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Citation: Straub, Alexandra N. et al. "Deployment Strategies for Reconfigurable Satellite Constellations." Accelerating Space Commerce, Exploration, and New Discovery Conference, November 2020, virtual event, American Institute of Aeronautics and Astronautics, November 2020. © 2020 Daniel Hastings

As Published: <http://dx.doi.org/10.2514/6.2020-4246>

Publisher: American Institute of Aeronautics and Astronautics

Persistent URL: <https://hdl.handle.net/1721.1/130579>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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Deployment Strategies for Reconfigurable Satellite Constellations

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With the emerging democratization of space, Earth Observation (EO) imagery is becoming increasingly important to a variety of industries. However, it remains difficult and expensive to build constellations that achieve continuous and high-quality global coverage. Reconfiguring a satellite constellation into different orbital planes to change its observational performance is traditionally a fuel intensive procedure. The concept of a reconfigurable constellation (ReCon) accounts for J_2 perturbation effects when making fuel efficient maneuvers to shift a satellite's ground track. ReCon reduces the cost of high revisit frequency, high-quality resolution, EO constellations compared to nonreconfigurable constellations by reducing the number of satellites required to achieve repeated observations of a given ground event on demand. This paper first explores the sensitivities of ReCon's performance against uncertainties in reconfiguration demand, design costs, and imagery value. The sensitivity analysis reveals that in cases of extremely low demand, ReCon fails to provide a cost-effective solution in terms of events responded to per dollar spent. In cases of high demand ReCon fails to meet demand altogether. A Monte Carlo analysis over a range of demand scenarios shows using a staged deployment for ReCon offers a flexible, cost-effective solution to the uncertainties in the demand of EO imagery. Deferring launch costs to the future, through a staged deployment, not only provides flexibility in constellation design, but also allows the designer to capitalize on the continuation of lowering launch costs and increasing launch opportunities. Staging the deployment of constellations also allows for the satellites' technology to evolve over time, facilitating the captured of higher value imagery and further enhancing the capabilities of ReCon. Implementing the option to deploy additional satellites in stages makes ReCon significantly better equipped to respond to the uncertainty in the demand of space assets.

I. Nomenclature

a	=	semi-major axis [km]	C_R	=	fuel penalty for reconfiguration
δ_{SSP}	=	latitude of sub-satellite point	ΔV_R	=	fuel used per reconfiguration [m/s]
ΔV_{pen}	=	total fuel imbalance penalty	ΔV_{sat}	=	fuel remaining per satellite
ΔV_{proj}	=	projected fuel remaining	e	=	eccentricity
η	=	efficiency factor	g	=	acceleration due to gravity 9.81 m/sec ²
G_{pen}	=	fuel imbalance penalty gain	i	=	inclination [degrees]
Isp	=	specific impulse [seconds]	j	=	satellite index
J_2	=	0.0010826269	M	=	mean anomaly [rad]
m_f	=	final satellite mass [kg]	m_i	=	initial satellite mass [kg]
m_{inert}	=	inert satellite mass [kg]	m_{pl}	=	satellite payload mass [kg]
m_{prop}	=	propulsion mass [kg]	n	=	mean motion [rad/sec]
N_d	=	number of days	N_o	=	number of orbits

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N_T	=	number of decision time periods	Ω	=	right ascension of ascending node (RAAN) [rad]
ω	=	argument of perigee [rad]	ω_e	=	rotation of the Earth $7.29211585530 \times 10^{-5}$ rad/sec
Ω_{et0}	=	the right ascension of Greenwich at epoch	p	=	semi-latus rectum [km]
P_j	=	power of propulsion system [W]	P_s	=	power supplied [W]
Ψ_{SSP}	=	longitude of sub-satellite point	R_e	=	radius of the Earth 6,378.137 km
t_{man}	=	maneuvering time [sec]	T_{RGT}	=	period of repeating ground track orbit [sec]
T_Ω	=	inertial period of Ω	$T_{\Omega G}$	=	Greenwich period of Ω
u	=	argument of latitude [rad]			

II. Introduction

EARTH Observation (EO) is one of the primary purposes of satellites in space [1]. These satellites provide important imagery and other observational data that positively influence multiple aspects of daily life, from predicting weather patterns to providing disaster relief [2, 3]. The increasingly global access to EO data provides for a large range of applications important for solving global problems such as improving agricultural efforts, tracking changes in land use, and monitoring climate change [4]. Most EO applications can be satisfied using weekly revisit times [5]. Natural disasters, on the other hand, occur in unknown locations and require an immediate response with high-quality, persistent imagery [6]. Responders rarely rely upon EO imagery as a primary data source in relief efforts [7]. While they appreciate the data from satellite sources, the imagery is often too expensive, slow, and inconsistent to be a primary source of mapping for real-time relief efforts. In a survey of state emergency responders, 30% answered that imagery received 72 hours after an event is already too late [6]. Mapping imagery is essential in the first few days following a disaster, but it is also helpful in the several weeks that follow in the most extreme cases. The delays and inconsistencies reported do not accurately reflect the potential capabilities of satellite constellations. Designing towards responsiveness, through constellation reconfigurability, is a promising solution to this problem [8–10].

