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SPACE TRAFFIC MANAGEMENT IN THE AGE OF NEW SPACE

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Abstract

New Space activity includes large LEO constellations, or LLCs, and small satellites such as CubeSats. It will radically change space operations and, combined with new sensor systems, will necessitate changes in the way space traffic management is conducted. For example, there are multiple constellations each with thousands of satellites being proposed to provide global broadband Internet services. A common feature of these LLCs is their concentration of satellites into small altitude regions in the Low Earth Orbit (LEO) regime, where orbits are lower than 2000 km above the Earth's surface. They can therefore pose a collision risk to other satellites residing either nearby or passing through such altitudes. Similarly, the disposal of these satellites when they reach end-of-mission life poses a potential risk to other satellites at altitudes away from the operational LLC altitudes. New sensor systems such as the Space Fence are also expected to add large numbers of smaller, previously untracked objects to the US Space Surveillance Network (SSN) catalog. As a result, both the constellation owners and other LEO operators will have to deal with increasing numbers of both collisions and conjunction alerts. Any Space Traffic Management (STM) system will have to take this New Space activity into consideration.

Space Traffic Management

Since the late 1990s, technology advancements have enabled high-functioning satellites to be much smaller and lighter. Coupled with similar improvements in launch technology, large numbers of new operators have gained access to space and have been placing an ever-growing number of satellites into orbit. Some of these new operators do not have extensive experience in space and are employing novel methods of satellite design, construction, and operation which could potentially lower levels of satellite reliability and increase the possibility of failures.

Compounding the problem, the Chinese Fengyun-1C anti-satellite test in 2007 and the Iridium-33/Cosmos-2251 accidental collision of 2009 doubled the amount of tracked debris (objects larger than 10 cm) that is on-orbit (Figure 1) plus added an even greater number of objects smaller than 10 cm that are not tracked but can affect the lifetime of operational satellites. The Cosmos-Iridium collision underscored the effects of accidental collisions in space and demonstrated the need for a consistent and unified system for all satellites to avoid future collisions. Ensuring that operational satellites can operate in a populated environment

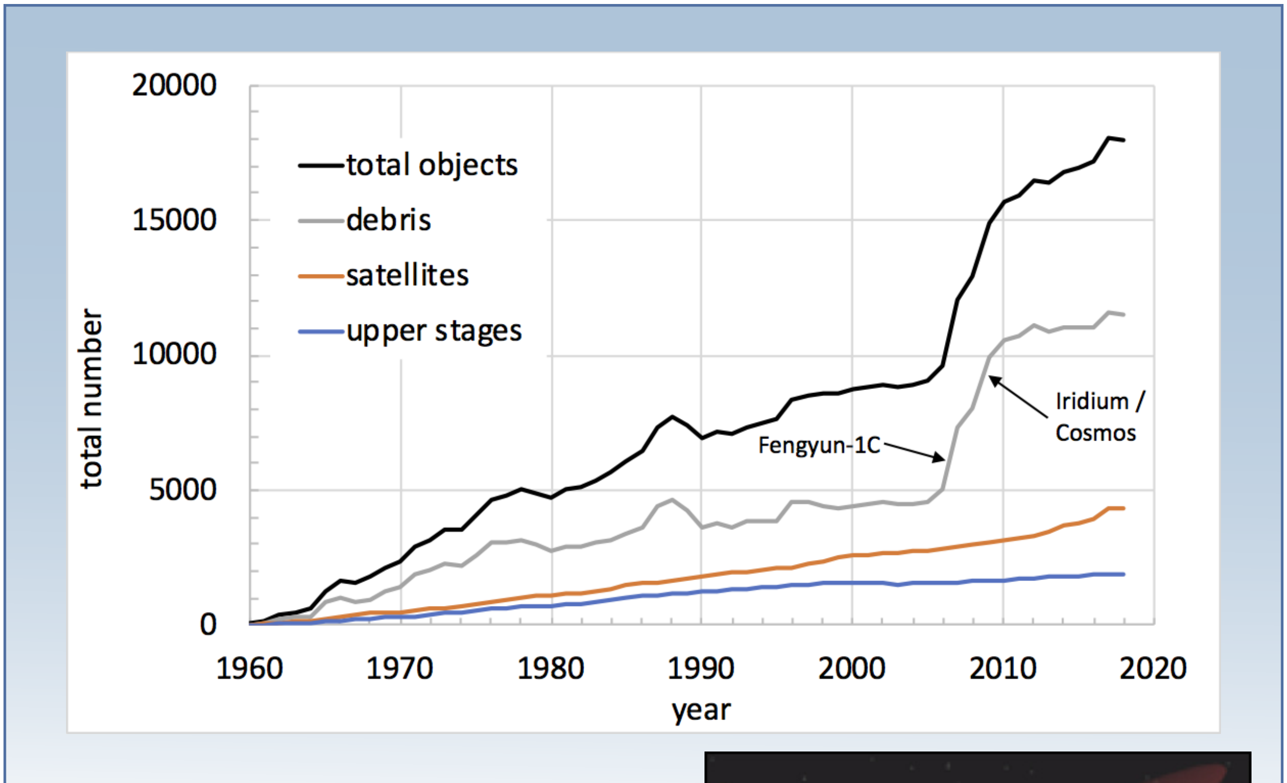

Figure 1: Number of objects in SSN catalog. The number of these objects has increased significantly during the past decade.

