An investigation into potential collision maneuver guidelines for future Space Traffic Management

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Abstract

As the number of objects in space has increased in recent years, the number of conjunction warnings has also grown significantly. However, formal guidelines to manage or coordinate responses to these warnings have yet to be adopted. As both industry and government agencies across the globe seek to utilize the near-Earth space environment with a variety of large satellite constellations, the total number of Resident Space Objects (RSOs) is projected to increase by a factor of five in the coming decade, with over 20,000 new satellites in Low Earth Orbit (LEO) and Middle Earth Orbit (MEO) projected to be launched into orbit. This is expected to lead to further increases in the number of potential conjunctions. While mission operators strive to ensure all satellites are operational, a certain percentage of these satellites will fail prematurely, creating inactive RSOs that may stay in orbit for years or decades, creating additional hazards not capable of maneuvering. While guidelines are in place for expected deorbit timelines after a satellite's end-of-life, e.g., 25 years, there is still no formal or widely accepted maneuver guidelines to ensure a future crowded LEO and MEO environment can be effectively managed. In the event a conjunction is predicted, the current system relies on satellite operators acting independently, with no requirement for action or for coordination with other operators or agencies.

If a set of formal maneuver guidelines were developed and adopted, the hypothesis is that the space environment could be well managed and would be able to sustain the current growth pattern in new satellites. This leads to the questions of what guidelines should be adopted, how they should be implemented, and how they should be enforced or monitored. To begin addressing these questions, this study seeks to explore the impact various "rules of the road" would have if implemented in future Space Traffic Management (STM) policy. We have developed a robust simulation environment in which the current RSO catalog is included and propagated in real-time to assess the frequency and circumstance (active vs. passive object, small vs. large object, nation of origin, etc.) of predicted collisions. Various collision avoidance guidelines were then implemented to evaluate their effectiveness in terms of both the number of predicted collisions, as well as other metrics, such as fuel costs.

Simulation parameters included, among others, the number of satellites involved, latencies in maneuver notification, and rate of maneuver compliance. The propagation of the satellite orbits used a full force-model approach, including non-spherical gravity, drag, solar radiation pressure, and 3rd-body effects, and spanned a time frame of one month. While collision avoidance among active satellites can be achieved with 100% compliance among satellite operators, the situation becomes more nuanced as various scenarios are explored when participation is varied, and when the maneuvering satellite is determined through a priority ranking, e.g., with lower-priority satellites assuming a larger role in the maneuver. This paper provides an overview of the simulation environment and guidelines evaluated, as well as an initial assessment on the relative effectiveness of the policies and scenarios that were modeled.

1.0 Introduction

After years of steady growth, the number of active satellites in orbit has increased dramatically in the past five years, jumping from fewer than 1,500 in 2016 to more than 4,000 in 2021. This rapid growth is expected to continue, with the development of new "megaconstellations," adding an estimated 20,000 new satellites over the next decade. As the number of objects in space increases, the likelihood of accidental collisions also increases. Collisions can damage or destroy valuable space assets, resulting in financial losses for satellite owners, and potentially degrading

or disrupting essential services – communications, weather, or navigation, for example – for people on the ground. Such collisions also generate significant amounts of debris, adding to the more than 20,000 existing pieces of debris already in orbit, and further increasing the likelihood of future collisions.

Avoiding these collisions requires accurate data, advanced warning, and coordinated action among satellite operators. Currently, the United States Space Command manages the largest global space surveillance network, conducts conjunction analysis for all operational satellites, and provides conjunction warnings free of charge for all space operators. Commercial actors, other nations, and international organizations also provide some of these services. While there is room for improvement in data collection, analysis, and communication of warnings, the existing system successfully provides key services.

The same cannot be said for coordinated action among satellite operators. Currently, there is no agreed-upon process or set of principles that govern whether, when, or how satellite operators should maneuver their spacecraft to avoid a collision. Instead, decisions are made on an ad hoc basis by individual satellite operators. Some operators carefully investigate conjunction warnings, purchasing additional data and analysis services from commercial entities and carefully planning maneuvers. Others may choose not to move their satellite, either because they perceive the risk of collision to be acceptably low, they view the cost (in terms of fuel expended) to be unacceptably high or, in some cases, satellites may not be capable of maneuvering. Efforts to coordinate, if they do occur, are conducted through direct operator-to-operator communications.

The danger of working within this ad hoc system, particularly given the rapid increase of satellites in orbit, was illustrated in September 2019. The European Space Agency (ESA) received a conjunction warning noting there was a 1/1,000 chance of its valuable environmental satellite, Aeolus, colliding with a satellite from SpaceX's Starlink megaconstellation. When ESA reached out to SpaceX to coordinate action, SpaceX did not respond to their message. ESA chose to unilaterally conduct a collision avoidance maneuver. SpaceX later explained that a glitch in their system had caused them to miss the message from ESA [1]. This episode helped to further illustrate the need for Space Traffic Management, defined by the United States as "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment" [2].