The potential capabilities a bird's eye view from space provided were immediately evident with advent of artificial satellites [1, 11]. The first image from an orbiting satellite of the Earth was from Explorer 6 in 1959. In 1960, the Television and Infrared Satellite 1 (TIROS 1) was launched as the first satellite entirely dedicated to one of the most common applications of EO: observing the weather [1]. One of the most prolific examples of an EO mission is the Landsat program, originally launched in 1972 with Landsat 1 [12]. This satellite is largely considered the first with an EO mission dedicated to global land cover observation [13]. It created an entire field of science in remote sensing by providing a new need to decipher every detail contained in the images captured from above, and is referenced in thousands of publications. With its 18-day revisit period, researchers could now evaluate change much

more consistently than images previously captured from aircraft. The impact of this program is just one example of consistent and wide-reaching effects of EO.

While governments have dominated in the realm of producing satellite imagery for the majority of spaceflight's short history, recent trends have put private entities in the forefront. Planet, a commercial satellite imagery company, launched the first of its Dove satellites in 2013 and continues to build its constellation through the present day [14]. Today their constellation achieves daily revisit times across the globe, providing imagery with a 3-5 m ground sampling distance (GSD) resolution. Planet satellites are much smaller than traditional EO satellites launched into higher orbits, but provide an alternative to the exquisite observational satellites that often require massive budgets.

Many industries have been able to take advantage of the boom in observational technology, but there are still many shortfalls that arise when relying on satellites for imagery. One notable issue is the frequency at which imaging occurs. Geosynchronous satellites are at an extremely high altitude, 35,786 km above the Earth's surface, which puts them in sync with the Earth's rotation. This orbit equates to complete regional persistence. Yet, the optics required to achieve adequate image quality at such distances are costly and lead to large, expensive projects. Therefore, when designing architectures, engineers often have to play with the tradeoff between persistence and resolution. Invoking this trade has been the traditional way of thinking for many years. Yet, recent work in the past decade has introduced a new mode of operation, known as reconfigurable satellite constellations [8, 10].

Satellites typically only maneuver to compensate for drifts in their desired orbits [15]. However, the reconfigurable constellation (ReCon) concept performs altitude changes to responsively maneuver a satellite to a more high-performance orbit when an event occurs [8]. In a time when massive satellite proliferation in low Earth orbit (LEO) seems to be the newest strategy in increasing coverage, having this kind of capability on a satellite would also enable an increasingly important conjunction avoidance capability. When using maneuvers to change orbital parameters, one must consider the J_2 effect due to the Earth's non-uniform gravity field. The J_2 effects on Ω , ω , and M are constant over time. The effects are directly related to the

size, inclination, and eccentricity of the orbit. Equations 1 - 3 illustrate the effects of J_2 on the orbital elements [15].

$$\dot{\Omega} = \frac{3nR_e^2 J_2}{2p^2} \cos i \quad (1)$$

$$\dot{\omega} = \frac{-3nR_e^2 J_2}{4p^2} (5 \cos^2 i - 1) \quad (2)$$

$$\dot{M} = \frac{-3nR_e^2 J_2}{4p^2} (3 \cos^2 i - 1) \sqrt{1 - e^2} \quad (3)$$

MIT's ReCon simulation maneuvers satellites into repeating ground track (RGT) orbits to respond to regional events. These are orbits where a satellite will complete an integer number of revolutions around the Earth in an integer number of days [16]. To find the parameters for these orbits, the J_2 effect must be considered as they effect the shift of orbital parameters, and hence the ground track, over time. Equation 4 shows that the period of an RGT is a function of the orbit's semi-major axis, inclination, eccentricity and desired RGT ratio [8].

$$T_{RGT} = \frac{2\pi N_d}{\omega_e N_o} \left(1 + 2\xi \frac{n}{\omega_e} \cos i \right)^{-1} \xi \quad (4)$$

Where:

$$\chi = 1 + \xi \left[4 + 2\sqrt{1 - e^2} - (5 + 3\sqrt{1 - e^2} \sin^2 i) \right]$$

$$\xi = \frac{3R_e^2 J_2}{4a^2(1 - e^2)}$$

$$T_{RGT} = \frac{2\pi}{n}$$

ReCon designs use circular orbits, dropping the eccentricity term out of solving for the RGT. Therefore, a given inclination and desired RGT N_d/N_o ratio dictates the semi-major axis of the orbit. These orbits exist at specific altitudes given an inclination, and they use the precession of Ω due to J_2 to ensure the satellite passes over the same ground location after a designated number of days.

The ReCon concept operates by deploying a constellation into a global observational mode (GOM), which meets a specified, global revisit criteria. While the ReCon concept can use a variety of satellite architectures, the following work focuses on symmetric Walker Delta patterns [17]. Walker Delta patterns evenly distribute orbits' ascending nodes at intervals of $2\pi/N_p$. Each satellite within a plane is evenly distributed at an interval of $2\pi/N_s$. Once an event occurs, the satellite maneuvers to a regional observation mode (ROM) to meet more frequent revisit requirements, such as once per hour, for a smaller region. Figure 1 shows how the ground tracks of the constellation shift to align over a regional target after an event occurs.

