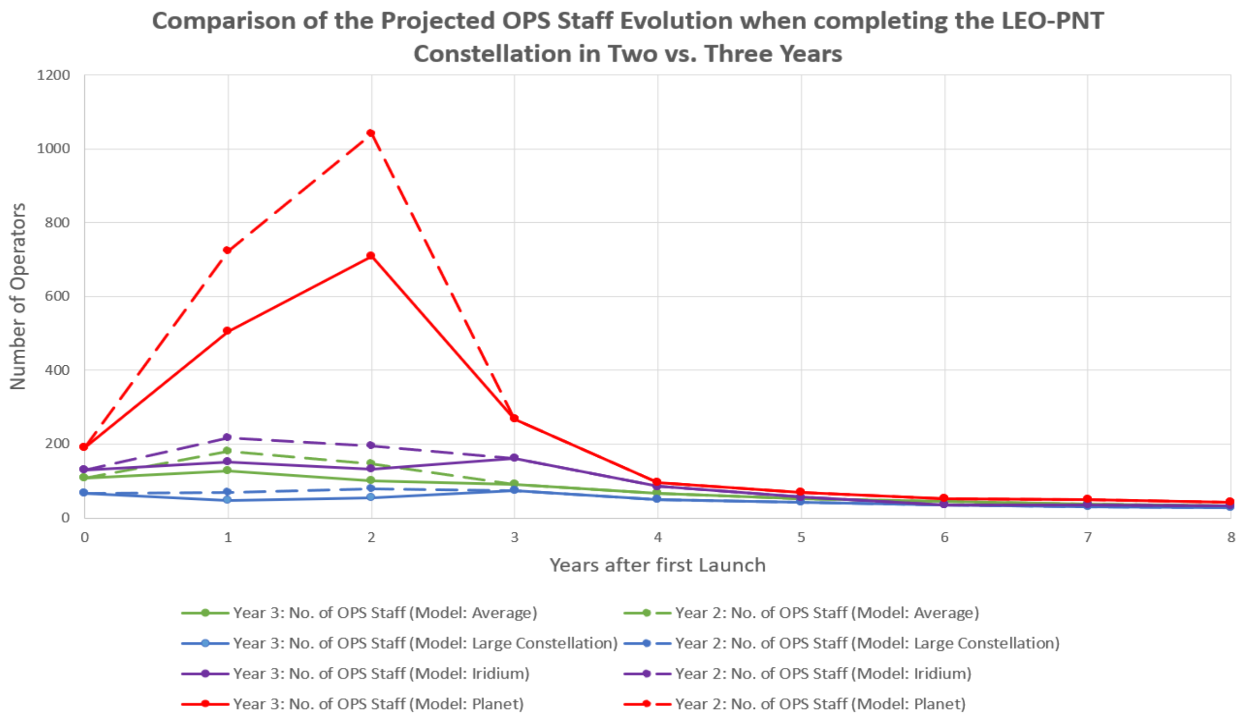

Figure 12. Comparison of the Projected number of Operators needed to complete LEO-PNT in two vs three years, assuming different automation efficiency models

5. Employing Machine Learning & Digital Twins with a LEO-PNT Constellation

In the literature Iridium and Planet explain how they automate their operations to save manpower support and move their operations teams from 24/7 support to solely normal working hours. Over the last years new technologies such as ML and DT are being proposed for use in satellite operations. By training ML algorithms up on historical telemetry data, they can be utilized to detect anomalies better and faster than classical out of limit checks. The challenge is that they require a lot of data to be trained up on before they can be deployed operationally. From our experience, it is not unusual for operators to acquire 12 months of data for the training of the ML algorithms. However, as Table 4 demonstrates, if current launch cadences are employed then a LEO-PNT constellation of 330 satellites, say, could be operational in around two years. This may therefore imply, especially as the OPS team is at its peak, that DT and ML approaches will unlikely be utilized to support or even automate LEOPs. Where less aggressive launch cadences are considered for deploying the constellation, then the use of DT and ML may be worth exploring to support the LEOP and commissioning phases. Their optimum use it therefore seems would be during the routine phase of the constellation's lifecycle.

At present, there is little data so far regarding the end-of-life phase of a constellation. Compared to the initial deployment, the end-of-life phase will likely be less abrupt, where managing the degradation and performing predictive maintenance will play a key role over many years. Furthermore, the constellation will have amassed large telemetry archives that form the basis of training up DTs. Consequently, this suggests ML and DT will find further adoption when managing the constellation's final stages. The OPS team will at that stage also need to balance the operations of the outgoing generation with the upcoming generation of constellation satellites.

6. Conclusions

By analyzing the publicly available launch data of several current constellation operators we identified the following themes and trends: i) a series of test or in-orbit demonstration satellites are launched prior to ramping up the constellation with their production grade satellites, ii) the test phase ranges between 0.7 and 2.5 years, iii) the average launch cadence ranges between once a month and once every 4-6 months, iv) the deployment rate of the production grade constellation occurs linearly over time, and v) once a constellation commences its ramp-up it seemingly proves difficult to accelerate this deployment rate. These insights into launch cadence and deployment rate offer a benchmark for future constellations.

