Decision-Making and Optimization Framework for the Design of Emerging Satellite Constellations

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With the parallel increase in global orbital debris due to passive object collisions, as well as in the number of proposed low earth orbit mega-constellations, in anti-satellite missile tests, and the fielding of new satellites, there is an inherent need for a framework to optimize the design of Low Earth Orbit (LEO) mega-constellations to avoid collisions while maintaining the functionality of the constellation. In this paper, we aim to provide a framework that unifies these considerations in the conceptual design phase of mega-constellations. We start with a discussion of metrics of importance for the design of mega-constellations, namely coverage, collision risk, collision avoidance, and station-keeping costs. With these metrics defined, we utilize the first principles of orbital mechanics and statistical models to analyze potential alternative mega-constellation designs. These designs are then optimized using Non-denominated Sorting Genetic Algorithm 2 (NSGA2) with our own defined objective function to create a repository of Pareto optimal configurations. We then showcase how a multi-criteria decision-making methodology can be utilized by a variety of unique stakeholders and subject-matter experts to select an optimal constellation design for a given scenario. A Pareto Frontier collection with optimal solutions of 10 constellations was produced by the framework. Radar plots to assess the significance of the weighted metric of the framework shows several trading options for conceptual designs of the constellations. We finally discuss the scope, limitations, applications, and future work for various scenarios.

I. Nomenclature

Notations
ΔV = Change in Velocity
h = Altitude
N = Number of Satellites
p = Number of Planes
P_c = Probability of Collision
ϕ = Elevation Angle
R_e = Radius of the Earth
Θ = Interior Earth Angle
Acronyms
LEO = Low Earth Orbit
DME = Decision-Making Environment
$MCDM$ = Multi-Criteria Decision Methodology
$TOPSIS$ = Technique for Order of Preference by Similarity to Ideal Solution

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II. Introduction

Satellite constellations have become an increasingly popular and useful tool in providing an array of services to our society. The increasing demand for global low-latency internet services has led to a rise in the number of mega-constellations to maximize the scaleable delivery of internet services to people on the ground. Looking at some of the major players, such as Starlink[1], Oneweb[2], and Project Kuiper[3], we see that there are plans for thousands of satellites to start occupying Low Earth Orbit (LEO) altitudes, which comes with natural concerns about this increase in space traffic management.

The overpopulation of resident space objects compounds the growing concerns of the Kessler syndrome [4]. In short, filling high-value orbital shells with many competing mega-constellations not only poses an increased individual risk of collision but cascading collisions as well. When these cascading collisions become self-sustaining due to the density of resident objects in a given shell, we see Kessler syndrome in practice.

Designing a satellite constellation that meets all requirements imposed internally and through regulatory bodies requires engineers to consider and trade all factors that will influence a constellation's architecture. These factors and requirements become all the more important once proposed constellations start to consider thousands of satellites for a given constellation. While these factors can be numerous, we wanted to address four key concepts we found particularly valuable to the satellite constellation design process: Risk of Collision, Coverage of Constellation, Cost of Station-keeping, and Cost of Collision Avoidance. These four factors are important for conceptual designers to trade the most high-level attributes of a given constellation. Due to the highly interlinked and complex nature of these metrics and the factors that drive them, making these conceptual design decisions in an informed manner represents a difficult challenge.

This necessitates the need to develop a methodology that tackles the complexities of optimizing conceptual mega-constellation design. The design framework should be used as an interface to model and analyze various scenarios, conduct trade-off analyses, and be able to evaluate constellation alternatives. This paper primarily proposes a unified decision-making environment to design and assess emerging constellation designs that account for collision risks and avoidance strategies, station-keeping costs, and coverage.

III. Background

Satellite constellations have been a useful tool in providing and expanding an array of services to society. Historically, they have been used for navigation, imagery, telecommunications, earth observations, and more recently, low-latency internet communication. Each of these constellations with multiple functionalities has its levels of design and operational intricacies. This paper will be focusing on the design of constellations for emerging satellite internet mega-constellations. The design of these constellations has an inherent complexity that is higher than standard satellite design, by virtue of the scale of design. We use this paper to propose a framework that allows for the creation of potential low-earth orbital satellite constellation designs and provides the capability to trade these designs with some simplifying assumptions.

A. Design Considerations

Designing a satellite constellation that is both feasible and robust requires the consideration and trade of multiple factors that influence the final design. The four primary design considerations we wish to investigate are collision avoidance and station-keeping costs, collision risk, and coverage. These are called out for economic viability, risk, and performance of constellation respectively. An important note is that all of these metrics will be championed by different stakeholders, and thus the concept of an optimal constellation is arbitrary and up to the designers. This framework will provide a collection of possible optimal solutions, but the final design is of course up to the conceptual designers and stakeholders.

1. Station-Keeping

Due to atmospheric drag, earth oblateness, solar wind pressure, and third-body perturbations, satellites tend to drift from their nominal orbital positions. In low-altitude orbits within the LEO classification, our primary concern is with atmospheric drag, however as nominal altitude increases, other factors become dominating. Consideration of station-keeping is significant to our designs, as higher propellant costs to maintain a nominal orbit can become prohibitively expensive considering mass launch costs. Station-keeping considerations become more difficult to capture in constellations because of the added dependency of the relative positions between satellites in a constellation, as well as the inertial position of the satellite relative to the earth[5].