2.0 Space Traffic Management

Although current trends in space are making the need for Space Traffic Management more palpable, the need for such a system has long been recognized by experts in both the academic and practitioner communities. In 2004, Nicholas Johnson argued "Proponents of space traffic management should develop an unambiguous set of proposals which could be implemented in a cost-effective manner and would result in a net benefit to space vehicle operators." He identified a number of questions to be answered, such as the level of acceptable risk, rules for "right of way," or the identification of "zones" in space [3].

In 2006, the International Academy of Astronautics (IAA) conducted a Space Traffic Management Study. The expert group concluded a regime was needed to provide traffic management rules, including the prioritization of maneuvers, specific provisions for Low Earth Orbit (LEO) constellations, "right of way" rules, and numerous other elements [4]. William Ailor argued such a system requires government action and the implementation of national regulations. The government must also monitor satellites to ensure actors abide by the rules [5]. Gerie Palanca suggested a new international organization could be created as a "middle man," conducting conjunction analysis and acting as a go-between for operators planning maneuvers [6]. Other authors have focused on the need to improve data [7] or the potential to implement autonomous Space Traffic Management capabilities on spacecraft [8]. Many authors have also identified potential similarities to air traffic management and maritime coordination systems [9].

In 2018, the United States highlighted the importance of this challenge in Space Policy Directive 3: National Space Traffic Management Policy. Among other things, the directive called for the United States to develop Space Traffic Management standards and best practices. The first step would include the development of U.S.-led minimum safety standards and best practices to be adopted in domestic regulatory frameworks. It noted regulations should account for future activities, such as active debris removal and on-orbiting servicing, which require extensive in-space maneuvers [10].

Across all of these articles and reports, there is strong consensus that Space Traffic Management is urgently needed. They identify important issues that need to be addressed within such a system, and offer suggestions on how such a system might be governed. However, they offer very little in terms of specific guidelines that could be included. Authors agree we need "right of way" rules, for example, but what should those rules be? What are the options available? How would various operators be affected by such rules? Which is most efficient overall? This paper seeks to address this gap by examining potential Space Traffic Management regulations and evaluating them using a model of the space environment.

3.0 Methodology

To achieve this goal, we first identify a range of potential space traffic management rules. While there are numerous issues such rules could address – such as zones, de-orbit procedures, or time to respond, in this paper we focus specifically on potential "right of way" rules, developing an array of reasonable rules to be tested. We also add an element of realism by varying the level of compliance with these rules, both by country and as a percentage of all actors. To examine and evaluate the impact of these rules – as well as compliance, we develop a model of the space environment. This model allows us to measure the impact of each rule on the number of conjunction warnings, collisions, and maneuvers needed. This model also examines the distribution of costs associated with the maneuvers – the number of maneuvers and velocity change (deltaV) incurred by each actor.

3.1 Model of the Space Environment

To examine the impact of various potential space traffic management rules, we created a model of the space environment. To ensure the simulations were representative of the truth, the Simplified General Pertubations-4 (SGP4) model [11] was used for high-fidelity orbit propagation of public two-line element (TLE) data from the U.S. Space Force's 18th Space Control Squadron (18th SPCS) [12]. Orbit perturbations considered included non-spherical gravity, drag, solar radiation pressure, and 3rd body effects.

3.2 Model Assumptions

To isolate the impact that the proposed "right of way" rules would create, and limit the trade space of the analysis performed, the simulations kept the following attributes consistent.

- The simulation was constructed from data gathered on August 14, 2021, and run for 30 continuous days, i.e., spanning from 7/14/21 – 8/14/21.
- The resident space objects included in the analysis were limited to those in low-Earth orbit , and included both active and inactive objects. The criteria used to determine inclusion in the set of LEO RSOs were that the mean motion of the objects orbit must be greater than 11.25 and that the orbit's eccentricity was less than 0.25. This resulted in 17,455 unique RSOs included in the simulations.
- Based on protocols used to generate the 18th SPCS "Concern list," a conjunction event was declared if two satellites would pass by each other within a 5 km range with a collision probability of 1e-7 or greater [13]. This assumption could be varied in future work to understand the trade-off between collision risk and total maneuvering costs, but is kept constant here. (We recognize other thresholds – such as a 1 km range and a collision probability of 1e-4 – are used in some other analyses; however, for the purposes of this study, our main focus is on the relative performance across scenarios, so the absolute number of conjunction warnings issued is of less importance.)
- The conjunction predictions were made with a 3-day propagation time, simulating a 3-day advance conjunction warning for a satellite operator.
- Upon receiving a conjunction warning, it was assumed operators would need one day to decide whether to maneuver and to command the satellite. As a result, any maneuver performed was assumed to be done over a 48-hour window.

