Exploring the Impact of Compliance with Maneuvering Guidelines for Space Traffic Management

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ABSTRACT

If the current estimate of proposed large constellations is realized, the near-Earth space environment will see more than 50,000 new satellites added to the catalog of resident space objects (RSOs) in the coming decade. This is an order of magnitude increase from the current population and poses new policy challenges as global operators seek to leverage the benefits these new satellite systems provide while also ensuring a sustainable approach to collision avoidance. Various guidelines have been proposed to date to support this effort, including the development of right of way rules to guide how a collision avoidance maneuver should be performed, and how the maneuver burden should be shared between the two satellites involved. However, it is very difficult to evaluate and compare proposed guidelines due to the complex nature of space traffic and the rapidly changing space environment. This study seeks to address this issue by utilizing the Virtual Environment for Space Traffic Analysis (VESTA), a high-fidelity simulation tool that has been developed at Georgia Tech over the past few years with the explicit purpose of evaluating the future of space traffic environment. Using this tool, a sensitivity study is performed that incorporates a likely set of future large constellations and provides metrics on the impact that a select set of proposed maneuvering guidelines would have on operators given realistic variations in spacecraft capabilities (e.g. maneuverability and propulsion capabilities), and other factors (owner-country, public vs. private, etc.). Specifically, this study compares three potential right of way rules: 1) a rule based on maneuverability proposed by the Space Safety Coalition, 2) a rule based on the geometry of the spacecraft rendezvous, and 3) a rule that equally distributes the maneuver burden between two operators. The results highlight general observations on the effectiveness and limitations of each of the proposed maneuvering guidelines. In addition to the choice of right of way rule, success of space traffic management will be significantly impacted by compliance – which operators, or how many operators, comply with the space traffic rules. The findings of this analysis have important implications for future methods that could be pursued to put in place right of way rules. For example, non-binding right of way rules may have variable levels of compliance that differ across actors. The impact of compliance by just one nation, or non-compliance by just one nation, help to demonstrate the impact of ensuring all major space actors coordinate on this effort. Overall, this analysis provides insight into the relative gains in safety (decrease in collision risk) that would likely result from more politically intense efforts to increase the number of countries implementing space traffic management rules.

1. INTRODUCTION

The sustainable and efficient coordination of the large number of Resident Space Objects (RSOs) expected to operate in the near future as new and large satellite constellations are deployed remains a significant challenge. These constellations are being operating by a diverse set of global operators representing both government and commercial interests and may have different risk postures and mission objectives that might impact the actions taken when a conjunction warning is issued. For example, some operators may choose to act on a conjunction warning issued several days prior to the predicted encounter, while others may choose to wait until much closer to the event to avoid unnecessary maneuvers. Layered on top of this challenge is the issue of compliance. At present, there is no requirement for spacecraft operators to coordinate or undertake a maneuver, regardless of the risk level or situation. In addition, many of the proposed right of way guidelines assume a steady and reliable communication line between operators. Even if operators are willing to coordinate and/or maneuver, challenges in efficient communication across countries and organizations may inhibit compliance with a rule. The lack of a maneuver, whether intentional or unintentional, increases the probability of a collision, especially if hundreds or thousands of such missed maneuvers take place.

For these reasons, this study seeks to explore the impact that a predefined set of guidelines regarding collision avoidance might have on the overall space population, as well as particular subgroups of satellites. We then study the impact of variations in compliance with these guidelines. Using a robust simulation environment, a series of experiments were run on a projected future catalog that explored variations in right of way rule and degree of compliance. While not exhaustive, the simulations totaled over 12 independent runs and 2548 CPU hours, and provided valuable insights into what aspects a generalized collision avoidance strategy would have the most impact on in terms of operational complexity (number of collision avoidance maneuvers), spacecraft design (level of maneuverability), and effectiveness (overall increase or reduction of collision risk).

2. SPACE TRAFFIC COORDINATION GOVERNANCE AND COMPLIANCE

Today, global space traffic coordination is largely an ad hoc, human-in-the-loop process. At present, when a spacecraft operator receives a conjunction warning, they must determine whether the conjunction meets their organization's threshold for action based on their own risk tolerance levels. If they determine that a collision avoidance maneuver is warranted and the other spacecraft involved in the conjunction is also maneuverable, they need to reach out to that operator to coordinate a response. One or both of the operators will develop a collision avoidance maneuver based on their own flight dynamics analysis and preferences. Spacecraft operators are not obligated to respond to warnings nor to attempts by other spacecraft operators to communicate and coordinate.

In recent years, there has been growing recognition that the status quo is not sufficient to ensure a safe and sustainable space environment [10]. However, the path forward is complex, and requires technical, organizational, and political coordination. Some actors in this domain have focused on defining clear and efficient right of way rules that would provide spacecraft operators with clear direction on when to carry out a maneuver, and in the event that both spacecraft involved in a conjunction are operational, which of them should take the responsibility to maneuver. Right of way guidelines or rules could allow for quicker and more straightforward coordination in the event of a predicted conjunction.

In addition to identifying the thresholds and right of way rules themselves, there are challenging issues related to the implementation of any such rules. Typically, there is a trade-off between the complexity of the governance regime for implementing rules and the level of compliance with such rules. For example, from a political and organizational perspective, the easiest path forward for implementation may be to develop non-binding guidelines, perhaps through a bottom-up, industry-led process. (In fact, at least one such effort has already occurred in the context of the Space Safety Coalition, as described below.) However, compliance with these types of non-binding guidelines may be quite low, since there is no requirement that operators follow them. By contrast, some have called for a binding international agreement on space traffic management, which would include requirements to maneuver in the case of risky conjunctions. Such an agreement might be expected to have full, or nearly full, compliance, since nations that sign the treaty (and through domestic legislation and regulation, all spacecraft operators in those nations) would be required to follow such rules. However, developing this type of international agreement is very politically challenging and time consuming.

Between these two extremes, there are a number of alternatives. For example, one nation or region may choose to lead the way by implementing domestic law or regulation and putting in place maneuver requirements, even absent any international consensus or requirement. If the nation implementing this plan was a major space actor, it is possible this would have a significant impact on the safety and sustainability of the space environment. Another possibility is that, rather than acting alone, a small group of like-minded nations may mutually agree to implement principles to support spaceflight safety and sustainability. A third possibility is that many, or even most spacefaring nations agree to implement right of way principles, with just one, or a small number, of nations opting out of such an agreement.