2. Collision Risk

The risk of collision in low earth orbit has been steadily increasing as more mass and individual particles populate orbits of interest. With data from the debris generation of the intentional destruction of the Fengyun satellite and the Iridium-Kosmos collision, it becomes obvious that one collision poses a grave threat to every satellite in the same orbit and altitude.[6] In the absolute worst-case scenario, it is theorized that above a certain critical mass collisions will cascade which, effectively, creates unusable orbits that are full of debris. This is called Kessler Syndrome. [7] This potential for catastrophic collisions will only increase with the adoption of mega-constellations, and minimizing the risk of collisions should be an inherent consideration for any satellite constellation. A statistical method is employed as outlined in IV.C.3 to quantify the risk of collisions over the course of a given year.

3. Collision Avoidance

Once a conjunction event has been identified, which is going to be almost a certainty for a large-scale constellation over the course of its lifetime, the ability to quantify the costs related to avoiding potential collisions would be a critical and essential factor in the design framework. Similarly to station-keeping, carrying extra propellant for collision avoidance maneuvers can become exponentially expensive when considering mass launch costs, thus we have the incentive to minimize the number of maneuvers performed throughout the constellation. Utilizing a similar statistical method outlined in IV.C.3, we can extract the expected number of collision avoidance maneuvers required to ensure an acceptable margin of safety. We also propose simplistic collision avoidance maneuvers based on first principles to estimate ΔV costs throughout the constellation.

4. Coverage

Coverage is a key design factor as it defines the operational viability of the constellation. Currently, there are no mechanisms in place to resupply fuel needs for satellites and this limits the lifetime of the satellites due to the maintenance from on-linear orbit perturbations. Coverage as a parameter needs to be maximized and is heavily reliant on the type of mission the constellation performs. A constellation aiming at providing an internet connection has constraints on the broadband and quality of the links: the main frequency of the downlink signal and its atmospheric dumping are to be chosen wisely as the altitude varies; when an Earth-observing constellation will be limited in its altitude by its optical parameters[8]. Coverage is often computed as revisit time or quality coverage of the main points of interest on the surface of Earth. For this paper, we opt to investigate only low-latency broadband internet constellations and coverage associated with this particular type of constellation. This paper also focuses on maximizing coverage in a single plane keeping inclination and number of satellites as the metrics of interest.[8]

B. Decision-Making Environment

As mentioned in III.A, various stakeholders may have competing and conflicting views on which design consideration is the most important. Attempting to find an objective optimal constellation configuration is beyond the scope of this paper, thus we will propose a collection of Pareto optimal satellite configurations, along with a decision-making environment which will provide the capability of selecting an optimal satellite configuration depending on input weights. An in-depth discussion of this approach is outlined below.

1. Trade-off and Ranking

The main objective to achieve with the DME is to create and assess various alternatives. TOPSIS is used as the tool to rank the various alternatives. TOPSIS utilizes the Euclidean distance between the alternatives available in the design space to the ideal solution in the N-dimensional space and computes the normalized weights. The framework is used to assess the current and future results with the aid of visualizations. Subject matter experts and stakeholders can evaluate alternatives while discussing weights that are valuable to the requirements for the constellation. The DME must be able to store the constellation alternatives to give the user a sense of understanding between weighing scenario and alternatives value. It can also be used as a basis to study the sensitivity of weighing schemes on the alternatives options and scenarios. Essentially, the tool must serve as a solid background to study the implications of the constellations even before it reaches orbit i.e. conceptual design analysis of constellations.

IV. Methodology

A. Decision-Making Framework Overview

While looking at the design of optimized satellite constellations, we decided to formulate our approach as a decision-making problem. In essence, we propose that the creation of a constellation is highly dependent on the stakeholders and by the nature of multi-objective optimization, we will have a wide selection of potentially "optimal" solutions to choose from. Fig 1 shows the breakdown of our technical approach to this problem.

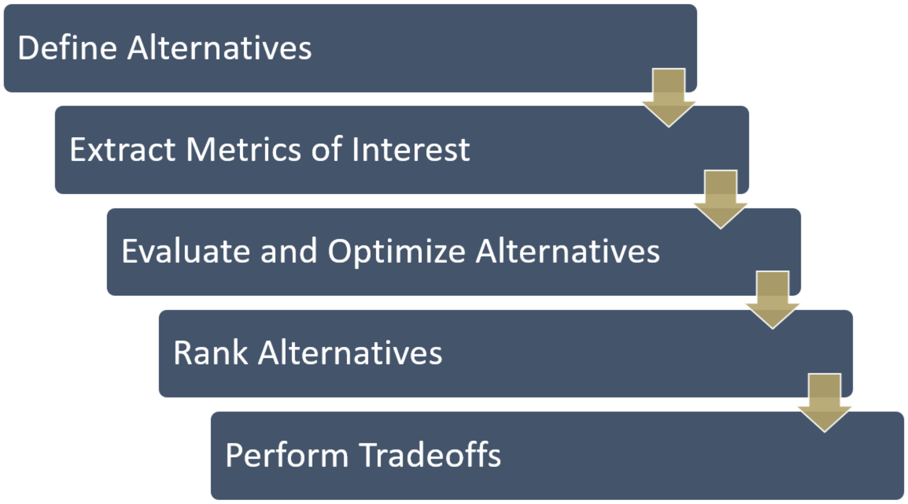


Fig. 1 Flowchart of Decision-Making Methodology

Each of these steps will be highlighted in the subsequent subsections.