We compared reported manpower support and the impact over time of automation on the evolution of operations teams for three active constellations. We defined and derived an efficiency metric based on the number of satellites an operator can control during the lifecycle of their constellation. We found the manpower effort and its evolution over time to be similar between these three constellation operators. Our computed unweighted average between these three models offers a first approximation of a benchmark for how the satellite operations of a constellation can be sized and automated over time.

We subsequently combined the derived analysis of launch cadence and evolution of manpower support to a possible LEO-PNT constellation in order to estimate a) when the constellation may become operational, b) the required size of the operations team, c) the evolution of the team over time as the workflows become increasingly automated and d) the impact on the sizing of the operations teams if more or less aggressive launch cadences are employed.

Due to the amount of required training data and currently feasible launch cadences, we suggest that machine learning and digital twins will unlikely be utilized to support the launch and early orbit phases. Their optimum use therefore is during the routine phase and managing the end-of-life stage of the constellation's lifecycle.

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Appendix A (Launch Cadences of different Constellations)

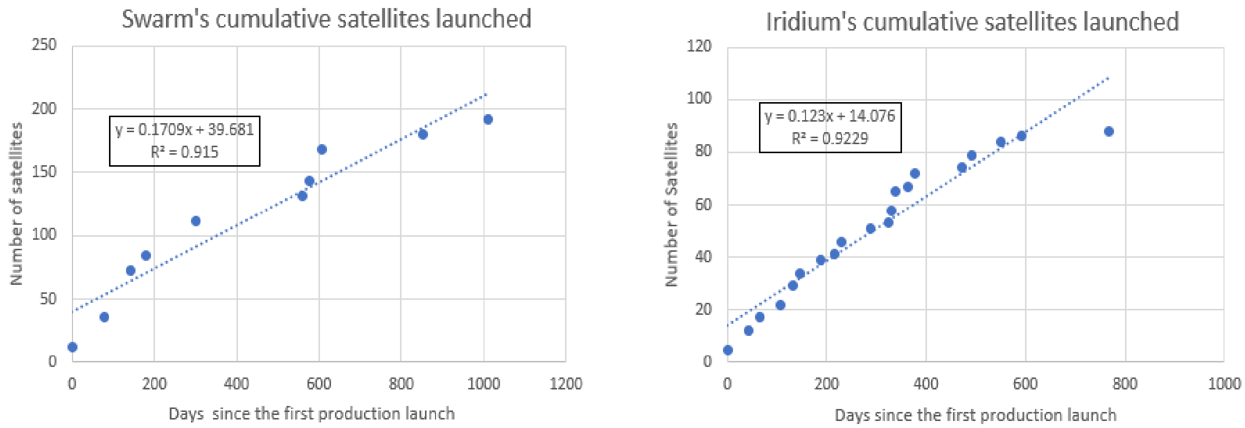

Fig. 11. Cumulative production satellites launched by Swarm and Iridium with linear best fit models

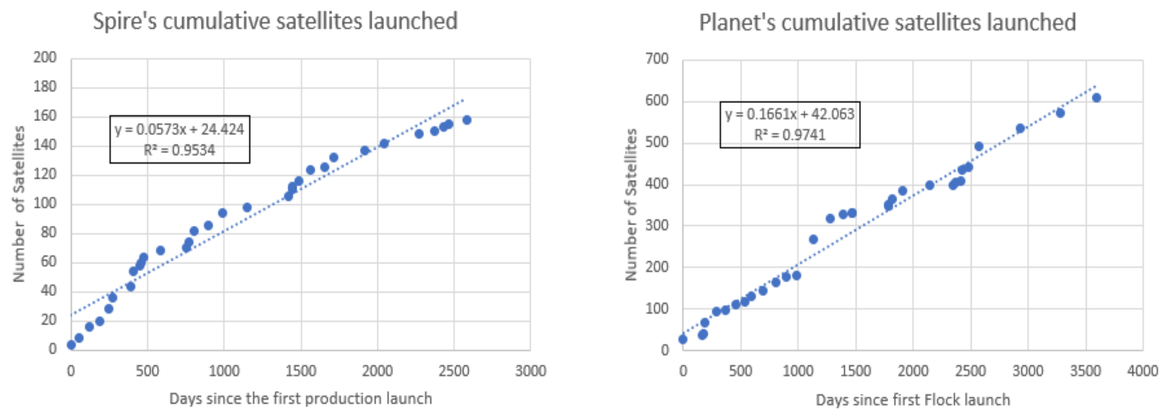

Fig. 12. Cumulative production satellites launched by Spire and Planet (Doves) first phase launches with linear best fit models

Appendix B (Projected LEO-PNT Evolution)