It is possible that these middle-ground scenarios may provide the best mixture of political feasibility and effectiveness. However, that is difficult to determine without some way to systematically assess and compare the relative effectiveness of each potential governance regime. This paper addresses that issue using a simulation of the space environment to examine how expected variations in compliance associated with each of these regimes would affect the number of expected collisions over a given period of time.

3. METHODOLOGY

3.1. Virtual Environment for Space Traffic Analysis (VESTA)

The Georgia Tech Virtual Environment for Space Traffic Analysis (VESTA) tool is a high-fidelity dynamic simulation environment capable of collision risk assessments (using both static and time-varying covariance models), collision avoidance maneuvers (including impulse phasing maneuvers and the recent addition of low-thrust maneuvering) and executing various right of way scenarios for both current and future space populations. A summary of the simulation functionality is provided here, but the reader is encouraged to refer to [2][3][4][11][12] [11]for more details.

VESTA utilizes two-line element (TLE) sets to initialize the RSOs present in the space environment under consideration, and the mechanics and orbital propagation of those objects are handled using the Simplified General Perturbations 4 (SGP4) model. The SGP4 model handles physical factors like atmospheric drag, solar radiation pressure and non-spherical gravity [6]. The TLE set will vary depending on the run of interest, and runs can include large TLE catalogs (250,000+ objects) leveraged to represent a variety of future space environments. With a variety of code optimizations and access to high-performance computing, in this instance through the Georgia Tech Partnership for an Advanced Computing Environment (PACE), the tool can run on relatively modest computing solutions (e.g. a single node with 10+ GB of memory and 20+ compute cores). Performance is well optimized, with most runs typically completed under one calendar day when only considering collision detection, but computation time varies greatly when comparing varying risk postures and the maneuvers associated with performing collision avoidance maneuvers that may involve complex comparisons of many satellite attributes.

There are a multitude of settings that can be varied within VESTA to test different scenarios. For this study, probability of collision (Pc) for RSOs is calculated using Chan's method [5] with a user defined, spherical screening volume. Conjunction warnings are generated when the Pc exceeds a certain set threshold and computed at a user defined number of hours prior to time of closest approach (TCA). Collision avoidance maneuvers can then be enabled with action commit times depending on the operator-specific risk posture defined by the input compliance guidelines. The generation of position covariance is also customizable, with an existing method for deriving covariance values from historical TLE data (and utilization of default values for objects without a TLE history) as well as the recent implementation of a historical covariance (HC) model based on fitting a cubic spline model to historical tracking data provided by the 18th Space Defense Squadron (18th SDS) [13]. Maneuvering guideline compliance is an adjustable setting too, with options like country-specific maneuvering, assigning burden based on the operator type (government, commercial, university, etc.), or adherence to more specific proposed guidelines, such as those developed by the Space Safety Coalition. Efforts were made to ensure all satellites were modeled appropriately, including their mass and hard-body radius, a key variable in calculating Pc, as well as knowing the operator type.

Each test case requires adjustments to input parameters, but some are kept constant. For this study, the following settings were used across all runs:

- Screening volume of 25 km for Pc calculations
- Pc threshold of Pc > 1e-5 for conjunction event notifications
- Simulation duration of 1 month
- Covariances calculated using the HC model
- Avoidance maneuvers enabled
- Low-thrust maneuvering for constellations, impulse phasing maneuvering for all other spacecraft
- Future space environment catalog (67,000+ RSOs)
- Two-minute propagation step time
- 72-hour notification time and 48-hour maneuver action time prior to TCA
- Intra-constellation conjunctions were not considered

The aforementioned TLE data set is used to initialize all objects in the simulation environment, with computation of starting position and velocity as well as association with requisite metadata. VESTA then propagates the orbits of objects forward by the prescribed step time increment and checks for conjunction events in the future based on the set notification time (e.g. checking for possible conjunctions in the next 72 hours). If there are conjunction events found to have a Pc over the threshold in this search, event notifications are incremented by one for the objects involved. After a notification is generated, then based on the objects involved and their maneuvering capabilities, which may vary depending on what settings are enabled for compliance, requisite avoidance maneuvers are performed beginning at a set time prior to TCA (with each notification time having an associated action time, in this case 24 hours after notification). The latency between notification and maneuvering is to simulate operator involvement, as satellite maneuvering in an operational environment would require some time for planning and spacecraft commanding. Maneuvering decisions and priorities are dependent on satellite properties and the compliance settings for each run, as ranked priorities and certain attributes (such as spacecraft age or country of origin) affect which satellite(s) involved in the conjunction event takes on the maneuvering burden. The maneuvers that RSOs can do in the simulation are elaborated on further in the paper but objects can perform impulse phasing and low-thrust maneuvers, depending on associated metadata and compliance schemes.

As the simulation is designed to run over long simulation timeframes and with large catalogs to generate sizeable amounts of conjunction event notifications, there are station-keeping behaviors programmed into VESTA to prevent premature deorbiting and significant orbital element changes for large constellations that may occur over time. In short, the station-keeping function checks if constellation satellites are moving away from their designed orbits beyond a certain set of bounds, and when such behavior is detected will trigger maneuvers to return the affected satellites to an expected orbit. Given that large constellation operations and maneuvering will likely require strict adherence to specific orbits in a future environment, this functionality is intended to parallel the behavior of an operator in a situation where significant alterations to a planned orbit have occurred.

Much of the functionality of VESTA is further elaborated upon in [2][4], but new additions to the tool as described in [11] have provided an opportunity for increased realism in modeling. In contrast to the TLE data residual method for position covariance estimation, the HC model fits a cubic spline model to historical data enumerating median covariance size as it varies with propagation time and accumulated ground tracks as explained in [13]. The use of this model allows for a more robust and time-varying solution to covariance calculations for objects in the predicted future space catalog. It should be noted that the time-varying nature of the HC model does introduce a certain degree of randomness to the simulations, resulting in variations in conjunction counts of a few percent. The low-thrust maneuvering for constellation satellites is also a novel feature and serves to add realistic maneuvering for large constellations in line with the current methodology used by Starlink satellites. The inclusion of further realism in the VESTA tool provides more confidence in the applicability of simulation results to assess and evaluate future space scenarios and suggested guidelines.