B. Definition of Alternatives

In classical orbital mechanics, a single satellite has an orbit that can be completely defined by 6 different elements [9]. Expanding this to a constellation of N satellites, we would have 6N parameters for which to describe a constellation alternative. For mega-constellations that utilize hundreds to thousands of satellites, this quickly becomes too large a design space to explore for optimization. We thus limit the scope of this paper to Walker Delta constellations, which are widely used and allow for uniform continuous global coverage through symmetrical patterns. An example of a polar walker delta constellation is shown in fig 2. Walker Delta Constellations have the same semi-major axis, inclination, eccentricity, and argument of periapsis for all of their constituent satellites. Limiting our scope to the Walker Delta constellations considered by Guan, et al.[10], we can break our constellation into five parameters that define an entire constellation: The number of satellites, Inclination, Altitude, Number of Planes, and the Phasing parameter. The ranges of these parameters used for the framework are outlined in table 1.

Fig. 2 Iridium Walker Constellation reproduced from [10]

Parameters	Range of Values	Unit
Number of Satellites	100 - 1900	-
Inclination	70 - 105	deg
Altitude	150 - 2000	km
Number of Planes	1 - 100	-
Phasing Parameter	1 - (p-1)	-

Table 1 Constellation parameters for Walker Delta Configurations

C. Extracting Metrics of Interest

After the definition of an alternative, we must have a method to compare and contrast the various alternatives. We choose to define four core metrics of interest, which will represent the suitability of each alternative constellation design with various stakeholder needs and wants. The primary considerations are outlined in section III.

Each of these considerations is assigned a quantifiable metric to compare alternatives:

- Coverage: Probability of coverage
- Station Keeping: Station-Keeping ΔV
- Collision risk assessment: Probability of Collision
- Collision avoidance: Collision Avoidance ΔV

1. Coverage

Coverage as a global consideration can be defined as the area that can be observed by the satellite's optics or in which a broadcast signal from a particular satellite can be received. Walker [11] briefly worked on what became the Walker constellations where every point on the earth's surface can always see at least one satellite above some minimum elevation angle which is evenly spaced for uniform coverage. To reach a quantifiable metric of coverage, first, we must define the ground track of each of the satellites that creates a given constellation alternative. (see Fig 3)

Fig. 3 Representation of a Single Satellite Ground Track

Based on this ground track we can define some requirements on the walker constellation parameters to have global coverage [8]:

Based on the Earth's central angle defined in fig 4, we have the following relationships:

$$\frac{N}{P} > \lfloor \frac{2 * 360}{\theta} \rfloor \tag{1}$$

$$P > \lfloor \frac{360}{\theta} \rfloor \tag{2}$$

where based on fig 4 we have:

$$\theta = arcsin(\frac{\rho sin(90 + \phi)}{h + R_E}) \tag{3}$$

with (ϕ is the elevation angle):

$$\rho^2 - 2R_E\rho cos(90+\phi) = (R_E + h)^2 - R_E^2 \tag{4}$$

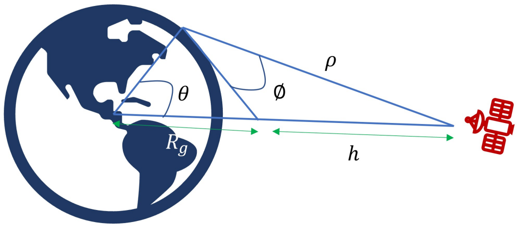


Fig. 4 Coverage geometry

Constraints on the parameters P and N allow for ground tracks to overlap on both the same orbital plane as well as on adjacent orbital planes (fig 5) to allow for global coverage. In this paper, these constraints we chose allow for the coverage to be global, continuous, and also superimposed, and redundant as shown in fig 5.

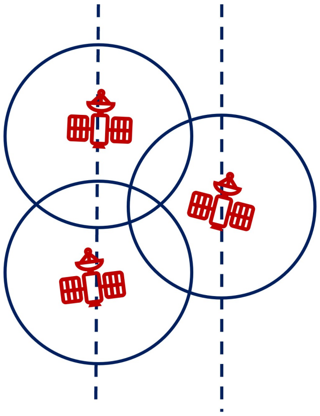


Fig. 5 Example of overlapping ground tracks

We also introduced a new parameter in this model which is the elevation angle, for which we will consider values between 25 and 55 based on current values of operations as well as regulations. However, to compare the most clearest alternatives, we need a quantitative metric. We use Al-Hourani's definition of probability of coverage[8]. This probability is given as the sum of two terms:

- The first part of the probability of coverage is defined as the probability that any receiver on the ground has a satellite available above at a certain elevation angle. This probability is based on the density of satellite approximation in space above the receiver which is valid due to a large number of satellites. This probability is given by the formula:

$$p_{cov_1} = 1 - exp[\frac{-Nh}{2(R_E + h)}] \tag{5}$$

- The second part is defined as the probability that the downlink signal is received accounting for two perturbations of the signal called Satellite-to-Ground Path-Loss, a graph of the modeled phenomenon is presented in fig 5.7[12]:
  - A probability of line of sight that takes into account elements that are on the path of the signal, especially in an urban environment.
  - The second part accounts for losses due to atmospheric absorption.