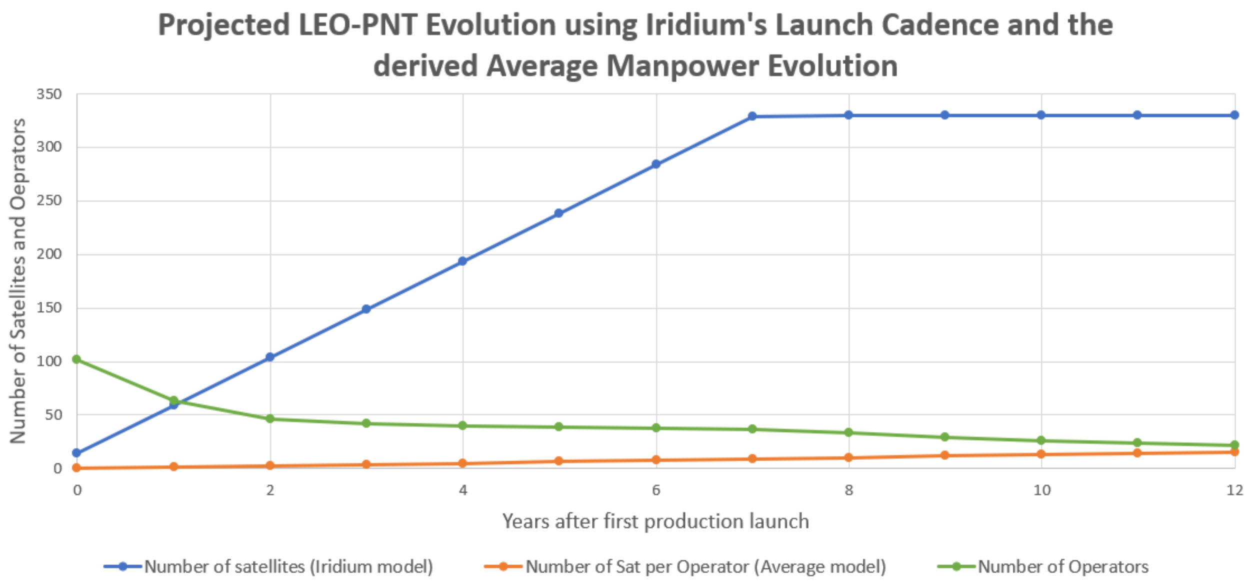

Fig. 13. Projected Evolution of LEO-PNT considering the launch cadence model of Iridium and the average automation efficiency model to describe the Sat/Op ratio

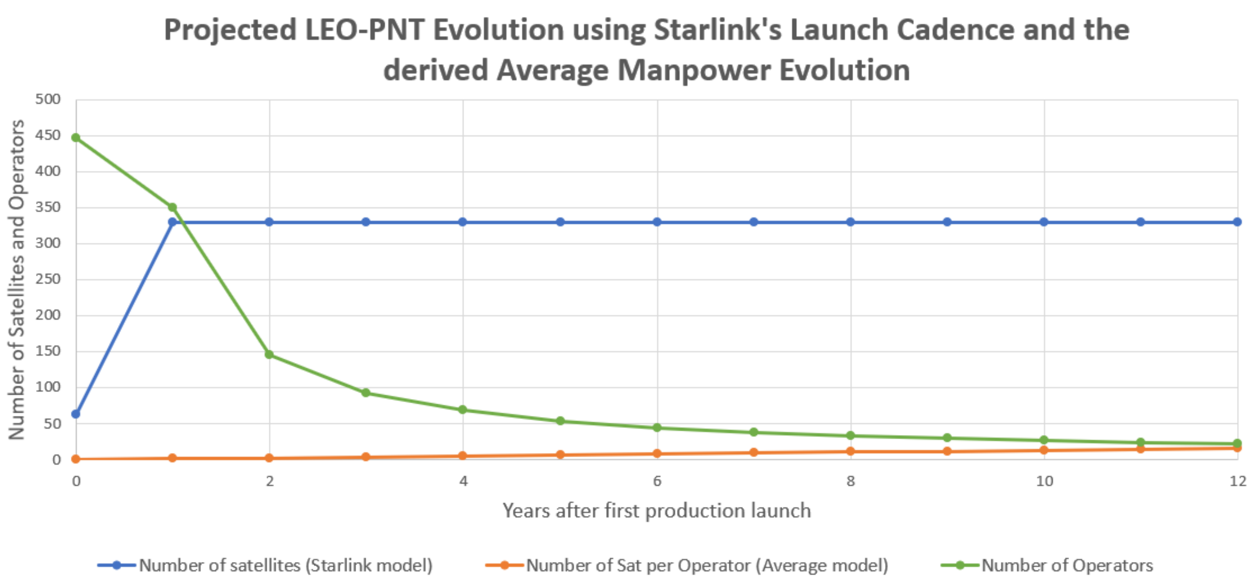

Fig. 14. Projected Evolution of LEO-PNT considering the launch cadence model of Starlink and the average automation efficiency model to describe the Sat/Op ratio

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