3.2. Modeling current and future space populations

For the purposes of this paper, the current catalog consists of all 7,792 RSOs captured by Space-Track on February 4th, 2023. Given the orbital parameters of these satellites, as well as a literature search (including sources such as FCC filings, etc.) to determine potential future constellation plans [1], an extended future catalog was developed that added five major constellations. Table 1 provides a summary of the added constellations, relative size, assigned NORAD ID range (needed later for certain maneuvering decisions), and operator information. Factoring in the 7,792 objects in the active Feb 4th catalog and the extended constellations, the total future catalog used for the simulation consists of 67,626 RSOs (accounting for existing Starlink satellites in the current catalog).

Table 1. Predicted Future Satellite Constellations in the Extended Catalog [10]

Constellation	Company	Country	NORAD ID	# of Satellites
Guowang (GW-2/GW-A59)	China Telecom	China	> 114,000	12,992
Astra	Astra	USA	100,000 - 113,999	13,620
Kuiper	Amazon	USA	90,000 – 99,999	3,236
Starlink (Gen2)	SpaceX	USA	60,000 – 89,999	29,988
OneWeb	OneWeb	UK		648
Total				60,484

Many of the physical properties of the extended catalog are based on assumptions, as not all constellations had public designs and datasheets available for use. Details on specific assumptions made for various constellations pertaining to factors such as mass and hard-body ratio can be found in [1]. These physical properties and orbital parameters are in-line with existing knowledge and allow for enhanced realism without explicit operator confirmation. While it is likely that the real specifications and orbits of future constellations will differ in some ways from the assumptions used in the simulations, the simulation is designed to be sufficiently accurate to fulfill its purpose of demonstrating the challenges of space traffic coordination in a future that involves multiple large constellations.

Figure 1 shows a histogram of the active space environment as of Feb 4th, 2023, correlated with inclination and altitude, as well as a histogram of the future space environment where the constellation satellites referenced in Table 1 are also included. These figures show the dramatic change in population density in certain orbital regimes, as well as the expected future co-location of multiple large constellations. This visualization helps to demonstrate the limitations of studies that focus only on the current spacecraft catalog. It is essential to examine future-oriented simulations, such as those enabled by VESTA, to ensure that space traffic management strategies are well-suited to the future challenges of the space environment.

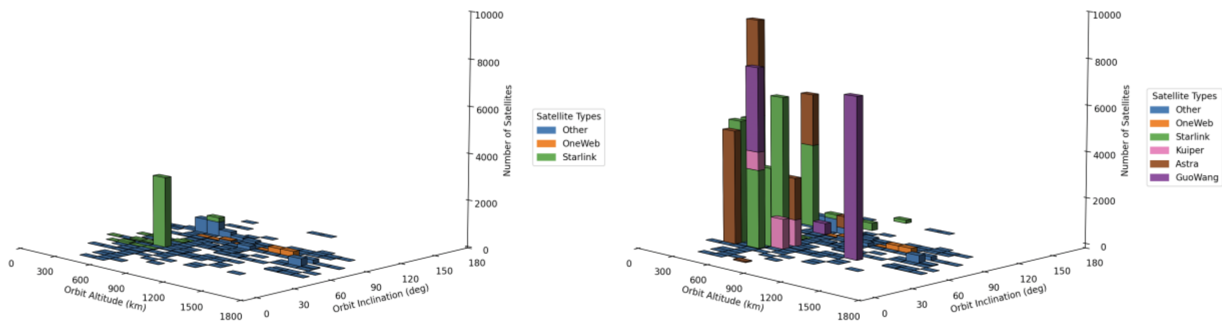

Figure 1. Histogram of Current (left) and Future (right) RSO Catalog.

3.3. Proposed guidelines

This study implemented three different right of way guidelines to compare their impacts on space operators and space traffic overall. In particular, we examined how changes in right of way guidelines would impact the total number of maneuvers undertaken over the course of a month, as well as the number of maneuvers undertaken by particular subgroups, such as large constellation operators. We then examined how variations in compliance would change these impacts, allowing us to better understand the relationships between right of way rules and compliance. For this study, we focused on three potential guidelines: 1) guidelines based primarily on maneuverability, developed by the Space Safety Coalition [7], 2) guidelines based on the geometry of the conjunction proposed by Burgis et al [8], and 3) a simple guideline that requires operators to equally share responsibility to maneuver for each conjunction.

3.3.1. Space Safety Coalition Right of Way and Maneuver Prioritization Guidelines

The Space Safety Coalition (SSC) is an international organization of satellite operators, government entities, industry representatives, and others that seek to promote space safety through the development of international standards, guidelines, and practices. In 2019, SSC released its “Best Practices for Sustainability of Space Operations” report, which provided guidance on actions for spacecraft operators and other space actors. In April 2023, an updated version of this document was released, which included rules of the road and maneuver prioritization guidelines [9].

The SSC guidelines differentiate based on five levels of spacecraft maneuverability capabilities: 1) non-maneuverable, 2) minimally maneuverable, 3) maneuverable, 4) on-ground automated collision avoidance, and 5) on-board automated collision avoidance. They also have special rules for conjunctions involving crewed spacecraft. In addition to taking into account spacecraft maneuverability, these right of way rules also consider whether a spacecraft is in a transiting orbit or if it is in its mission orbit. For the purposes of this simulation, however, we assume all satellites are in their mission orbit.

Based on these characterizations of the spacecraft involved, the standard identifies which spacecraft should take the initiative to maneuver in the event of a conjunction. Generally, these rules direct the more maneuverable spacecraft to maneuver, and when a crewed vehicle is involved, the crew vehicle undertakes the maneuver. In cases involving two spacecraft that are equally maneuverable, or two crewed vehicles, the guidelines suggest that a bi-lateral discussion should occur. (For the purposes of these simulations, the result of that discussion is approximated with an "agreement" that the spacecraft with a higher NORAD ID will take responsibility to maneuver.) These SSC rules are outlined in Figure 2. [7].