  Those two components are then modeled as a white-noise Gaussian mixture. The second part of the probability is then defined as the probability that the signal-to-noise ratio is superior to a predefined threshold:

$$p_{cov_2} = -\int_0^{\varphi max} F_{\zeta|\varphi_0}(\frac{\gamma W}{P_t l(\varphi)})\, d\varphi \tag{6}$$

where φ is the Earth Centered angle, F is the cumulative distribution function of the white noise Gaussian mixture, γ the threshold, P_t the radiated power, and $l(\varphi)$, is the free space path-gain

2. *Station Keeping*

Station Keeping represents all the strategies that are used to mitigate the natural orbit perturbations.
A summary of how those perturbations are mitigated is given below:

- Earth's Oblateness (J_2) creates a node drift that only depends on inclination, therefore, the overall coverage is unperturbed as we are considering a constant inclination across the constellation. The node drift would be too costly to mitigate if we wanted to maintain the same orbits as the original ones.
- Higher Order Harmonics are naturally mitigated for eccentricities of around e = 0.0013
- Solar/Lunar gravity adds inclination and node drift that can be left uncompensated

Therefore, the perturbations that need to be mitigated are:

- Solar Radiation Pressure
- Atmospheric drag

For that we will be using the following method presented by Low and Xian [13], modeling the orbital decay accounting for the two perturbations above as a function of time.

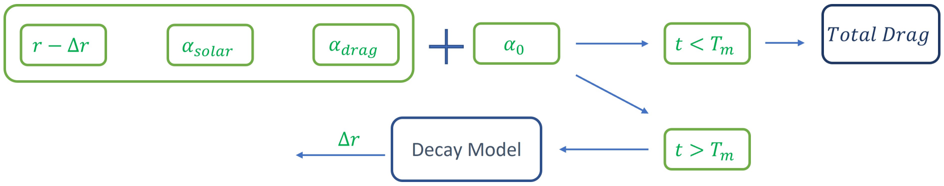


Fig. 6 Orbital Decay Flowchart

where

$$\alpha_{drag} = -\frac{1}{2}\rho C_d \frac{A}{m} V^2 \tag{7}$$

$$\alpha_{solar} = \frac{A(1+r)}{m} P \tag{8}$$

Final decay is given by:

$$\frac{dR}{dt} = \frac{(\alpha_{solar} + \alpha_{drag}) * T}{\pi} \tag{9}$$

We then set up a threshold altitude so that we can calculate the time the orbital decay is strong enough to cross that threshold. We then divide the time of the mission by the crossing time we found to have the total number of maneuvers per satellite needed.

Each maneuver is then modeled as a two-impulse Hohmann Transfer to take the satellite back to its nominal orbit. An example of a Hohmann transfer is given in fig 7

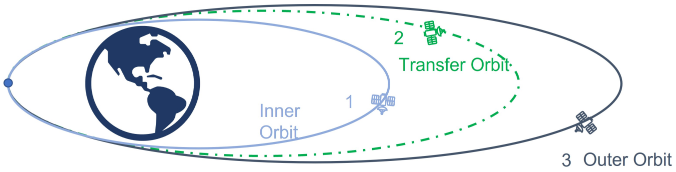


Fig. 7 Example of a Hohmann Transfer

The metric is finally given by:

$$\Delta V_{SK} = N_{Sat} N_{Maneuvers} \sqrt{\frac{GM_e}{a_{nominal}} \frac{H_{Box}}{2a_{nominal}}} \tag{10}$$

We can then further optimize the size of the box, leveraging between numerous small impulses for small boxes or bigger, less frequent impulsive maneuvers for a bigger box.

3. Collision Risk Assessment

To quantify the probability of collision, we utilized a statistical and probabilistic model outlined in a standard text on space debris models[14]. Originally, this method was developed by Foster [15] and has since been implemented in the European Space Agency's Debris Risk Assessment and Mitigation Analysis (DRAMA) Software. The ESA was gracious enough to allow us to utilize their software to automate this statistical analysis. With a given input of orbital characteristics outlined by our assumption of a Walker Delta configuration within the set parameters in 1, we can investigate the number of maneuvers and risk of collision for a single satellite within the constellation, and extrapolate over the entirety of the constellation.