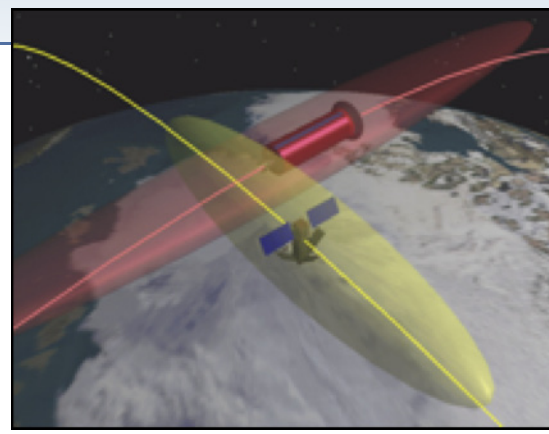

Figure 1b: Conjunction between two objects with uncertainty bubbles (Illustrative purposes only: bubbles are typically much larger than shown here).

without a high risk of collision is a priority, both for current operators and for future operators who might have to face the debris from future collisions. Thus, the goal for any current or future STM system is this: limit the risk of collision.

Any system for avoiding collisions attempts to limit the risk by tracking individual objects and identifying close approaches (conjunctions) between any two of them. Both objects can be in orbit or one can be launching while the other is orbiting. Since tracking systems are not perfect and cannot predict the exact orbits of objects, there is uncertainty in the predictability of object locations during a conjunction. As a result, there is a predicted location for each object, but in reality, the object could actually be anywhere within an oblong "bubble" surrounding that predicted location (Figure 1b).

The uncertainties that form this bubble are the result of a combination of inaccuracies in the sensor measurements and errors in predicting how the object will move in its orbit to the point of the conjunction. In general, the bigger the uncertainty bubble (or covariance), the greater the number of false alarm conjunctions an STM system will produce. Once a conjunction is identified, the risk of collision is computed considering the intersection of the uncertainty bubbles, and the STM provider or owner/operator must then decide whether or not to take action. Some actions might be to request more observations to try to get a better orbit estimate and shrink the uncertainty, coordinate with the owner/operator of the other object should it be another operational satellite, and/or plan and execute an avoidance maneuver.

The US Air Force 18th Space Control Squadron currently generates warnings in the form of Conjunction Data Messages (CDMs) and sends them out to