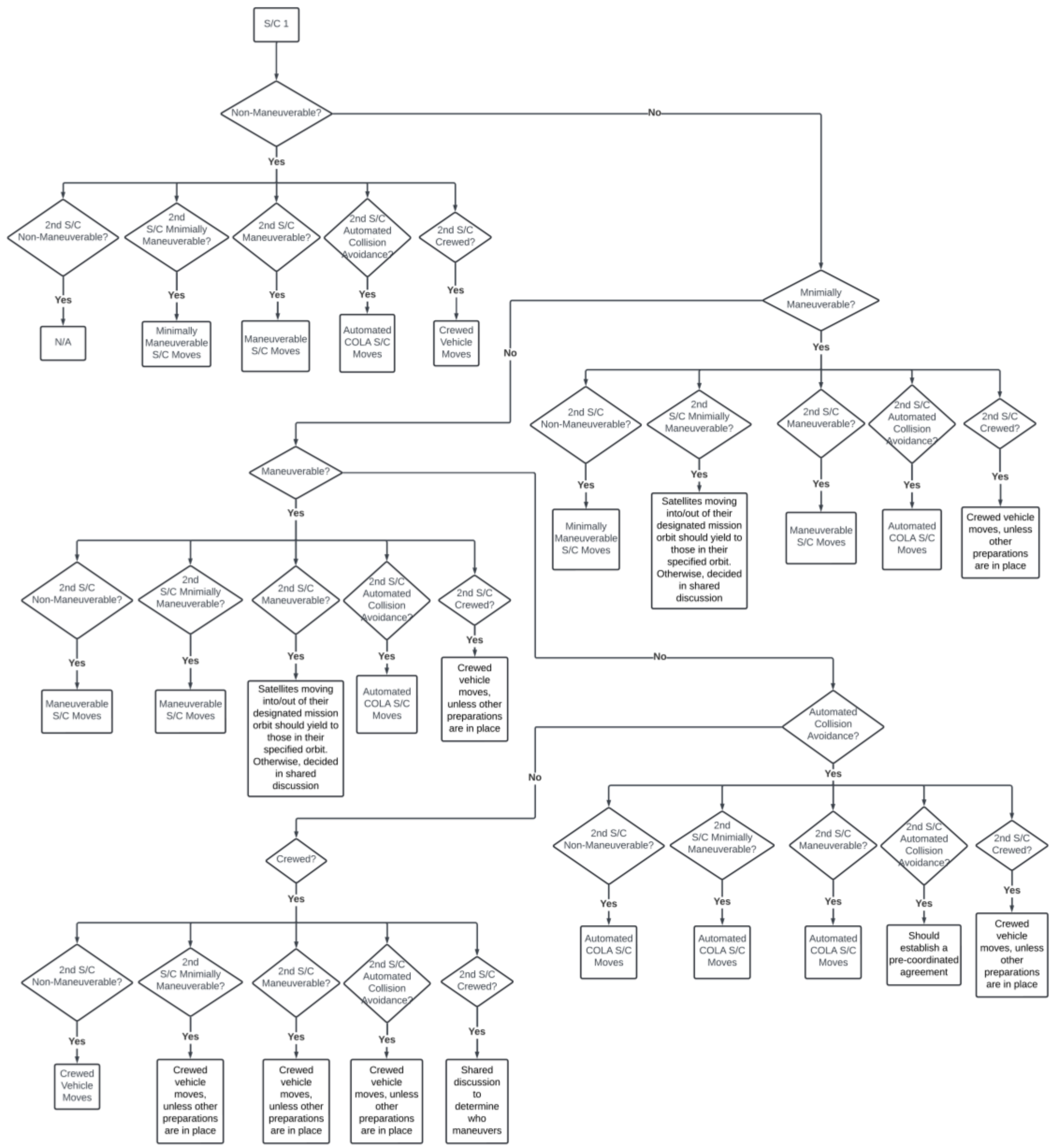

Figure 2. Summary of the Space Safety Coalition Space Debris Mitigation Guidelines [7].

Table 2. Distribution of Spacecraft by Maneuverability

SSC Maneuverability Type	Number of satellites	
Non-maneuverable	804	1.2%
Minimally maneuverable	339	0.5%
Maneuverable	2200	3.3%
Automatic collision avoidance	64183	95.0%
Crewed	2	0.003%

The categorization of the satellites used in the future catalog in terms of SSC maneuverability are described in Table 2. For this table, satellites from the Planet constellation, as well as university satellites, were assigned as minimally maneuverable (presumably able to use differential drag for limited maneuvering). Objects such as rocket bodies or other debris objects were designated as non-maneuverable. All other satellites in the Other subgroup that were not already part of one of the large constellations were labeled at normally maneuverable. Large constellations are already beginning to leverage automated maneuvering, due to the large number of intra-constellation maneuvers that must take place. For this reason, we assume that by 2030, all large constellations will have implemented automated maneuvering. This results in about 95% of all spacecraft in orbit falling into the automated maneuvering category, as shown above. In conjunctions between satellites that are both in large constellations, the responsibility to maneuver is determined based on the NORAD ID, specifically the spacecraft with the higher NORAD ID maneuvers.

3.3.2. Geometric Option

An alternate right of way strategy was proposed by Burgis et al [8] that was originally designed with the Iridium constellation satellites in mind. The maneuver is based on the relative position at the time of closest approach of the two spacecraft, and essentially directs the spacecraft that is at a higher altitude to speed up, further increasing its altitude, while the lower altitude spacecraft (the spacecraft closer to Earth) would conduct a retro burn to further lower its altitude. In mathematical terms, this maneuver relies on rectilinear equations to determine burn direction based on the desired miss distance required to meet a certain degree of probability of collision (Pc). The equation returned is quadratic and yields two roots of the opposite sign corresponding to Figure 4a. The root with the smallest absolute value indicates the direction to move such that the object does not cross the intersection “O”. If the corresponding root belongs to the primary satellite, the primary satellite will burn prograde while the secondary spacecraft will burn retrograde (blue line case). Likewise, the reverse is true when the root belongs to the secondary spacecraft (purple line case). In Figure 3a, A, B and C, D represent the distances of the primary and secondary spacecraft to the intersection point, M* represents the miss distance, and Vp/Vs represents the velocity planes.