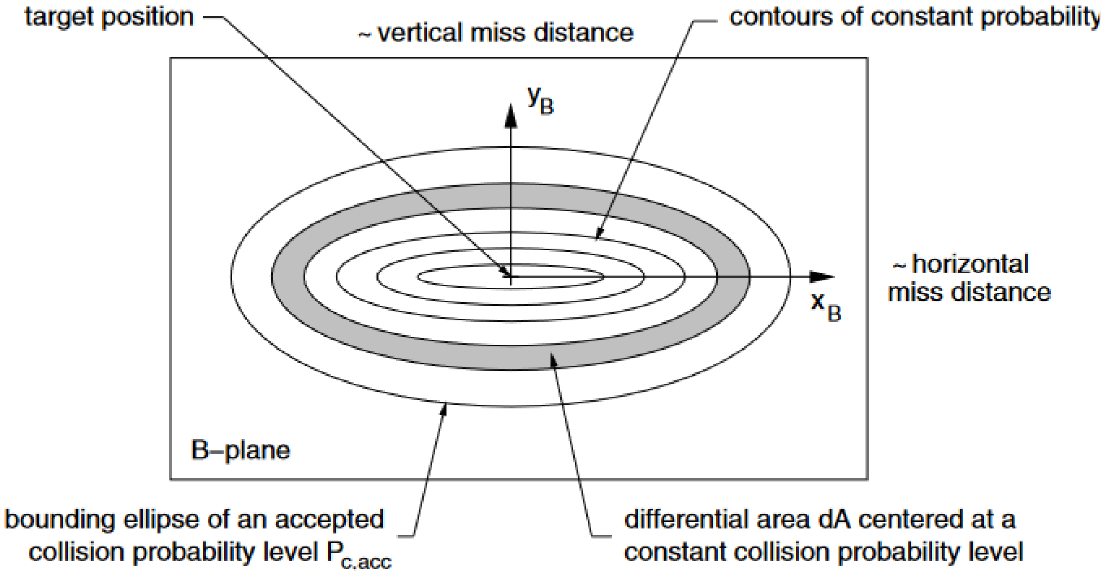


Fig. 8 Visual Representation of Collision Estimate Process By Klinkrad[14]

The collision risk assessment module outputs over the course of a year, what the probability of collision will be if no maneuvers are performed for a given satellite, and how many collision avoidance maneuvers will have to be performed to ensure each satellite reaches an arbitrary $1 * 10^-6$ probability of collision. Risk of collision is its stand-alone metric to be fed into the optimizer, however, the number of maneuvers required per satellite is then put into our collision avoidance module to model the cost of performing these risk-reducing maneuvers.

4. Collision Avoidance

Once we have the number of maneuvers from the collision risk assessment module we need to define our avoidance maneuvers. For our purposes, we consider two different strategies to carry out a collision avoidance maneuver, those being an in-track maneuver, and a radial maneuver. The overreaching methodology for collision avoidance calculations comes from Fernandez, Radtke, and Stoll [16].

- The first avoidance maneuver we consider is an in-track maneuver defined by a miss distance. It creates a time displacement by long-term orbit change.

The strategy corresponding to this type of maneuver is that it is a more fuel-efficient maneuver. However, it requires an earlier execution, leading to a longer period of time outside of our nominal orbit.
A sketch of the maneuver is presented in fig 9

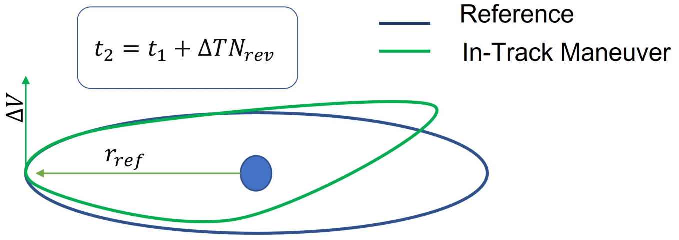


Fig. 9 Sketch of the In track initial maneuver reproduced from [16]

- The second we are considering is the radial maneuver defined by the same miss distance as the in-track maneuver. This time, the satellite transfers to a higher or lower altitude than the initial conjunction point.
  The strategy corresponding to this maneuver is that the impulse has a much bigger magnitude so the coverage loss is less important. Therefore the priority of the maneuver is on coverage.

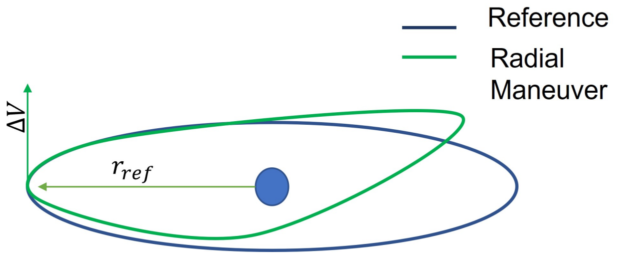


Fig. 10 Sketch of the Radial initial maneuver reproduced from [16]

The total ΔV for this maneuver is finally given by:

$$\Delta V_{CA} = 2(\sqrt{\frac{GM_e}{r_{ref}}} - \sqrt{GM_e(\frac{2}{r_{ref}} - \frac{1}{a_{maneuver}}))} \tag{11}$$

This formula is the same for both maneuver strategies, the only difference being the semi-major axis of the maneuver orbit. For the radial maneuver, this value is fixed by the miss distance and the maneuver is started half a period before the initial conjunction point. For the in-track maneuver, this value is variable, depending on the number of periods before the conjunction point you want to be on the maneuver orbit. As this number increases, the fuel expenditure of the maneuver decreases at the expense of the coverage loss.

After that maneuver a last re-phasing maneuver is applied, similar to the in-track maneuver but with a semi-major axis smaller than the nominal orbit.