From an initial starting point, the simulations checked for conjunction events every two minutes, which was the default time interval used in the analysis. Rigorously propagating and checking for conjunctions at this short interval with 17,455 objects is computationally intensive, so a series of preliminary checks were instigated to quickly eliminate objects that would never come within close proximity of each other in the 3-day moving window used to check for conjunctions. We used an adaption of the "Smart Sieve" approach originally developed by Rodriquez et al (2002) for this, with more complete details provided in Macke et al (2021) [14]. While the calculation of miss distance is one indicator of the number of potential conjunctions, collision probability was also computed, as this is a metric that more closely determines whether two objects will actually collide. The method outlined by Alfano and Oltrogge (2018) was used to compute this probability, involving the calculation and

propagation of a covariance ellipse of the RSOs current position and velocity forward in time to determine whether another RSO's orbit will cross a projected uncertainly plane. To create the covariance ellipse for each RSO, historical TLE data was used over the equivalent propagation time, which in this study was 3 days, to estimate variances of position and velocity.

For a number of the scenarios explored, it was important to have additional meta-data on the objects involved in the conjunctions, such as the country of origin, satellite mass/dimension, owner-type (military, civilian, etc.), and active/inactive status. This information was partially obtained from the 18th SPCS public archive, but also from the Union of Concerned Scientists' Satellite Database (UCSSD) [15], the NORAD Satellite Situation Report, and the European Space Agency DISCOS database [16]. The attributes for each Resident Space Object (RSO) were recorded for each computed conjunction to help evaluate the impact of any rules on specific groups or sectors.

In the event of a predicted conjunction, and assuming the satellites can be actively controlled, one or both of the satellite operators may elect to conduct an evasive maneuver. The maneuver strategy adopted in this study was a basic phasing maneuver in which the satellite performs a small in-plane thrust commensurate with the time-frame (2-day) required to move the spacecraft outside of the collision range (> 5 km). After the conjunction event has passed, a restoring movement is then applied to maneuver the satellite back to its original orbit configuration. The total velocity change required for these maneuvers is tracked, as well as the number of maneuvers each satellite performs. It is possible the initial orbit maneuver creates another conjunction event with another RSO. To account for this, a "satisficing" approach was developed which calculates these secondary conjunctions and adjusts the first phasing maneuver appropriately. These secondary conjunctions are also recorded to evaluate the down-stream impact of any maneuver strategy.

For conjunctions with two active satellites, the satellites could share the maneuver, or only one satellite would maneuver given a set of rules (priority, country, etc.). While it is optimal to have 100% compliance in the maneuvers, a random compliance factor was also implemented to explore situations in which operators only partially comply with maneuvers from a conjunction event, e.g., only 50% of operators maneuver when given a conjunction warning.

Additional assumptions were also made. For example, while we recognize some operational satellites, such as small university CubeSats, are not capable of maneuvering, we do not include this complexity in the current model. All satellites are assumed to be capable of maneuvering. (This assumption could be updated for future research. Its impact could help to identify the value of a regulation requiring that all satellites be maneuverable.) We also assume perfect knowledge among operators regarding relevant attributes of space objects (as described in section 4.0 below). In reality, such information could be provided as part of a conjunction warning or through globally available registries.

3.3 Model Baseline: Worst Case, Status Quo, and Best Case

As a baseline for comparison of right of way rules, we ran three models. One represents a "worst case" scenario in which satellites never maneuver. The second model aims to approximate the current status quo. In this model, "right of way" is determined randomly by the model. This approximates the current situation in which there is no agreement on priority or right of way rules, and satellite operators themselves determine whether or not to maneuver based on their own internal criteria. We also set compliance to 50%, i.e., maneuvers are only conducted for half of all potential conjunctions. This level was chosen to approximate the current situation in which operators may not choose to maneuver at all, despite a conjunction warning. (This percentage is necessarily an educated guess. In reality, there is no clear information regarding how often operators choose to maneuver in response to a conjunction warning.) A final, "best case" scenario implements the same random maneuvering priority as the status quo model, but assumes 100% compliance – all conjunctions will result in a maneuver to eliminate the collision risk.

3.4. Evaluation Metrics

The following metrics are used to evaluate the results of the model when implementing different STM rules:

1. ***Expected number of collisions involving active satellites:*** A key metric in evaluating these rules is the number of expected collisions each month This is calculated by adding together the probability of collision for every conjunction detected in the model. In the case that the "right of way" rules are followed with 100% compliance by all space operators, we expect to see zero expected collisions; maneuvers are undertaken to avoid all potential collisions. However, this metric becomes more useful when evaluating

cases with less than full compliance. Even without full compliance, given our relatively short timeline (30 days), we expect to see very few actual collisions during the model run. However, fractional values can still be usefully compared to each other to understand relative differences across various model instantiations.

2. ***Number of conjunction warnings with a risk above 1/10,000,000:*** We track the number of conjunction warnings that would be generated at a risk threshold of 1/10,000,000. This metric helps us to understand how the total number of conjunction warnings provided to operators varies depending on the rules imposed. We expect the number of conjunction warnings to be relatively consistent across models, with slight changes due to follow-on conjunctions caused by earlier maneuvers. We also breakdown this metric by country and operator type to understand the distribution of these warnings across users.
3. ***Number of maneuvers required:*** We track the number of maneuvers required. In the full compliance model, the number of maneuvers will be equal to the number of conjunction warnings with risk above 1/10,000,000, since operators are required to maneuver. However, when there is not full compliance, this number will differ. Understanding this metric allows us to determine the total "costs" of a given rule. The distribution of those costs can be examined by breaking this metric down by country or owner-type (military, civil government, commercial, other).
4. ***Total Delta-V required for maneuver:*** We calculate the amount of delta-V required for each maneuver undertaken in the model. This correlates to the fuel cost of the maneuver, and gives us a more precise way of measuring the costs. Once again, the distribution of these costs can be calculated by country or owner-type.