Fig. 1 Responsive Groundtrack Shifts

The resulting coverage is much better over the desired region but suffers in the areas not covered by the RGTs. MIT's ReCon simulation code models the reconfiguration process and the resulting performance of the maneuvering satellites. An assignment process allocates the satellites within the constellation to either change their orbital altitudes or remain in place. In Figure 1 the top and middle satellite groupings move into RGTs, but the bottom grouping does not maneuver. The satellites will not maneuver if too much fuel is required to maneuver, if the maneuver is infeasible for the required response constraint, or if the assigned maneuvers achieve the required revisit metrics without needing full reconfiguration.

A four-burn maneuver moves a satellite from GOM to ROM. An initial, instantaneous burn places the satellite into a transfer orbit to intercept the desired drift orbit. This transfer lasts half of the period of the transfer orbit, which is typically approximately 45 minutes for a LEO transfer. A change in altitude into a drift orbit causes the satellite's ground track to shift at a different rate relative to the rotation of the Earth. The satellite remains in its drift orbit until it phases into the designated Ω and u values, directly related to the desired sub-satellite point (SSP), the regional target's location. Allowing the Earth to rotate beneath the satellite changes the SSP without executing a plane change burn. After proper placement, the satellite then performs a second Hohmann transfer into an RGT, entering ROM to complete the maneuver.

The SSP is the latitude and longitude point on the Earth the satellite instantaneously passes over. It is defined by i , u , and Ω . The SSP changes throughout the entire reconfiguration. Equations 5 and 6 show this change using the final values of u and Ω as calculated considering the perturbation equations shown above [18]. The rate of change in u is directly related to the size of the drift orbit. The ReCon simulation models different drift orbits to minimize the amount of time it takes to position the SSP in the correct location. The initial orientation of the Earth is represented

by Ω_{et0} .

$$\delta_{SSP} = \sin^{-1} \sin i \sin u \quad (5)$$

$$\Psi_{SSP} = \tan^{-1} \frac{\cos i \sin u}{\cos u} - \omega_e(t_{man}) + \Omega - \Omega_{et0} \quad (6)$$

In the ReCon simulation, the allocation process, which uses a dynamic programming approach, chooses enough satellites to reconfigure to meet a given revisit requirement. Instead of designing a constellation that achieves a high revisit frequency globally, the ReCon concept allows for a smaller number of satellites to achieve a high revisit frequency regionally on-demand. The advantage of using ReCon is that it can provide high-quality coverage to many locations without requiring intensive global coverage.

Adding this capability to satellites is not unreasonably expensive. ReCon achieves superior performance over five years with the addition of only 300 m/s of ΔV . While adding extra weight to a satellite increases launch costs, these costs are continuing to decrease. The value-added for making the satellites heavier on launch is significant, especially since this reduces the total number of satellites on-orbit, and thus the number of launches needed in the long run. One way to reduce the mass added is by using more efficient propulsion systems. Low-thrust, electric propulsion (EP) technology is becoming more commonplace as the propulsive capabilities improve. Using this technology, either in place of or in conjunction with chemical propulsion, introduces important tradeoffs. Exploring these options allows a designer to decide which option is best for their particular mission.

Another way to alleviate the costs associated with adding fuel to the satellites is to explore alternative deployment options. Staging the deployment of satellites is very effective for long-duration programs [19]. As shown by the fifty-year lifetime of the Landsat mission, the utility of EO imagery has remained strong and will likely remain strong for decades. Using a staged deployment strategy allows satellites to carry less fuel initially and for the user to launch fewer satellites upfront. The user can wait to observe what the demand of their constellation actually is and add satellites accordingly over time. As the landscape of the space enterprise continues to shift, alternative launch strategies make the concept of ReCon more adaptable to the uncertain demands of EO imagery.

The concepts presented in the following work were all tested through the lens of the Dr. Legge's ReCon simulation. ReCon is a layered simulation, which uses dynamic programming to optimally determine the best reconfiguration strategy for a constellation and genetic algorithms to mutate the design of a constellation to improve its performance vs. cost ratio. However, the final product of ReCon is the recommendation of a constellation design. The testing presented in the following work relies on a common design output of a one satellite per plane Walker constellation [8].

III. Mass Tradeoffs

Low-thrust propulsion systems are emerging as a more common part of space missions as the technology matures [20]. One of the most important benefits of low-thrust technology is the potential mass savings they provide for a satellite. This mass savings generally allows for either an upgrade of payload capabilities or a reduction of overall mass general, which correlates to the overall constellation cost. In an effort to reduce the mass of the propulsion one could consider the use of EP. To investigate whether or not using EP is useful in ReCon, one must consider the tradeoff concerning the mass of the propulsion systems with the increase in mass of the electrical power system. The mass tradeoff analysis considers the propulsion system detailed in Table 1 [15]. While the tradeoffs presented vary dependent on the propulsion system chosen, this thruster is representative of the current state of technology.