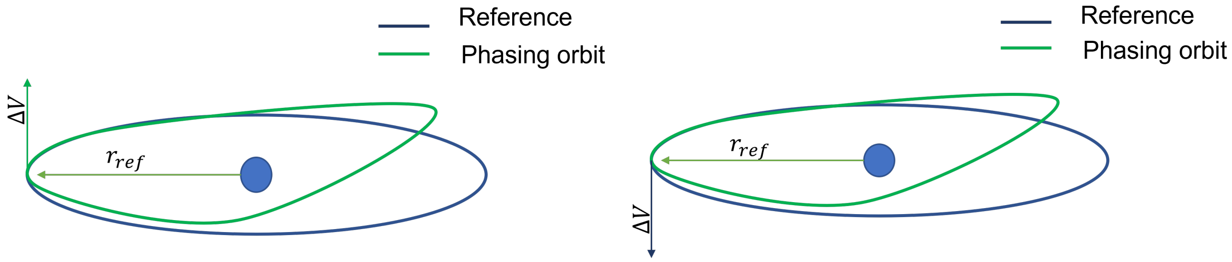


Fig. 11 Sketch of the common re-phasing maneuver reproduced from [16]

The total ΔV for this maneuver is finally given by:

$$\Delta V_{CA} = 2(\sqrt{\frac{GM_e}{r_{ref}}} - \sqrt{GM_e(\frac{2}{r_{ref}} - \frac{1}{a_{phasing}})}) \tag{12}$$

Again, the formula is the same but the $a_{phasing}$ is also given by the number of periods of the phasing orbit to catch up on the nominal orbit.

For both the phasing maneuver and the in-track, we set up the number of periods at 10 leveraging, for a small loss of coverage and a relatively small fuel expenditure.

D. Optimization of Alternatives

With various competing metrics presented, it becomes apparent that a multi-objective optimization scheme is required to provide a collection of alternative constellation designs for primary stakeholders to select from.

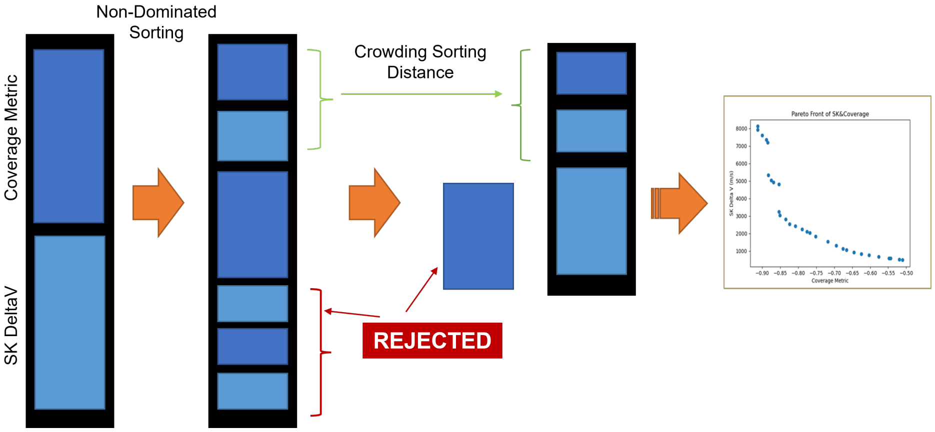


Fig. 12 Visualization of NSGA2 reproduced from [17]

$$\min J = -C + \Delta v_{SK} + \Delta v_{CA} + P_c$$

Fig. 13 Objective Function Defined by Design Considerations

We selected NSGA2, or the non-dominated Sorting Genetic Algorithm for this multi-objective optimization problem, graphically represented in fig 12. An objective function was defined based on the design considerations, as shown in 13. In this objective function, coverage is to be maximized, while ΔV for station-keeping, ΔV for collision avoidance, and probability of collision are minimized. During the optimization, all components of the objective function are normalized between zero and 1 for equal weighting. This algorithm was set up with a $\frac{1}{5}$ mutation rate, 85% crossover, and a population of 10. The algorithm was run until an objective function tolerance of $1e-6$ was reached, or until after 150 generations have been run. The constraints imposed on the solutions available have been outlined in the previous parameter sections. NSGA2 will evolve the population until a final Pareto front is created. This optimizer was used within the PyMOO package [18], with our overarching coding taking place within Python. An important limitation within our optimizer is the computational requirements of DRAMA within the optimizing framework. Due to unforeseen computational requirements of DRAMA, each member of the NSGA2 population was required to run on an individual processing core. This limited the population to a minuscule 10, however, given more processing power, this population could, and most likely should, be increased into the hundreds.

E. Trade Alternatives

The main objective to achieve with the Design Making Environment (DME) is to create and assess various alternatives. TOPSIS is used as the tool to rank the various alternatives. TOPSIS utilizes the Euclidean distance between the alternatives available in the design space to the ideal (also called Utopian) solution in the N-dimensional space and computes the normalized weights. The DME must be able to assess the current & forecast-ed future results with visualizations. Python was chosen as the platform to create it, as the modeling and simulation package already exploits the python environment. This creates an easy pipeline for the dashboard. The key to the DME is the PyDash library that also has another tied-up package plotly to enable interactive visualizations. The environment has three main functionalities, firstly the ability to vary the weighting scenario from the metrics of the subsystems, utilizing the radargram of TOPSIS results to visualize the rankings, and the ability to filter the constellation parameters. This has allowed the team to vary and create multiple scenarios to assess the alternatives.

From the optimization of constellation 12, the Pareto frontier where each point represents the constellation design parameters. Each of these points is an alternative. Each solution or point is a unique value of its own. As seen in the figure, the point shows one constellation's orbital parameters in the form of the total number of satellites, altitude, elevation angle, inclination, number of planes, number of satellites per plane, and relative phasing between satellites as discussed in detail in the earlier sections of the report.

There's a need for the user to be able to trade these solutions. SCOOP aims to cater to the needs of various stakeholders who might use this tool. It could range from a constellation design engineer to a central regulatory body. Each of these stakeholders has its version of optimum and thus, weights must be a user-defined feature in the decision-making framework.