By looking at these four metrics for each rule implemented in the model, as well as a base case, we can understand the relative trade-offs between risks (expected number of collisions) and costs (conjunction warnings received, number of maneuvers completed, and delta-v required).

3.5 Descriptive Statistics

Before describing the results of the simulations, it's useful to provide a few statistics that help to describe the satellites represented in the database. There are 67 nations that own and/or operate satellites in Low Earth Orbit (commercial satellites are represented by the country in which the company resides). Fig 1 shows this breakdown. The United States accounts for about 67% of all satellites in the database, followed by China with 10%, the United Kingdom with 6%, and Russia with 3%.

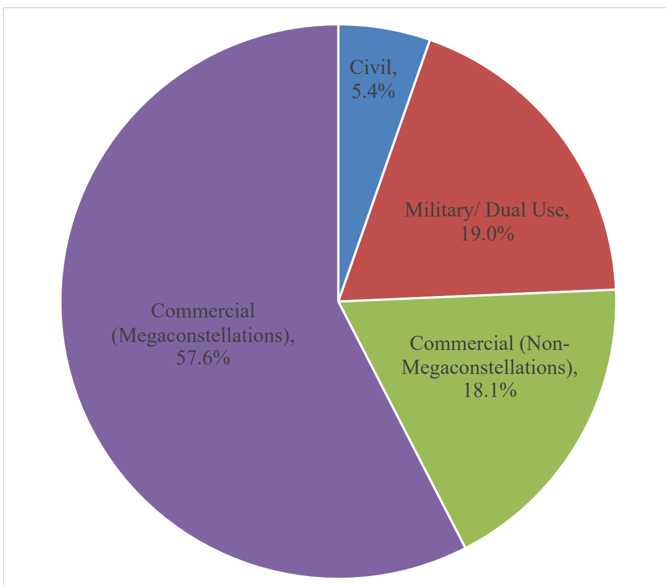

Fig 1. Distribution of all LEO Satellites by User-Type

In both the United States and the United Kingdom, commercial satellites represent more than 90% of the satellites lofted by the country, as shown in Fig 2. This is largely due to the impact of megaconstellations. The United Kingdom is home to the OneWeb system. SpaceX, Planet, and Spire all have large constellations developed in the

United States. These four constellations make up 57.5% of all satellites in LEO. The user-type break down for each country is shown in Fig 3.