Table 1 Test Thruster Parameters

Thrust	80 mN
Efficiency (η)	0.5
Power (P)	1350 W
Isp	1600 s
g	9.81 m/s ²

To determine the efficacy of an EP system, the following analysis considers the additional mass added to a satellite due to the increased power loads when using EP. First, the model must consider the added power load by using the efficiency factor found in Table 1. An efficiency factor represents the proportion of power provided to the thruster that the system turns into actual propulsive power.

$$P_s = \frac{P_j}{\eta} \quad (7)$$

Although the thruster does not fire throughout the entire maneuver, it could be firing for days continuously, and therefore P_s is added to the average power load. The total dry mass of the system is a sum of the payload mass and the inert mass of the EP system. The inert mass is directly related to the power required through a β term, which is a characteristic of the power system. In this case, the satellite model uses solar thermal dynamic EPS design, which has a β range of 0.06-0.1 kg/W [15]. This analysis uses a β of 0.06 kg/W.

$$m_{inert} = \beta P_s \quad (8)$$

The initial mass of the system is a sum of the mass of the fuel and the satellite's dry mass. In this case m_{pl} includes everything on the satellite that is not power or propulsion system related. The rocket equation, defined in Equation 9, relates the resultant ΔV on a satellite to the change of

the satellite's mass and the propulsion systems specific impulse.

$$\frac{m_i}{m_f} = \frac{m_{prop} + m_{pl} + m_{inert}}{m_{pl} + m_{inert}} = e^{\Delta V / (Isp * g)} \quad (9)$$

In general, to increase thrust, the efficiency of the system decreases if the power levels remain the same. For the purposes of this analysis, thrust and power remains constant. Instead of optimizing the system's Isp , this analysis assumes the thruster's capabilities are fixed and rather examines what other factors are necessary for its use to be beneficial.

The mass saving benefits for using an EP system are not inherently obvious due to the additional power loads imposed on the system. Ideally, a design would apply any mass savings to making the aperture of the satellite larger, allowing for either increased image quality at the design altitude or equivalent image quality at an increased altitude. Since meeting a GSD resolution requirement drives the design of ReCon, there is a benefit to increasing the altitude of the constellation if using a larger aperture. Higher altitude orbits have a lower orbital velocity. A longer pass time means more opportunity for the satellite to capture many unique point images. The challenge arises in pairing this potential altitude increase with the use of RGT orbits. At any given inclination, these orbits typically exist between 100-200 km apart from one another due to their unique properties. Using RGTs means if the user is unable to change inclination due to other constraints in the system, such as a mandated latitude band, the design must increase the aperture size in large, discrete steps to get the same resolution. The design cannot move incrementally to a higher altitude.

To examine the tradeoffs, a 1-m GSD resolution requirement was set to size the power and dry mass of a the satellite using chemical propulsion. The satellite is modelled at different RGT altitudes at a 60° inclination. The dry mass was determined from Legge's previous modeling, a sum of Equations 10 and 11 [8]. The power was derived from the payload power equation from Legge's original work in Equation 12. This was assumed to be 46% of the total average power, which is a representative value for LEO satellites with propulsion from SMAD [15].

$$m_{payload} = 498.82D^2 - 190.17D + 57.11 \quad (10)$$

$$m_{bus} = 1639.2D^2 + 13.78D + 96.47 \quad (11)$$

$$P_{payload} = 594.86D^{2.041} \quad (12)$$

Although the aperture size scales linearly with height, the mass and power scales as a square to the diameter. Moving from a 200 km to 400 km altitude RGT may only require 50 kg of mass to be added to the bus, but moving from 800 km to 1000 km increases the mass by several hundred

kg. The real trade comes when looking at the total mass added for propulsion in the low- Isp , chemical propulsion design vs. the total mass added for power and propulsion for the high- Isp , EP design. For this analysis, several values of ΔV were used and compared across different altitudes. The standard rocket equation calculates the propellant mass added for both the chemical and electric propulsion systems. The analysis recalculated the average power required for the satellite to calculate the mass added for the electrical power system accounting for the use of the Hall effect thruster. Figure 2 shows the difference between the electric propulsion design and the chemical propulsion design for several ΔV values and RGT altitudes.

Fig. 2 Mass Trades for Using Low-Thrust Propulsion

The red shaded region in Figure 2, above 0, is where the mass of the EP satellite is greater than that of the chemical propulsion satellite. This region is undesirable all of the time. Note, that the 500 m/s ΔV solution falls within this region for all RGT altitudes. The ReCon design code typically does not add more than 500 m/s of fuel for reconfigurability onto a satellite to fulfill its 5 year mission lifetime. The fuel is enough to satisfy a constellation's reconfiguration to 20-25 events, which corresponds to the projected frequency of high impact natural disasters [7, 8]. However, there may be instances where reconfiguring much more often is desirable, and higher ΔV cases are of use. Even then, most of these solutions fall into the yellow region of the graph between 0 and the cutoff line. In this region, the EP satellite weighs less than the chemical propulsion satellite, but the mass savings are not enough to make the jump to the next RGT altitude. Therefore, it would be better to remove mass from the satellite and create a lighter version, than to increase the RGT altitude and increase the payload diameter. The only solutions that were able to make the jump were those moving from 650 km to 850 km with greater than 3.5 km/sec of ΔV on board. This trade shows how important a factor the ΔV requirements are for making design decisions.