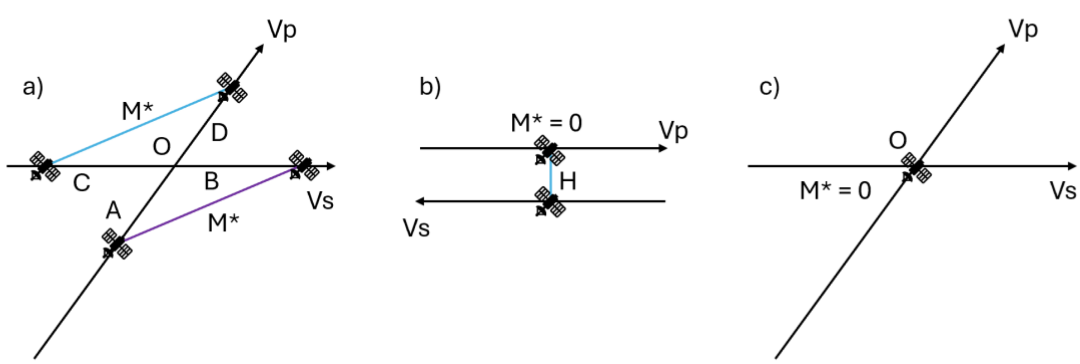

Figure 3. Geometric Maneuver Cases Based on Quadratic Roots, with a) describing the prograde (blue) and retrograde (purple) primary maneuver, b) scenario with perfect velocity alignment (higher object always burning prograde), and c) the case with zero intersection distance (higher catalog number burning prograde).

When the roots of the equation simplify to a height separation vector plus or minus the desired miss distance, Figure 3b is produced. The figure showcases perfect velocity alignment, meaning there is no triangle that needs to be solved and thus the higher object will burn prograde and the lower object will burn retrograde always. In Figure 3b, M* is replaced with a new variable, “H”, which is used to instead represent additional separation distance. Finally, Figure 3c shows the case if the distance of the intersection is found to be zero, the object with the higher catalog number will perform a retrograde maneuver while the secondary object will perform a prograde maneuver. It is worth noting that an intersection value of exactly zero is extremely rare and has not been encountered in the last 11 years of Iridium's collision assessment data [8].

3.3.3. Shared Option

A third option is a more simplistic rule in which the two spacecraft involved share the responsibility to maneuver. In a shared maneuver, both satellites are assumed to have knowledge of the conjunction and split the maneuver burden. One satellite would perform an apogee raise maneuver (using either impulse phasing or low-thrust), and the other would perform an apogee lower maneuver, to avoid maneuvering in the same way and creating a secondary conjunction. The notion of the shared maneuver is that each satellite only needs to spend half of the total dV of the CA maneuver, but there is no distinction between type or priority of satellite. This also assumes both satellites involved in the conjunction are maneuverable. In the instances where only one satellite is maneuverable, then the CA maneuver reverts to a single-satellite maneuver.

3.4. Maneuver Types

This study examined two different types of maneuver strategies to explore how different options affect the overall performance and collision risk of the catalog as a whole, or to certain subgroups. The chosen maneuvers certainly do not represent the full spectrum of potential maneuvers possible, and it is recognized that more optimized maneuvers exist, but they do provide insight into what level the choice of maneuver type plays in the development of general STM guidelines. The primary maneuver types include: 1) a phasing maneuver, and 2) a low-thrust maneuver.

3.4.1 Phasing Maneuver

This maneuver is intended to be a straightforward implementation of a CA maneuver that only utilizes an in-track impulse propulsion burn. In its simplest form, if a satellite is travelling in a circular orbit and a small impulse thrust is applied, it will induce a slight change in eccentricity and either raise or lower the apogee depending on whether the impulse is applied in the forward or aft direction. The change in eccentricity changes the orbital period with respect to the nominal circular orbit, either increasing or decreasing the time it takes to complete one orbit. In either case, there is a phasing offset in the time it takes the satellite to return to the same point where the impulse burn took place. Every orbit, the satellite arrives at the point earlier or later, depending on the new orbit period, which translates to a small offset in distance. This distance grows by the same increment with each orbit.

For the simulations in this study, a miss distance of 25 km was established, meaning that the impulse burn of the phasing maneuver was sized so that this miss distance would be achieved by the set action time, e.g., 48 hours. The shorter the action time, the larger the dV would be required to make the 25 km miss distance.

Figure 4 shows how the phasing maneuver results in a small distance offset with each orbit. If desired, after reaching the desired miss distance, an impulse burn in the opposite direction could be used to return the satellite to its original orbital location. This was not done for these simulations; instead, the station keeping maneuvers described earlier were used to eventually return the satellite to its original orbit slot.

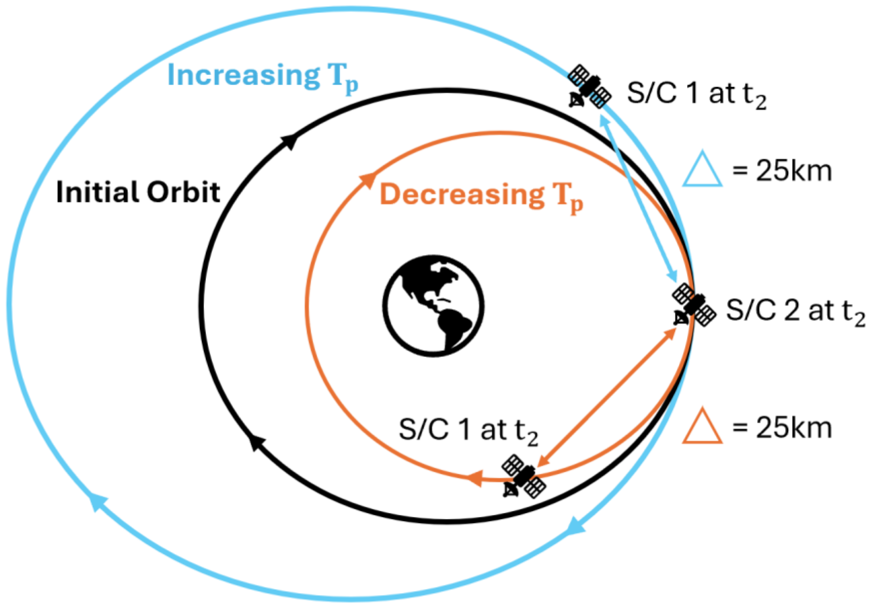

Figure 4. Standard Impulse Phasing Maneuver for both an apogee raise (blue) and apogee lower (orange) maneuver. The change in orbital period, Tp, create a distance offset with each orbit from the original orbit (black).