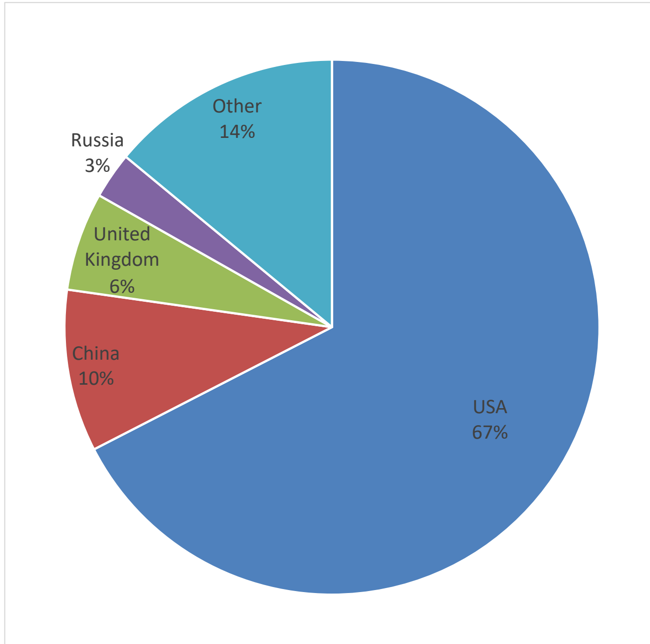

Fig 2. Distribution of LEO Satellites by Country

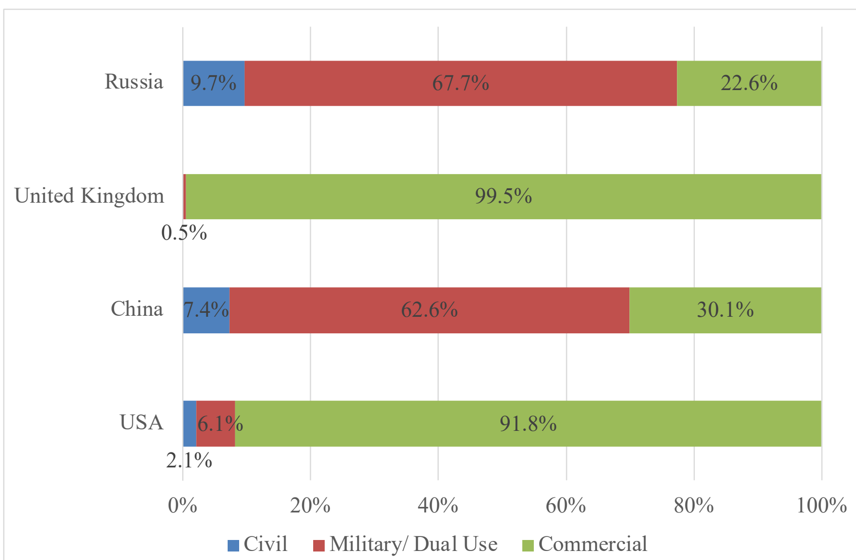

Fig 3. Distribution of Satellites by User-Type for Top Four Countries Operating Satellites

4.0 "Right of Way" Rules for Space

Right of way rules are perhaps one of the most basic, but also most critical, element of a Space Traffic Management Regime. Just as actors must understand which vehicle is supposed to move first at a traffic intersection on the ground, or which ship has priority in a busy port at sea, space actors should have a clear understanding of their responsibilities to maneuver in the event of a potential conjunction in orbit. We examine the impact of rules that vary based on satellite mass and satellite value. We also look at the impact of adding a prioritization regime based on the type of owner (government, commercial, or non-profit/ university). Finally, we examine the impact of adding

a regulation that requires mega-constellation satellites to maneuver in all cases. Details on each of these variations, and the reasoning behind them, is described below.

Right of way based on value

Value is approximated based on the mass and age of the satellite, using the formula

(1) Priority value = (60 - (2021 – [satellite launch year]))*[satellite mass]

with larger, newer satellites having high value and older, smaller satellites having lower value.

1. More valuable satellite maneuvers: In this regime, the more valuable satellite is required to maneuver. This reflects the idea that more valuable satellites are likely more capable of maneuvering: The valuable satellite is more likely to have thrusters, and it is likely to have a larger number of operations personnel associated with a single spacecraft. The operator of a more valuable spacecraft also has a greater incentive to maneuver, because losses from a collision would be large.
2. Less valuable satellite maneuvers: The opposite rule could be imposed instead. An argument in favor of this rule is based on the fact that a less massive satellite could use less fuel to maneuver, increasing the efficiency of the regime as a whole. It also aligns with the idea that large, expensive satellites should not be required to expend fuel to "save" smaller, cheaper satellites.

Prioritization by owner-type, then value

Under this rule, priority would be determined first based on the owner-type of the satellite – military, civil government, or commercial, or other. If both satellites are of the same type, then responsibility to maneuver falls to the satellite with the greatest value (as described above).

3. Priority order - Military, Civil government, Commercial: Under this rule, if a military satellite is involved in a conjunction warning, it must maneuver. If no military satellite is involved, then a civil government satellite must maneuver. If no civil government satellite is involved, then the commercial spacecraft must maneuver. The logic behind this rule is the government (and particularly the military) has the greatest ability to absorb the costs of maneuvering and also typically has significant human resources to enable these activities. Given the importance of government space assets, which often carry out critical public activities such as reconnaissance or weather, they have a large incentive to avoid collisions. This could reflect the fact that, as the creator of regulations, the government may have the most responsibility to put them into action.
4. Priority order - Commercial, Civil government, Military: For this rule, if a commercial satellite is involved in a conjunction warning, it must maneuver. If no commercial satellites are involved, then civil government spacecraft must maneuver. If no civil government satellite is involved, then the military satellite must maneuver. The logic behind this rule is because commercial entities are operating based on a profit motive, they have a responsibility to fully absorb the costs their activities impose on the space environment (e.g. pay the costs of maneuvering to avoid causing collisions). The government, by contrast, operates spacecraft for the public good and as part of national critical infrastructure, and thus should not be required to use additional fuel to avoid collisions. Further, because military satellites are the "most" critical assets, other spacecraft (e.g. civil spacecraft) should maneuver around them.

5.0 Model Compliance

In our initial models, we assumed full global compliance with the rules. In reality, it is unlikely all space actors will perfectly implement a given Space Traffic Management rule. Therefore, we re-ran our models considering different types and levels of compliance. We breakdown compliance in two ways: by country and by percentage.

Country-based Compliance: The case of country-based compliance recognizes a globally accepted Space Traffic Management regime may be difficult to achieve. It may be more practical to begin with a smaller scope. For this reason, we consider the following compliance cases:

1. U.S.-only: This represents the case in which the United States chooses to act as a first-mover, implementing a Space Traffic Management regulation through domestic law. Under this regime, satellites associated with the United States (government, commercial, or other) fully comply with the rule, while other actors never maneuver.

Percentage-based Compliance: Another way to consider compliance is based on a percentage across all users. This can be used to represent a case in which STM rules are set up as voluntary guidelines, for example. It may also represent how compliance may be difficult to monitor or enforce, resulting in less than perfect compliance.