The factors that most influence the effectiveness of EP when it comes to making mass trades are ΔV and β . Given a ΔV , one can find the required β that leads to an equivalent mass tradeoff between the electrical and chemical propulsion satellites. Figure 3 shows the different β requirements for different ΔV values. The dashed lines show the upper range for current capabilities of large solar electric power systems, as well as the near term target values [21]. As the satellite's altitude increases, the diameter of the payload, and power required for the payload increases as well. For the low ΔV options, the propellant mass added to equate the amount of effective ΔV onboard is a smaller fraction of total satellite mass than for the high ΔV options. At the minimum point of these curves, the relative amount of mass added for fuel is the smallest compared to the change in mass due to payload and power requirements. This difference is why the higher ΔV options reach their lowest β requirements at lower altitudes. The relative amount of fuel added to maintain the same amount of ΔV is higher at each altitude jump for the higher ΔV options. Yet, the power requirements are dependent on the altitude alone and are fairly similar across ΔV designs. The increase in mass for fuel occurs at a much faster rate for the higher ΔV designs, which is why these designs have their strictest β requirements at lower altitudes compared to the lower ΔV requirements. Regardless, carrying more fuel lends itself to being more advantageous for EP systems.

Fig. 3 Determining β Requirements

The more ΔV needed, the less strict the β requirement. Increasing energy density is an extremely high priority for NASA. The current β capabilities are between 0.01-0.02 kg/W on the best technology, however, further improving this number is extremely important to not only those interested in the space industry but in many other technology industries as well [21]. This analysis did not consider a cost trade associated with changing to a system with a lower β . A designer must consider whether or not switching to a more power efficient system still allows cost savings

through a decrease in mass before pursuing this change in the propulsion system. These values are again reflective of the values needed to make large altitude jumps. However, there is always the option to remove mass in general at a lower altitude to launch a lighter satellite. Unlike the changes in altitude, this occurs incrementally and is the recommended approach for a constellation already deployed at a higher altitude RGT orbit.

IV. Staged Deployment

While changing the propulsion system of the satellite can have mass savings effects in some instances, changing the deployment of the constellation allows for cost savings without fundamental satellite design alterations. The amount of fuel added to a satellite to compensate for reconfigurations was a design variable in the original ReCon simulation that adjusted to satisfy this demand and typically converged to around 300-400 m/s worth of ΔV [8]. This is much lower than the values presented above that corresponded to a recommended use of an EP system. However, the original design considered a five year lifetime, with 20-25 events occurring throughout the duration of the satellite's life. The reality of the required demand on the satellite is unknown prior to launching the satellite. A staged deployment is an implementation of a flexible design to account for this uncertainty. Flexible systems may perform worse than an optimized design in the "most likely" forecasted scenarios that drive the original design optimization. However, the advantage of the flexible design is that it performs well in a large range of scenarios by giving decision makers the ability to execute a variety of options when operating the system [22].

The design presented in the following analysis considers a longer lifetime of 15 years and expands the number of events considered. With the "democratization of space" emerging internationally and analytics proving to be extremely valuable to almost every industry, it is hard to predict what the demand for this information may actually be [23]. Perhaps there may be users who want regional persistence to monitor climate change effects in a region over long periods of time, and the demand may be much higher than initially expected.

Reconfiguring to satisfy a customer's regional needs has many potential applications, but specifically, the modeled demand for this constellation matches natural disaster frequency. The analysis derived demand through historical data, but natural disasters are challenging events to predict accurately [7]. This variability in demand significantly impacts the design of the system. The analysis models demand to be as little as zero events per year, or as often as one event per month, with a distribution shown in Figure 4. The cost model used to design the satellites in this constellation is the same as the one used in the original ReCon design

Fig. 4 Probability Distribution of Imagery Demand

found in Legge’s thesis [8]. This model was derived from the space mission engineering textbook, Space Mission Analysis and Design (SMAD) and the following analysis applies a 5% learning curve [15]. Using this model, the cost of manufacturing typically levels out to approximately \$30 million per satellite when applying the 1-m resolution requirement in a 15/1 RGT orbit. The prices used in this analysis assume very high-quality imaging satellites, but there is no reason a similar performance analysis cannot translate to cheaper CubeSat missions.

When considering a staged deployment strategy, an interesting forecast is the future of launch providers in the aerospace industry. There are dozens of companies proposing a new launch vehicle for use in the next two to three years. Companies are offering significantly cheaper options and a variety of payload capabilities, providing more ways to get a satellite into orbit [24]. Five of these probable providers are used for this simulation shown in Table 2. The analysis models the costs of each of the constellation options using these five options.