TOPSIS or Technique for Order Preference by Similarity to Ideal Solution is a multi-criteria decision-making method that utilizes the geometric closeness to an ideal solution as illustrated in figure 14.

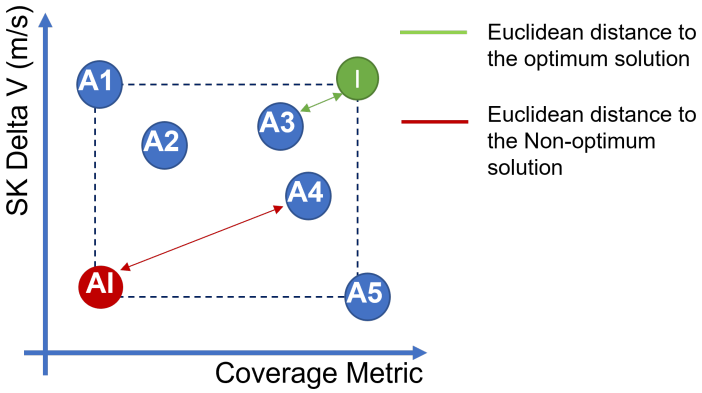


Fig. 14 Representation of TOPSIS algorithm reproduced from [19]

The user input weights would be utilized to select the optimal solution for the user from the Pareto frontier. The method of compensatory aggregation compares a set of alternatives by identifying the user-defined weights for each criterion of the system model, the normalizing scores for each criterion are computed which is used to calculate the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion. Further, ranking is then provided for all the points obtained from the Pareto.

The users will have real-time access to alternatives to the constellation. The radar plot is used to visualize the ranking of the alternatives and provides a great basis of intuitive understanding for the user to assess the alternatives and weighting scenario in real-time. The radar plot for a scenario assessed by the framework is illustrated below at 15.

V. Results

Post optimization, we have been able to achieve a collection of Pareto optimal solutions based on the metrics outlined in section IV.C. Fig 16 is a collection of plots showcasing the multi-dimensionality of the Pareto frontier produced by the framework. Three particular cases are called out by shapes to showcase potential constellation configurations that different stakeholders may select as optimal.