Table 1. Full Set of Model Runs

	Rule	**Compliance by Country**	**Compliance by Percentage**
Baseline	Worst Case: No satellites maneuver	NA	NA
	Status Quo: Right of way is randomly assigned	Global	50%
	Best Case: Right of way is randomly assigned	Global	100%
Value	More valuable satellite maneuvers	Global	100%
	Less valuable satellite maneuvers	Global	100%
User-type	Priority order - Military, Civil government, Commercial, Other (If same, then more valuable satellite maneuvers)	Global	100%
	Priority order - Commercial, Other (Non-profit/ university), Civil government, Military (If same, then more valuable satellite maneuvers)	Global	100%
Country-based Compliance	More valuable satellite maneuvers	U.S. only	100%
Percentage-based Compliance	More valuable satellite maneuvers	Global	50%

6.0 Analysis and Discussion

In our baseline "worst case" scenario, in which a potential conjunction is identified when two satellites pass by each other within a 5 km range with a collision probability of 1e-7 or greater, and no maneuvers are undertaken, we find a total of 560 conjunctions involving two active satellites. An additional 120 conjunctions involve one active satellite and one piece of debris. We found the total number of conjunctions was similar across all cases, as expected.

We also find that Megaconstellation satellites are over-represented among the conjunctions identified in the model. Megaconstellation satellites account for 1171 of the 1240 (non-unique) satellites involved in these conjunctions: 94.4% of the satellites involved in these conjunctions involve megaconstellation satellites.

Our comparison of right-of-way rules focuses on the relative performance of the scenarios according to total DeltaV (e.g. efficiency of the rule) and total collision probability (effectiveness of the rule). Because total collision probability is zero in cases of perfect compliance, we focus on relative differences in DeltaV for the first set of scenarios. We then examine how differences in compliance affect total collision probability.

6.1 Relative Efficiency of Right-of-Way Rules

When comparing the relative efficiency of right-of-way rules, we looked at five scenarios:

1. More valuable satellite maneuvers, U.S.-only compliance
2. More valuable satellite maneuvers, full compliance
3. Priority order - Military, Civil government, Commercial, Other (If same, then more valuable satellite maneuvers), full compliance
4. Priority order - Commercial, Other (Non-profit/ university), Civil government, Military (If same, then more valuable satellite maneuvers), full compliance

The least efficient scenario was the one in which the more massive satellite maneuvers first and there is full compliance with the rule. This is not surprising, as larger satellites are going to require more DeltaV to move than smaller satellites.

Our preliminary analysis suggests a 10.1% decrease in the total DeltaV for the system as a whole can be achieved by adding a priority order that required commercial satellites to move first, followed by civil and military satellites. Changing the priority to military, civil, commercial was slightly more efficient – 12.4% better than simply moving the most massive satellite. The result was the same when using only satellite value (approximated using a metric representing mass and age) is used to determine priority – i.e. the more valuable (larger, newer) satellite maneuvers. This model was also 12.4% better than maneuvering the most massive satellite.

The most significant gains occurred in the model in which the more valuable satellite maneuvers, but only U.S. satellites are compliant with the rule. This rule required 31.2% less DeltaV than the rule in which the more massive satellite maneuvers. This is nearly 20 percentage points higher than the value-based rule with full-compliance. The exact reason for this is still being explored, but the particular subset of maneuvering satellites for this case is dominated by satellites from megaconstellations, which tend to have lower relative mass, and would likely require less DeltaV to maneuver. Overall, the analysis does demonstrate that having a priority-based system has a noticeable impact on the overall efficiency of the STM strategy, at least in terms of total DeltaV.