Table 2 Launch Provider Options in Analysis

Launch Vehicle	Mass to LEO [kg]	Cost Per Launch [\$M]	Cost Per kg [\$k]
Electron	170	5	29.6
Antares	6,200	70	11.29
Falcon-9 Reusable	22,800	43.7	1.92
LauncherOne (2020)	400	10.06	25.16
Firefly Alpha (2020)	400	12.58	31.45

The biggest constraint on meeting demand is the amount of fuel on-board the satellites. The ReCon simulation uses a variety of factors when deciding how to maneuver satellites and which ones to maneuver. It maneuvers as many satellites as needed to meet the temporal resolution

requirement set, but also attempts to minimize the fuel cost of doing so. When there is a time constraint imposed on the constellation to respond to an event, the amount of fuel used per maneuver increases substantially. However, typically the amount of time a constellation has to respond is set to two weeks, and giving the constellation this amount of time to reconfigure allows the fuel usage per maneuver to level to approximately 25 m/s of ΔV per satellite per maneuver. Giving the constellation time to reconfigure allows for the constellation’s true demand capacity to be shown without compounding effects.

Figure 5 shows the rate at which different sized constellations deplete their fuel averaged across the entire constellation. The x-axis shows the target number the constellation is responding to in sequential order, and the y-axis shows the amount of fuel remaining on average per satellite in the constellation in terms of m/s of ΔV . The rate of depletion is linear until the constellation begins to run out of fuel. In the scenario depicted, the temporal resolution requirement was a six-hour revisit frequency during daylight hours. This requirement means the satellite must view the area only twice per day, which is an achievable revisit time for a constellation of a small size, used to reduce the computational complexity of the problem in this analysis. The event capacity of each constellation size increases as the constellation size increases. The constellation always saves some fuel for its disposal at the end of its life, so the average fuel will never quite reach zero. However, once it reaches below approximately 25 m/s on average, the constellation can no longer adequately respond to events.

Fig. 5 Fuel Usage for Different Sized Constellations

Adding fuel at all to the satellites in a constellation is already one way in which flexibility is implemented in this design, allowing them to maneuver to meet demand. However, the expected demand for the satellite’s imaging largely tailors the design. One way to resolve this restriction is to add more fuel to each satellite. At some point, this becomes impractical, and the upper limit for fuel added for reconfigurations is 500 m/s for this analysis. However, the ability to add more propellant would be an extremely valuable way to address increased demand. In the case where fuel is limited, another option is to launch additional

satellites into the constellation as they are needed. In this scenario, the constellation can grow as demand occurs and value changes, instead of the constellation having an excess of resources or running out of fuel too quickly.

It is important to note that building satellites is not a trivial matter, and therefore the decision timeline for this project is on a three-year cycle. In this design, satellite manufacturing takes two years to complete, and satellites cannot launch until the next year. These decision making opportunities are not rolling but instead occur every three years, although this could be adjusted in future work. In a simulation for a 15 year mission lifetime, the remaining fuel across the constellation informs the decision to expand every three years. The simulation assumed that the average demand would remain constant throughout the given three year time period, and the simulation projected the value observed in the first year of the period forward to calculate the average remaining ΔV on each spacecraft. When this value dropped below 500 divided by the current staging period number in Equation 13, the simulation triggered the manufacturing of two more satellites to be launched. The first staging period is when the initial constellation launches, so the decision rule used to launch more satellites starts at period two.

$$\Delta V_{proj} < 500/j \quad (13)$$

$$j = 2, 3, 4 \dots N_T$$

A Monte Carlo analysis showed the effectiveness of using a staged deployment instead of launching an entire constellation at once. The simulation ran over a 15 year lifetime. The simulation used the uncertainty distribution in Figure 4 for the average demand in each three year period. The nominal constellation launched 19 satellites upfront with 500 m/s of ΔV on board the satellites and did not launch again throughout the mission's lifetime. The staged deployment started with only 15 satellites launched and could expand by launching two satellites every three years if the decision rule dictated that the fuel on board would likely not be sufficient for the mission.

This analysis values the constellation in terms of Net Present Cost (NPC). This term is more often referred to as Net Present Value (NPV), which subtracts revenue over time from costs over time. However, there is no estimated revenue in this model. While several commercial products could apply the ReCon concept, it also could be fielded by nonprofits or governments who do not evaluate value in terms of monetary compensation. Therefore, this analysis evaluates the capital spent on the project in terms of NPC. Using NPC involves applying a discount rate to capital spent in the future. Discount rates represent the fact that when a designer chooses not to spend money on a given project right now means they can use the money can for something else later. Discount rates are very high in high-risk industries, such as start-up businesses. Yet, they are

very low in the government [22]. The Federal Reserve publishes the recommended discount rate for use, and it was around 2% in early 2020, making the 5% rate over three years a reasonable approximation for this analysis [25].

Figure 6 shows the result of a Monte Carlo simulation. The chart on the left is the most significant. It shows the relative frequency of the capital required for each design. The nominal design has the same capital expenditure no matter what the resulting scenario ends up as. This consistency is because the entire cost is upfront, regardless of the outcome. On rare occasions, the staged deployment expended as much capital as the nominal solution, when demand was extremely high. However, the majority of the solutions saved about \$100 million when compared to the nominal solution. This cost savings comes with an equal performance compared to the nominal solution. The middle chart shows the performance of the constellation in terms of the value it captured per million spent. The lines represent the cumulative frequency of occurrence, and the black line, representing the performance of the staged solution, shows a slightly better performance overall, as it shifts to the right of the nominal solution, shown in the gray line. The final graph shows the percent of the demand actually captured. The constellations performed equally in this metric, meaning the staged deployment was not missing targets despite being deployed slowly. In the worst case scenarios, neither the staged or nominally deployed satellites captured fewer than 85% of all demand seen.