3.4.3 Low Thrust Maneuver

The low thrust maneuver is implemented to represent the maneuvers that modern constellations currently implement, which utilize more efficient electric propulsion engines and involve a small, constant acceleration over time. Based on the relative efficiency of low-thrust engines, we assume all future large constellations will also use them, and this constitutes approximately 90% of the future satellites modeled. For computational efficiency, while maintaining the same degree of propagation fidelity, the low-thrust maneuver is implemented within the SGP4 framework. Every time-step during a maneuver, a small adjustment is made to the mean motion to slightly raise or lower the altitude of the satellite. The extent of the adjustment is designed to achieve a 25 km miss distance at the predicted TCA.

3.5. **Compliance**

For this analysis, the key independent variable we considered in the simulations was the impact of compliance with a given right of way guideline, i.e. what happens when operators choose not to maneuver, even if a rule suggests that they should. In these cases, for the geometric and shared maneuvers, which require both operators to coordinate on a CA maneuver, if one spacecraft was non-compliant with the rule, no CA maneuver occurred – neither satellite would maneuver. In the case of the SSC guideline, which only requires one operator to maneuver, if one spacecraft was non-compliant, it was assumed that the other spacecraft would undertake a maneuver as long as they had maneuvering capability (e.g. maneuverable, minimally maneuverable, automated maneuvering, or crewed). If the other spacecraft involved was non-maneuverable, it was assumed that no CA maneuver would take place.

To develop an understanding of the impact of variations in compliance, we calculate an expected number of collisions per month, based on the risk associated with predicted conjunctions in which no satellite maneuvers. To do this, we note the risk of collision associated with each of the cases in which no maneuver was undertaken. The probability associated with each of these cases is summed together to determine an expected number of collisions over the course of the month (e.g. 10,000 conjunctions, each with a probability 1e-4, would result in one expected collision that month).

4. RESULTS

4.1. Full Compliance Scenario: Right of Way Rules: Maneuverability (SSC), Geometric, Shared

The first set of simulations involved a comparison of the three approaches to right of way rules discussed above: rules based on maneuverability proposed by the SSC, geometric-based rules, or a simple shared-responsibility rule. In all cases, the threshold for maneuvering was set at a probability of collision of 1/100,000 (i.e., 1e-5) or higher. It is important to note that for the purposes of these results, we do not consider intra-constellation conjunction events. These events (and any risk associated with them) is dropped from the analysis.

Table 3 demonstrates that the total number of conjunctions was relatively consistent across all simulations, and within risk classes. Total conjunctions varied up to 3% between simulations due to randomness in the simulation from the time-varying covariance modeling, as well as secondary conjunctions based on differences in maneuvering. Variation at higher risk levels (e.g. Pc>1/100) is sometimes higher due to the smaller number of conjunctions involved. In Table 4, we see that the total number of maneuvers also varies in a predictable way. When the SSC right of way rules are implemented, and just one satellite maneuvers, the number of maneuvers is very similar to the number of conjunctions. (The number is slightly lower, since some conjunctions involve two non-maneuverable spacecraft, and thus no maneuver is undertaken.) If shared or geometric maneuvers are undertaken, the number of maneuvers is doubled, since two satellites are maneuvering for each conjunction.

Table 4 shows that for the Shared and Geometric guidelines, the number of maneuvers undertaken by each large constellation, or by other satellites overall, is quite similar across runs. This is expected, since maneuverable satellites undertake a CA maneuver in response to every conjunction event in which they are involved. For each large constellation, the proportion of total conjunction events in which they are involved, as shown in Table 4, is not directly related to the proportion of total space objects that constellation represents (as shown in Table 1 above). Once again, this is not surprising, since the number of conjunction events a constellation experiences are related not only to the number of satellites in the constellation, but also to the location of that constellation relative to other satellites. Figure 1 shows that some constellations have more overlap in location than others.

Table 5 provides more insight into which constellations experience frequent interactions, using the example of the simulation implementing the SSC guideline. In particular, Guowang and Kuiper experience a significant number of conjunctions – 746 in this particular scenario. Guowang also experiences 287 conjunctions with Starlink and 345 conjunctions with satellites outside the selected large constellations (i.e., the "Other" subgroup). Starlink's conjunctions, by contrast, are primarily with satellites in the "Other" category, with 876 such conjunctions in this simulation.

When the SSC right of way rules are implemented, there are significant shifts in the number and proportion of maneuvers that each of the major constellations undertakes. The decrease in total maneuvers is expected, since only one satellite is maneuvering in response to each conjunction, rather than two in the other simulations. However, shifts in the proportion of maneuvers undertaken are related to the specific implementation of the SSC guidelines. In this case, we see that satellites in the "Other" category rarely maneuver. This makes sense, since those satellites are less maneuverable than large constellation satellites. For this reason, maneuvers only occur in conjunctions involving two satellites from the "Other" category. In some cases, if neither satellite is maneuverable, no maneuver occurs. All maneuvers that involve a large constellation satellite and a non-large constellation satellite (the "Other" category) now require a maneuver to be undertaken by the large constellation satellite. For constellations that see frequent interactions with "Other" category satellites, such as Starlink, Guowang, and Astra, this results in an increase in their proportion of maneuvers.

When it comes to conjunctions involving satellites from two different large constellations, because the maneuverability is the same, in this simulation, the maneuver responsibility is determined by the NORAD ID. These were assigned such that Guowang has the highest NORAD ID, followed by Astra, Kuiper, Starlink, and OneWeb (see Table 1). For this reason, in this simulation, Guowang will take responsibility to maneuver any time it is involved in one of these conjunction events, resulting in that constellation taking on more than half of all maneuvers. This also results in Kuiper, for example, taking on a relatively low proportion of all maneuvers. While this particular distribution of maneuvers among large constellations is an artifact of the way NORAD IDs were assigned to systems in the model, alternative possibilities can be considered by examining the distribution of conjunctions shown in Table 5.