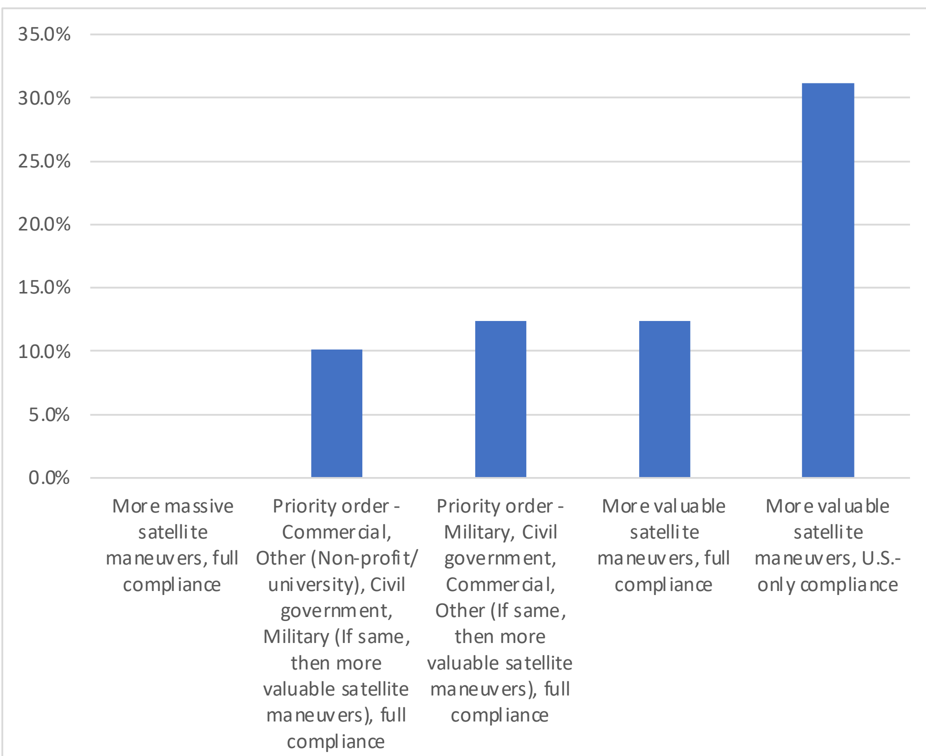

Fig 4. Percentage improvements in efficiency (decreases in DeltaV) compared to scenario in which more massive satellite maneuvers.

6.2 Relative Effectiveness under Different Compliance Regimes

In our baseline "worst case" scenario, in which no maneuvers are undertaken, we calculate a total collision probability for two active satellites of 0.256. This suggests, in the current system, if no maneuvers were undertaken, we would expect to see about one collision every four months. By contrast, in the scenario for which only the U.S. is compliant with right-of-way rules (i.e. only U.S. satellite maneuvers), this probability is reduced to 0.00053. The significant reduction is not too surprising, given that of the 560 conjunctions involving two active satellites, only three did not involve a U.S. satellite.

We also examined the impact of percentage-based compliance with right-of-way rules. Essentially, for each conjunction, each satellite operator has a certain percentage likelihood of complying with the rule (that percentage is defined for the scenario). This is representative of the fact that it is difficult – perhaps impossible – to achieve perfect compliance for various reasons. It also roughly accounts for the number of active satellites not maneuverable.

For this analysis, we focused on the general scenario involving conjunctions between two maneuvering satellites. When we varied compliance from 0% to 100% in 5% increments, and examined the results from a Monte Carlo run of 1000 realizations (to reduce the effect of randomness) at each level, we find the impact of compliance on total collision probability is quite linear. The higher the percentage of compliance, the lower the total collision probability. This suggests there is value in pursuing efforts to gain high compliance, as we do not see a clear point of diminishing returns.

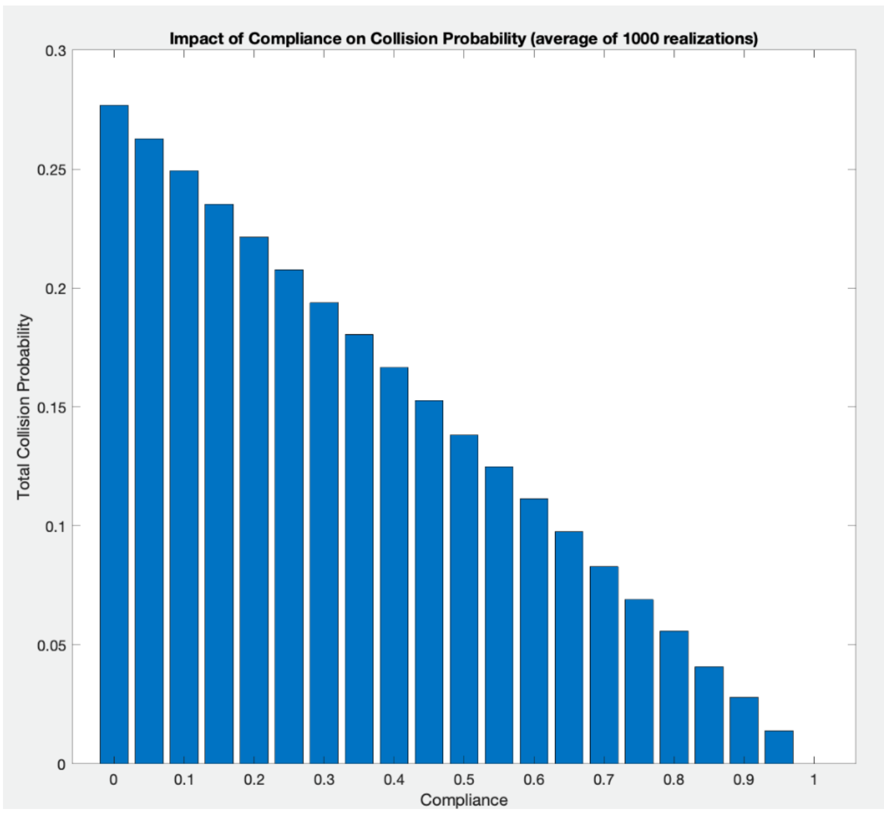

Fig 5. Probability of collision based on compliance of satellites for the case of two maneuvering satellites.