Fig. 6 Distribution of Constellation Cost

The decision rule in Equation 13 was relatively conservative, ensuring performance was not lost using staged deployment. However, decision makers with different priorities can use different decision rules. For example, to reduce the risk of a loss of a large initial capital investment, a smaller constellation upfront would extend the tails of the cost distribution histogram. Low demand environments would require less upfront capital, but more capital would be needed to catch up in these environments. Decision rules could also be changed to reflect the current status of the cost of the launch and manufacturing of satellites. If costs are low, it is more beneficial to launch more satellites to meet potential demand, but if costs are high, it may be beneficial to wait if the current constellation can meet demand. Regardless of the exact priorities of the decision maker, it is important to give managers the ability to execute options throughout a project's lifetime.

A final note on using a staged deployment, in general, is the potential benefits of making upgrades in the technology of a system when launching more satellites over time. These upgrades may have some detriments to the learning curve effects leveraged. However, the value of the imagery captured would be higher, and thus the value per cost would still increase. For longer mission lifetimes, like the 15 year timeline previously discussed, the ability to upgrade technology every few years could prove to be invaluable. There are several implementation challenges involved in this approach. Constraints in the staged simulation ensure a built-in delay between deciding to build additional satellites and getting them on orbit. However, the ability to have a team continuously available to build satellites could prove challenging. Getting on the proper launch manifests that are most cost-efficient is also not guaranteed. It may be easier to distinctly separate the development and operation stages for the sake of the workforce, despite the financial incentive to build as needed. However, staged constellations are not a novel concept, and the commercial sector is leading the way in shortening the timeline needed to build satellites with the same designs [14, 26]. This implementation also assumes that each replenishment uses the same design. This consistency is to keep testing costs down, but there will likely be a temptation to upgrade as time goes on. The problem with upgrading designs is the testing that follows from design changes in satellites. Additional trades would be required to decide if a design upgrade is worth the cost for the potential increase in imagery value.

The flexible approach to design is more beneficial in situations that have long timelines or fast turnaround for the flexibility options. The space industry is a traditionally slow business, often with exquisite satellites that can last decades. The positive effects from the increases in launch and manufacturing tempos only make this idea more, not less, viable. In situations where the system is slow to respond to demand, flexible decision making may be difficult to implement, which is why this is not very prevalent in today's space market. Finally, it is important to note that this strategy showed how applying a second form of flexibility over a first can add to a system's performance, especially in the face of uncertainty. The solution for many problems is not often one strategy or the other, but instead a mix of both.

V. Conclusion

The purpose of this work was to explore the design of reconfigurable constellations in ways that previous work did not fully analyze. Important questions remained for the potential implementation of ReCon. Although this work is not a design of a single constellation for a single mission, it provides context to decision makers, informing the consideration of additional trades when designing a

responsive constellation.

Analysis showed the use of EP is not yet worth exploring given its current state, but is an option to consider as maneuvering requirements increase. ReCon does not benefit from using an EP system, as its ΔV requirements fail to reach high enough values for the mass savings in fuel reduction to balance against mass increases due to power load increases. This trade could change as additional fuel requirements emerge from an increase of expected maneuvers or as technology continues to drive the mass required per unit of power down. In terms of the implementation of new technologies, it is recommended that further work looks at alternative means of mass reduction. This should include the use of on-orbit servicers, which could refuel, repair, and upgrade reconfigurable constellations.

An engineering options analysis showed that mission planners should consider the use of alternative deployment strategies, but only if they are willing to make changes to the traditional process of satellite development. A staged deployment strategy was explored through the lens of engineering options. The performance of ReCon is hindered when the fuel onboard is limited and the true demand for reconfigurations is unknown. This section showed how the use of staged launches does not significantly decrease the performance of a constellation. However, it can defer costs to the future when the demand picture is more refined, and launch and manufacturing costs are likely below where they are presently. In general, it could be difficult to execute both of these options due to the typically rigid structure of satellite programs.

While this work explored different launch strategies, it did not investigate the optimal strategy. Further work should include finding the optimal decision rule for staged launch given different observed demands. Future work should also include refined cost models used for staged deployment. Any further work should more thoroughly research the process of implementing a continuous production line for satellites and operational costs for ReCon.

Acknowledgments

This research was conducted primarily under the support of the Massachusetts Institute of Technology Department of Aeronautics and Astronautics through a research assistantship. This research was also made possible through the support of the United States Air Force. The views expressed are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense or the United States Government.

References

- [1] Eyres, H., *Seeing Our Planet Whole: A Cultural and Ethical View of Earth Observation*, chapter and pages, pp. 77–87.