Table 3: Total conjunctions for different right of way guidelines

Guideline	Pc > 1E-2	1E-2 > Pc > 1E-3	1E-3 > Pc > 1E-4	1E-4 > Pc > 1E-5	Sum
Geometric	43	280	899	1320	2542
Shared	28	282	914	1385	2609
SSC	28	302	920	1398	2648

Table 4: Total maneuvers for different right of way guidelines (full compliance)

Guideline	Starlink	Astra	Guowang	OneWeb	Kuiper	Other	Sum
Geometric	1033	291	1305	33	794	1626	5082
Geometric %	20%	6%	26%	1%	16%	32%	
Shared	1033	291	1305	33	794	1626	5082
Shared %	20%	6%	26%	1%	16%	32%	
SSC	780	294	1437	0	111	44	2666
SSC %	29%	11%	54%	0%	4%	2%	

Table 5: Distribution of conjunctions by subgroup (SSC Simulation, full compliance)

Secondary	Starlink	Astra	Guowang	OneWeb	Kuiper	Other	Sum
Starlink	N/A	18	287	3	3	876	**1187**
Astra	18	N/A	0	1	0	266	**285**
GuoWang	287	0	N/A	27	746	345	**1405**
OneWeb	3	1	27	N/A	5	5	**41**
Kuiper	3	0	746	5	N/A	81	**835**
Other	876	266	345	5	81	46	**1619**
Sum	**1187**	**285**	**1405**	**41**	**835**	**1619**	**5372**
	22.10%	**5.31%**	**26.15%**	**0.76%**	**15.54%**	**30.14%**	

4.2. Non-Compliance of an Entire Constellation

The first non-compliance scenario that was investigated focused on the case in which one large constellation did not comply with the SSC guidelines. The Guowang constellation was chosen as non-complying in this hypothetical scenario, representing a situation in which U.S. and western-owned constellations choose to follow the SSC-developed guidelines, but they not are not successful in coordinating with the Chinese constellation operator to secure their compliance. The results are summarized in Tables 6 and 7.

Table 6: Distribution of Pc when one constellation is non-compliant

Guideline	One Constellation Non-Compliant	Pc > 1E-2	1E-2 > Pc > 1E-3	1E-3 > Pc > 1E-4	1E-4 > Pc > 1E-5	Sum
SSC	n	28	302	920	1398	2648
SSC	y	26	257	968	1464	2715

Table 7: Maneuvers when one constellation never conducts maneuvers

Guideline	One Constellation Non-Compliant	Starlink	Astra	Guowang	OneWeb	Kuiper	Other	Sum
SSC	n	780	294	1437	0	111	44	2666
SSC	y	1100	305	0	25	869	415	2714

Table 6 highlights that the total number and Pc distribution of conjunctions is approximately the same between the baseline and non-compliance cases, which is expected. Table 7 shows the distribution of maneuvers by the various subgroups. When Guowang satellites do not maneuver, we see a significant increase in the number of maneuvers undertaken by satellites in the Starlink, Kuiper, and Other subgroups. The Astra and OneWeb constellations are less affected, primarily due to the low overlap in orbit parameters between Guowang and these constellations (see Figure 1). This can also be seen in Table 5, where Guowang satellites primarily conjunct with Starlink (287 conjunctions), Kuiper (746 conjunctions), and satellites in the Other category (345 conjunctions). As observed in Table 7, these relative conjunctions counts are essentially added to each subgroup when the Guowang constellation no longer maneuvers.

In addition to the shift of responsibility to maneuver to other operators, the non-compliance of a large constellation also results in a small increased risk of collision. Even in the baseline case, in which all spacecraft comply, there is still some small risk of collision, because some conjunctions occur between two non-maneuverable spacecraft. The expected number of collisions is computed here as the sum of all Pc's from conjunctions in which no maneuver was performed. For the baseline case, this was essentially zero, as shown in Table 8, since nearly all conjunctions involve a maneuvering spacecraft in that scenario. For the case in which one large constellation (in this case, Guowang) never maneuvers, the expected number of collisions over the course of one month is 0.018, consisting of just 18 events, noting that this value is dominated by a single event with a Pc near 1e-2. As with the baseline case, the collision risk in this case is still very small because the other spacecraft involved in these conjunctions were nearly all maneuverable.

Table 8: Expected value of a collision when one constellation is non-compliant

Guideline	One Constellation Non-Compliant	Expected Value (Month)	Expected Value (Year)
SSC	n	0.000	0.000
SSC	y	0.018	0.237

4.3. US-only Compliance

An additional variant explored was the situation in which only US operators complied with the SSC guidelines. As the US currently operates the largest percentage of spacecraft, and should continue to do so in the near future, this scenario would assess the impact if the US were to implement a set of guidelines unilaterally. For the simulations, this meant that the Guowang and OneWeb constellation, as well as 3,162 non-US satellites in the "Other" subgroup, would not maneuver even if the guidelines directed it, but the US-operated spacecraft would have the opportunity to perform a CA maneuver if they were maneuverable. The results in terms of maneuver total and total expected collisions are shown below in Tables 9 and 10.

Table 9: Distribution of Maneuvers with US-only compliance

Guideline	Starlink	Astra	Guowang	OneWeb	Kuiper	Other	Sum
SSC	780	294	1437	0	111	44	2666
SSC (US-only)	1180	328	0	0	962	500	2970

Table 10: Expected value of a collision with US-only compliance

Guideline	Expected Value (Month)	Expected Value (Year)
SSC	0.000	0.000
SSC (US-only)	0.099	1.285

The results are similar to the case of Section 4.2, where the Guowang constellation did not comply, in that the distribution of maneuvers is shifted to other subgroups. In particular, the Starlink, Kuiper, and Other subgroup absorb the majority of the added maneuver responsibility. There are slightly more events without a maneuver at 219 for this case, which increased the estimated annual collision rate to approximately 1-2 collisions per year.

4.4. Randomized compliance

As a final test of the impact of compliance with right of way guidelines, a series of randomized cases were run in which only a percentage of the designated satellites actually performed the maneuver. Compliance percentages at the 50%, 75%, and 100% were evaluated, summarized in Tables 11 and 12. As in previous scenarios, for the SSC guideline, if the right of way guidelines designated a satellite to maneuver, and that satellite did not comply, then it was assumed that the other satellite would perform a CA maneuver as long as it was capable of maneuvering. For the shared and geometric guidelines, non-compliance meant no maneuver was performed by either satellite for that conjunction.