6.3 Discussion

There are a number of important take-aways we can gather from this analysis. First, the comparison of the efficiency of various rules suggested there are significant differences in efficiency across different rules. While political issues will still arise – e.g. does the military want to always have responsibility for maneuvering, or would they prefer to rarely maneuver in order to preserve fuel – this suggests it is worthwhile to also consider the efficiency of the maneuver.

The very high proportion of conjunctions involving megaconstellation satellites – disproportionately high compared to their representation among orbital objects – suggests that the ways rules affect megaconstellations will dominate the efficiency of the system. Since our analysis suggests moving smaller satellites may be more efficient, and because megaconstellation satellites are often quite small, a rule in which megaconstellation satellites are always required to maneuver may be the most efficient. As noted above, this may also be more fair, since these systems put a relatively large burden on the system. It also seems to have some tacit support from SpaceX, which has already committed to moving Starlink satellites autonomously in the case of any potential conjunction.

The analysis of compliance demonstrated a U.S.-only compliance system would make a significant impact on reducing the collision risks in orbit. This suggests it would be worthwhile for the United States to put in place STM rules in domestic law. This action would significantly improve the safety and sustainability of the space environment, as shown by the model. Since these benefits are shared by all space users, this could improve U.S. soft power, and put the United States in a position to be a leader in developing a global STM regime.

The examination of percentage-based compliance suggested that among any given actor, there is value in increasing compliance with the STM regime. While some nations or types of users may contribute more heavily to the number of conjunctions, and thus the potential reduction in risk, ensuring higher levels of compliance will continue to provide meaningful benefits within the system. Given this situation, it may be beneficial for nations to consider putting in place methods for monitoring and enforcing compliance. Such efforts would likely need to occur within domestic law, and would be consistent with the Outer Space Treaty's requirement that states provide continuing supervision of non-governmental entities in space.

7.0 Conclusions and Future Research

In this paper, we have identified a number of reasonable right-of-way rules that could be adopted as part of a Space Traffic Management regime. Using a model of the space environment, we have tested these rules to determine their efficiency (in terms of total DeltaV) and effectiveness (in terms of total expected collision risk). We found the choice of rules can have a significant impact on the efficiency of the system – something to which all space operators are sensitive. In general, requiring smaller satellites to maneuver will provide more efficient results. This suggests a system in which megaconstellations (typically made up of many small satellites) take responsibility for maneuvering in the case of conjunctions, may be a relatively efficient solution. Of course, there will also be many political considerations that must be taken into account, as well as, including national security, trust among spacecraft operators, and issues of compliance.

With respect to compliance, we find there is strong support for the U.S. taking unilateral action to put in place STM rules for domestic actors. Such action would significantly decrease the total risk of collision in space, benefiting all space actors. It would also provide the United States with experience and moral authority in the development of a global STM regime.

We believe the results from this initial analysis are interesting and important. However, we believe this approach can be improved and applied to a wide variety of other STM issues. For example, we would like to incorporate information on which satellites are capable of maneuvering, and examine the impact of this limitation on STM. We would also like to project the system forward – adding, in particular, additional planned and licensed mega-constellations to examine their impact on the system and the efficiency of various rules.

It is important to emphasize the results presented here are preliminary, and more work is needed to verify and expand the simulations before a formal set of guidelines would be proposed. For example, in this analysis, we kept the threshold for maneuvering constant. However, in future models, we could vary this level to try to understand the trade-off between the number of maneuvers required (and associated DeltaV) and the collision risk. Additional improvements are planned regarding how priority values are assigned, better classification of satellites into their appropriate user-type, and gathering statistics over longer simulation time frames (6 months, 1 year). While it is ideal to minimize collision risk as much as possible, it is also important operators are not inundated with requirements to maneuver to an extent that is too costly or simply impractical due to available resources. It would also be possible to examine more complex rules for requiring maneuvers – such as those that consider not only the likelihood of collision, but also the potential severity of such a collision (e.g. how much debris would be created).

We could vary the number of days in advance that warnings are issued, the type of maneuver performed, and the time operators have in which to make these maneuvers. Shorter warning times provide greater certainty in terms of risk level, but decrease time for coordination and planning, impacting DeltaV requirements, as maneuvers need to be made more quickly. The model could also be adjusted to approximate the implementation of an automated STM system.

Finally, we could use the model environment to examine the importance of data accuracy. If we can improve the precision of spacecraft tracking, or increase the number of objects that are detectable, how does this affect our ability to efficiently and effectively carry out STM actions?

There is broad agreement around the world that Space Traffic Management – and particularly more systematic cooperation among spacecraft operators – is urgently needed. In this paper, we have taken a first step in identifying and evaluating concrete aspects of such a system. As the launch of new spacecraft, including megaconstallations, becomes more frequent, the current ad hoc system for coordination among spacecraft operators will no longer be sufficient. As the number of possible conjunctions increases with every new satellite placed into orbit, these frequent risks will become impossible for operators to manage. A new system must be implemented to avoid collisions and keep a safe space environment. We hope this analysis will provide a first step in defining the form that system may take and identifying trade-offs among concrete options.

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