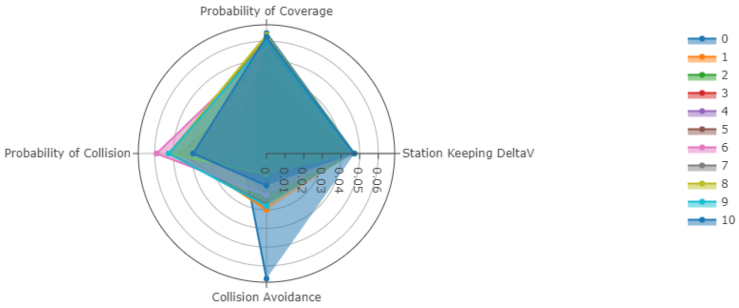


Fig. 15 Representation of the Radar plot for an alternative solution

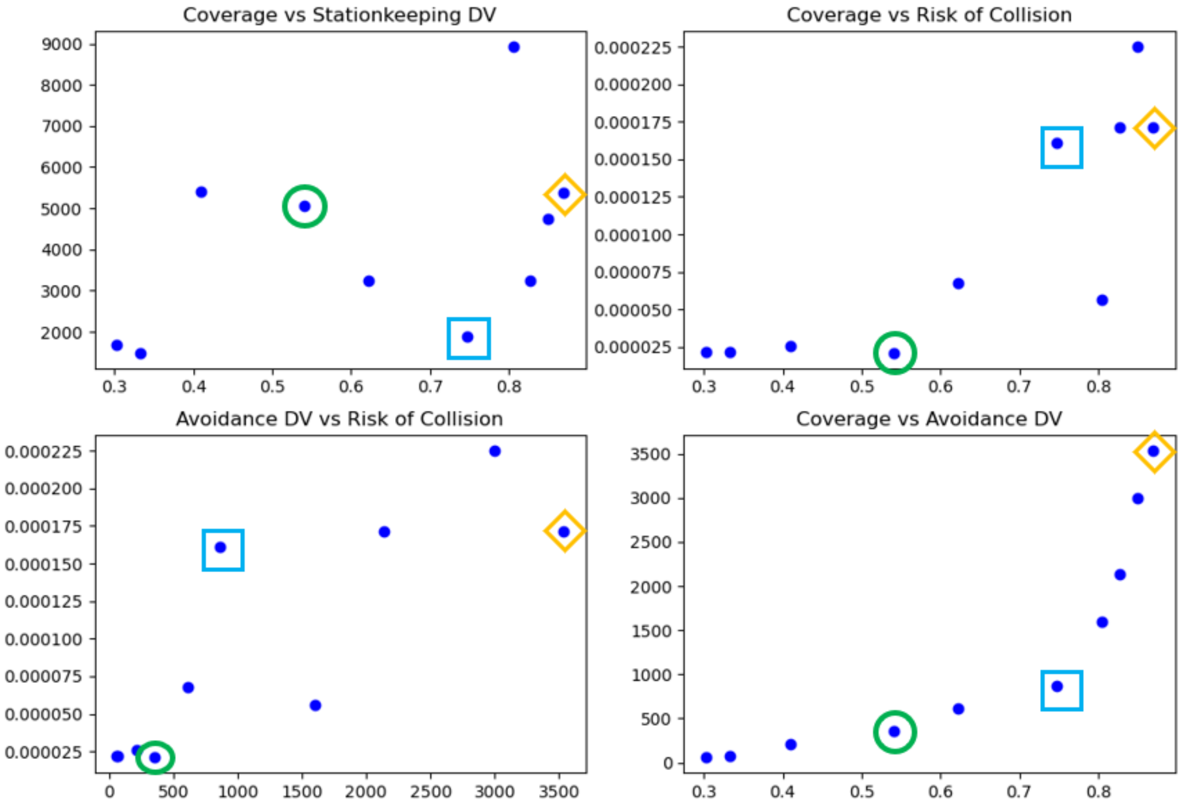


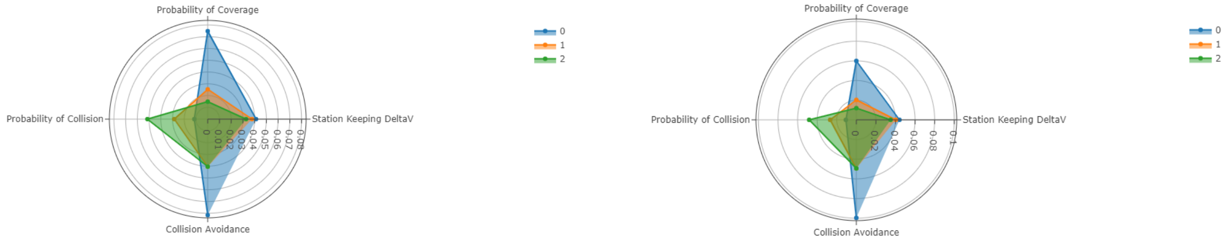
Fig. 16 Multi-Dimensional Pareto Frontier

These three called-out configurations are investigated in depth in Table 2. All proposed configurations produced by our framework can be investigated in depth, but for the sake of brevity, they have not been included.

These three called-out configurations can show three different hypothetical scenarios where stakeholders with various priorities can come to different conclusions about which configuration is optimal for their needs. For example, a company with a large capital investment that only cares about customer satisfaction may consider the diamond configurations to be ideal, as it produces the highest probability of coverage. A more financially concerned group of stakeholders may prefer the square configuration for its low station-keeping and collision avoidance requirements, while a particular risk-averse entity may consider the circle configuration ideal for its low risk. Regardless of the stakeholder's requirements, our framework produces a variety of results to be the initial trading process in the conceptual design stage.

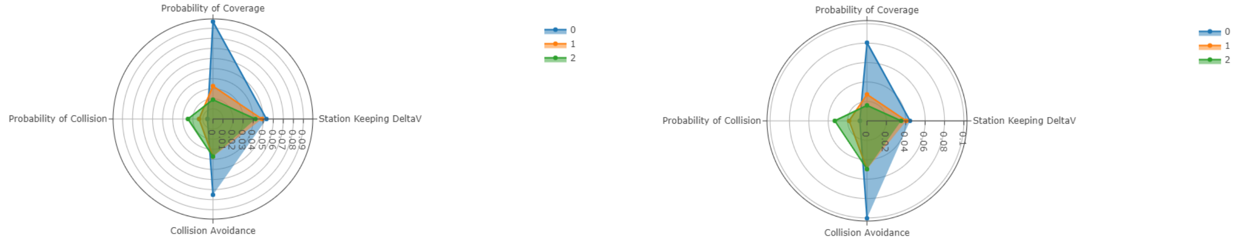
Symbol	Altitude (km)	Elevation Angle	Inclination	Number of Planes	Number of Satellites/ Plane	Relative Phasing	Probability of Coverage	Station Keeping ΔV (m/s)	Collision Avoidance ΔV (m/s)	Probability of Collision
○	1560.006	54.07686	100.6093	40	27	5	0.540489	5049.419	351.8975	2.11E-05
◇	973.8961	49.50604	77.88179	43	27	5	0.869266	5380.368	3533.552	0.000172
□	973.8961	49.96215	71.64299	15	27	5	0.74695	1876.873	862.8599	0.000161

Table 2 Satellite Configurations of Interest



(a) Baseline with Highest Probability of Collision

(b) Highest Weights of all metrics



(c) High Station-Keeping and coverage weighing Scheme

(d) Balanced Weighing Scheme

Fig. 17 Radar plots for Trading Weighting Schemes from the Pareto Frontier

VI. Conclusion

The capability we showcase in this paper shows promise as an initial but by no means exhaustive framework for the conceptual design of large-scale constellations. Using the four basic design considerations outlined in section III, a collection of stakeholders and conceptual designers would be able to investigate potential constellation designs to suit their needs and trade these alternatives. For a continuation of this research, more design considerations could be identified and implemented into the optimization scheme for a more varied and encompassing collection of designs. We also recommend a larger optimization population within computational feasibility. Finally, further researchers would do well to investigate less simple constellation designs, outside of the Walker Delta constellation. We recommend a multi-shell configuration, a flower-pattern, or potentially even highly elliptical configurations for further research.

Acknowledgments

The authors would like to thank Mr. Loïs Visonneau, Georgia Institute of Technology, for his support and advice during the development of the framework, which helped us to improve the quality of our paper.

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