Table 11: Conjunctions with randomized compliance

Guideline	Compliance	Pc > 1E-2	1E-2 > Pc > 1E-3	1E-3 > Pc > 1E-4	1E-4 > Pc > 1E-5	Sum
Geometric	100	43	280	899	1320	2542
Geometric	75	33	298	897	1374	2602
Geometric	50	38	278	927	1375	2618
Shared	100	28	282	914	1385	2609
Shared	75	34	289	922	1323	2568
Shared	50	29	282	948	1428	2687
SSC	100	28	302	920	1398	2648
SSC	75	31	301	954	1416	2702
SSC	50	43	333	973	1492	2841

Table 12: Expected value of a collision with randomized compliance

Guideline	Compliance	Expected Value (Month)	Expected Value (Year)
Geometric	100	0.000	0.000
Geometric	75	0.353	4.598
Geometric	50	0.676	8.819
Shared	100	0.000	0.000
Shared	75	0.357	4.653
Shared	50	0.863	11.255
SSC	100	0.000	0.000
SSC	75	0.011	0.145
SSC	50	0.042	0.553

In terms of risk, the expected number of collisions jumps quite noticeably for the shared and geometric guidelines, even if just a quarter of operators choose not to undertake maneuvers. For example, when compliance drops to 75%, we expect to see 4 to 5 collisions each per year. If only half of operators maneuver in accordance with right of way rules, we see 8 to 11 collisions per year. For the SSC guideline, the expected collisions are much lower, since for this guideline the second satellite is given the opportunity to maneuver. In a relative sense, there is a near doubling of the collision risk for the SSC guideline when going from 75% to 50% compliance, which is also observed in the shared and geometric cases. The annual collision rate for the SSC guideline at 50% compliance is not negligible at 0.553 (i.e., one collision every two years), but does highlight that some resiliency can be achieved even with relatively high levels of non-compliance.

5. DISCUSSION

The results of these initial simulations highlighted some important observations in terms of the impact of compliance on the behavior of the various right of way guidelines, and on the overall collision risk for a future space object population. The first is that the choice of right of way guideline can have a significant impact on the distribution of maneuvers. For example, Table 4 showed strong variations in maneuver counts between constellation satellites and those in the Other subgroup depending on the guideline implemented. That said, the assignment of NORAD IDs was arbitrary when the extended catalog was assembled, with values grouped sequentially by constellation (see Table 1), which is not likely how the values would be assigned in practice. This assignment impacted the behavior of certain maneuver guidelines, e.g., if both satellites were in the same category, such as an automated maneuverable satellite in the SSC guidelines, the maneuver burden was assigned to the satellite with the higher NORAD ID (i.e., the newer satellite maneuvered, since NORAD IDs are typically assigned once a satellite reaches orbit). Since these IDs are grouped by constellation, this unevenly distributed maneuvers to certain constellations. Future work will look into more realistic distributions of NORAD ID if it continues to factor into maneuver guidelines.

A second observation taken from the simulations is that when a large constellation does not comply with a given guideline, the maneuver burden shifted to other operators, with some subgroups being disproportionally affected (Table 9). The overall collision risk of the population remained low, however, under the assumption that a high percentage of the population was maneuverable and that they were given the notification and time to respond to the non-complying spacecraft (see Table 10).

The experiments involving random compliance were a coarse attempt to assess intermittent compliance due to a variety of potential reasons, such as communication interruptions, differences in operator risk postures, human error, or any other cause. Not surprisingly, as the percentage of compliance dropped, the rate of expected collisions increased, with a peak rate of up to 11 annual collisions for the shared guideline. The collision rate depended heavily on the chosen guideline, with the SSC guideline showing much lower collision rates (0.553/yr) due to its rule set. These cases underscored the importance of compliance and/or maneuverability by all operators to successfully mitigate collisions. Worth noting is that the object catalog considered consisted almost entirely of full-sized operational spacecraft, as well as a selection of the larger known debris objects (rocket bodies, etc.), which carry a larger fragmentation risk. Furthermore, the collision rates simulated here would be in addition to any conjunctions involving smaller debris objects.

The simulations made use of time-varying covariances based on historical orbit determination data in an effort to provide greater covariance realism. Comparing these relatively new covariance estimates with other methods showed them to be significantly smaller than other methods, which reduced the number of estimated conjunctions. While the overall number of estimated conjunctions may have reduced, the dilution associated with larger covariances would have also been diminished, which presumably resulted in more accurate Pc calculations. It is suspected that this may have also contributed to the relatively consistent range of Pc distributions across the various cases (see, e.g., Table 11), which in turn may have limited the variability of performance across the difference guidelines. Additional work is needed to implement more appropriately sized time-varying covariances that better represent those seen operationally. That said, when 95% of the spacecraft population fall into the same category (e.g, automated maneuvering), then the differences between the guidelines will be naturally limited, and will mostly affect non-constellation satellites.

6. CONCLUSION

This study explored the impact of compliance on a select set of right of way guidelines using Georgia Tech's Virtual Environment for Space Traffic Analysis (VESTA) simulation tool. A potential future space object catalog was developed from publicly available data sources, which included the current set of 7,992 resident space objects, along with approximately 60,000 additional satellites spread across five large constellation operators. Three right of way guidelines were incorporated into a series of month-long simulations, which included a simple shared-maneuver approach, a geometric-based guideline, and a guideline based on spacecraft maneuverability proposed by the Space Safety Coalition (SSC). VESTA was used to implement each guideline with a robust set of modeling capabilities, to include full force modeling, station-keeping, and impulse/low-thrust propulsion options. Throughout the simulation, meta-data was collected for every conjunction, and maneuvers were conducted in accordance to the right of way guideline and with varying degrees of compliance. As such, each simulation was a unique and dynamically evolving scenario. Compliance scenarios covered the spectrum of full compliance to only participation of select large constellation operators to a randomized participation rate. While more work is needed to explore a wider set of test cases and simulation parameters, the results obtained did highlight the importance of global compliance by space operators regardless of the adopted right of way guideline. Lack of compliance by individual constellation operators resulted in a maximum of 5-11 estimated collisions per year between active satellites (largely excluding collisions with debris, which would create additional collision events), but also demonstrated that these could be heavily mitigated when more spacecraft are maneuverable. In addition, the lack of compliance was shown to disproportionally affect other constellation or individual satellite operators.

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