- URL https://doi.org/10.1007/978-3-319-40603-9_8.
- [2] Sivakumar, M., and Hinsman, D. E., "Satellite Remote Sensing and GIS Applications in Agricultural Meteorology and WMO Satellite Activities," 2003. URL <http://www.wamis.org/agm/pubs/agm8/Paper-1.pdf>.
 - [3] Kansakar, P., and Hossain, F., "A review of applications of satellite earth observation data for global societal benefit and stewardship of planet earth," *Space Policy*, Vol. 6, 2016, pp. 46–54. URL <http://dx.doi.org/10.1016/j.spacepol.2016.05.005>.
 - [4] Townshend, J., and et al., "Integrated Global Observations of the Land: an IGOS-P Theme." Tech. rep., IGOL, 2008.
 - [5] Paek, S. W., Kronig, L. G., Ivanov, A. B., and de Weck, O. L., "Satellite constellation design algorithm for remote sensing of diurnal cycle phenomena," *Advances in Space Research*, 2018, pp. 2529–2550.
 - [6] Hodgson, M. E., Battersby, S. E., Davis, B. A., Liu, S., and Sulewski, L., *Geospatial Data Collection/Use in Disaster Response: A United States Nationwide Survey of State Agencies*, Cartography from Pole to Pole, chapter and pages, pp. 407–419. URL https://people.cas.sc.edu/hodgsonm/Published_Articles_PDF/Hodgson.
 - [7] Dilley, M., "Natural disaster hotspots: a global risk analysis, volume 5," Tech. rep., World Bank Publications, 2005.
 - [8] Legge, R. S., and Miller, D. W., "Optimization and Valuation of Reconfigurable Satellite Constellations under Uncertainty," PhD dissertation, Massachusetts Institute of Technology, 2014.
 - [9] Bogosian, J. R., "Image Collection Optimization in the Design and Operation of Lightweight Low Aerial-Density Space Telescopes," Master's thesis, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, May 2008.
 - [10] Paek, S. W., "Reconfigurable Satellite Constellation for Geospatially Adaptive Earth Observation Missions," Master's thesis, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, May 2012.
 - [11] The President's Science Advisory Committee, "Introduction to Outer Space," The White House, Mar. 1958. URL <http://plosin.com/BeatBegins/pdf/IntroductionToOuterSpace.pdf>.
 - [12] Belward, A. S., and Skoien, J. O., "Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites," *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 103, 2014, pp. 115–128. URL <https://doi.org/10.1016/j.isprsjprs.2014.03.009>.
 - [13] Lauer, D. T., Morain, S. A., and Salomonson, V. V., "The Landsat Program: Its Origins, Evolution, and Impacts," *Photogrammetric Engineering and Remote Sensing*, Vol. 63, No. 7, 1997, pp. 831–838.
 - [14] Inc, P. L., "Planet Products," <https://www.planet.com/products/>, 2020.
 - [15] Wertz, J. R., and et al., *Space Mission Engineering: the New SMAD*, Microcosm Press, 2011.
 - [16] Mortari, D., Wilkins, M. P., and Bruccoleri, C., "The Flower Constellations," *Journal of the Astronautical Sciences*, Vol. 62, 2004, pp. 134–142.
 - [17] Walker, J., "Circular Orbit Patterns Providing Continuous Whole Earth Coverage," Tech. Rep. AD0722776, Royal Aircraft Establishment, Defense Technical Information Center, Fort Belvoir, VA, Nov. 1970. URL <https://apps.dtic.mil/dtic/tr/fulltext/u2/722776.pdf>.
 - [18] McGrath, C. N., and Macdonald, M., "General Perturbation Method for Satellite Constellation Reconfiguration Using Low-Thrust Maneuvers," *Journal of Guidance, Control, and Dynamics*, Vol. 42, No. 8, 2019, pp. 1676–1692.
 - [19] de Weck, O. L., de Neufville, R., and Chaize, M., "Staged Deployment of Communications Satellite Constellations in Low Earth Orbit," *Journal of Aerospace Computing, Information, and Communication*, Vol. 1, No. 3, 2004, pp. 119–136. <https://doi.org/10.2514/1.6346>.
 - [20] Lev, D., Myers, R. M., Lemmer, K. M., Kolbeck, J., Koizumi, H., and Polzin, K., "The technological and commercial expansion of electric propulsion," *Acta Astronautica*, Vol. 159, 2019, pp. 213–227.
 - [21] "2015 NASA Technology Roadmaps," Tech. Rep. TX-03, National Aeronautics and Space Administration, Washington D.C., 2015.
 - [22] de Neufville, R., and Scholtes, S., *Flexibility in Engineering Design*, The MIT Press, 2011.
 - [23] Vernile, A., "The Democratisation of Earth Observation: A Revolution for The Downstream Sector? Possible Measures to Support a Development Of The Downstream Sector In Light Of New Space Trends," *70th International Astronautical Congress*, International Astronautical Federation, Washington D.C., 2019.
 - [24] Niederstasser, C., "A 2019 View of Impending Small Launch Vehicle Booms," *70th International Astronautical Congress*, Washington D.C., 2019.
 - [25] "Minutes of the Board of Governors discount rate meetings," Federal Reserve Policy Tools Webpage, Nov 4 - Dec 11 2019. URL <https://www.federalreserve.gov/monetarypolicy/discount.htm>.
 - [26] Satellites, O., "News," onewebsatellites.com, May 2019. Date Accessed: 2019-11-15.