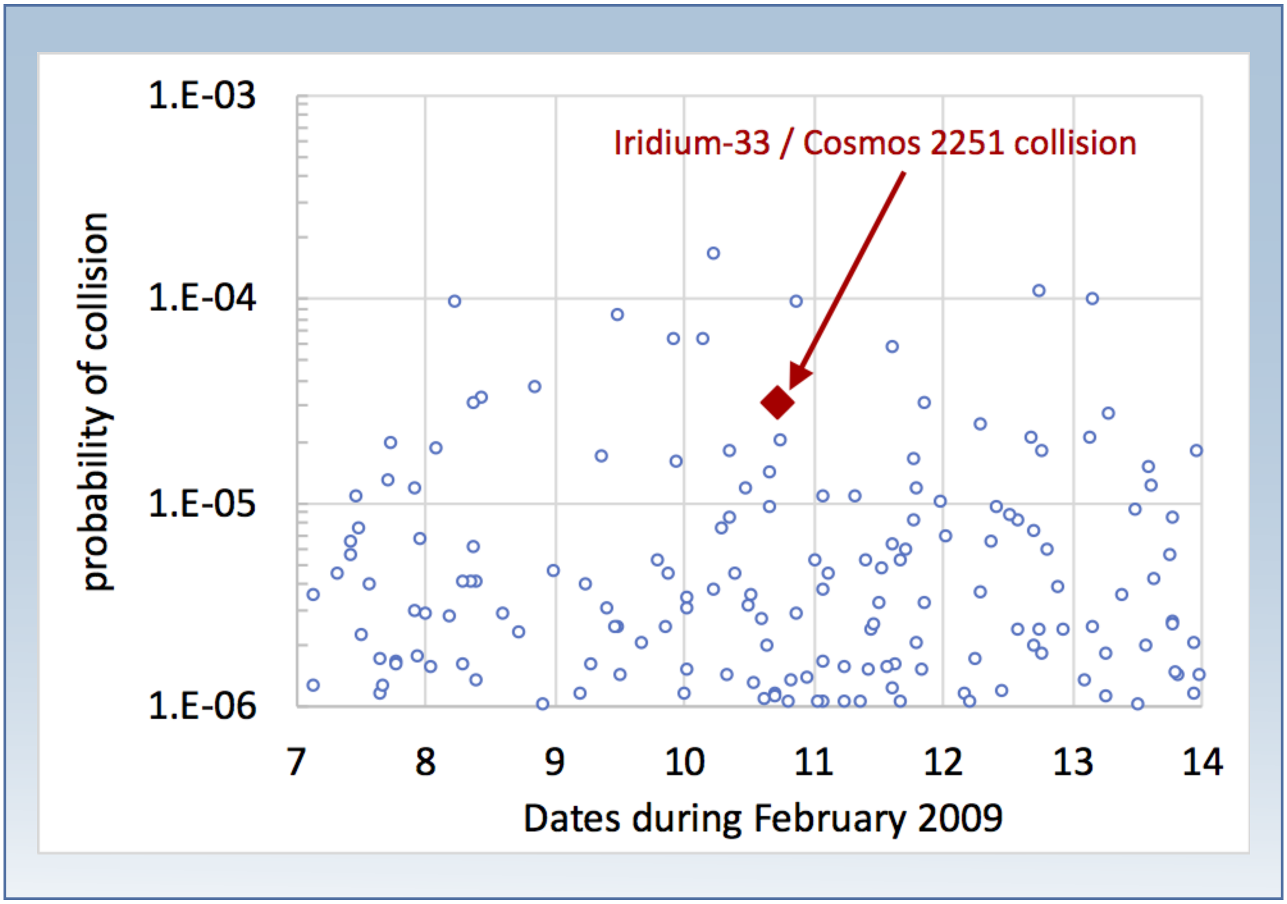

Figure 2: Iridium constellation conjunction probabilities during week of Feb 7, 2009. Under current tracking accuracies, the actual collision between Iridium-33 and Cosmos 2251 did not stand out from other conjunctions that week as being noticeably dangerous.

operators around the world. Those individual operators may have their own conjunction assessment methods to respond to the risk. Each of the potential responses to a high-risk conjunction may entail different actions by different parts of the organization, but they all require some type of resource to be expended by the owner (tracking resources, extra analyst attention, spacecraft fuel, potential disruption of the satellite's mission, etc.). Therefore, avoiding false alarms is a priority. The uncertainty bubble is the major driver for the number of false alarms, and currently objects are tracked to a level that is several orders of magnitude larger than the objects themselves. This makes operational decisions difficult: the decision-maker is faced with possibly negatively affecting operations based on levels of collision risk that are on the order of 1 in 100,000 to 1 in 10,000.

The February 9, 2009 collision of the operational Iridium-33 with the inactive Cosmos 2251 spacecraft noted earlier is a good example of the current situation. Under current tracking accuracies, that particular conjunction had a 3 in 100,000 probability of collision.[1] However, when considering the Iridium constellation as a whole, there were a total of 37 other conjunctions during that same week whose risk of collision exceeded 1 in 100,000. One conjunction probability was almost an order of magnitude higher at 2 in 10,000 (Figure 2). Clearly, the data available to Iridium satellite operators in this case was not sufficient to make a decision.

So, how should an operator respond when faced with this situation? Mission analysts cannot respond to large numbers of alerts that look dangerous but are not, as that would consume too many resources. A related problem is the complacency that naturally occurs when the mission analysts are inundated with large numbers of alerts that turn out to be false alarms. Yet operators must do what they can to protect their spacecraft, the spacecraft of other operators, and the future space environment in general. Therefore, identifying conjunctions that are truly dangerous without generating an excessive number of false alarms is crucial for any STM system.

What is Changing

Compounding the current STM situation is the expected growth in the number of satellites that will be launched in the near future. The number of objects orbiting the Earth has grown substantially in recent years (Figure 1) with well over 90% being dead objects (inoperative satellites, spent upper stages, and fragmentation debris). Multiple commercial companies (SpaceX, OneWeb, Theia, Boeing, etc.) have announced plans to place constellations of up to thousands of satellites in LEO (altitudes up to 2,000 km). If all of these plans materialize, the population of operational satellites in LEO would jump by over a factor of ten—from ~1000 today to over 16000 within the next 10 to 20 years.[2,14] This would almost double the objects being tracked by the Space Surveillance Network (SSN). Since most of these proposed large LEO constellations (LLCs) would operate in narrow altitude bands, the satellites of other operators with altitudes either near or crossing these LLC altitudes may have to deal with large numbers of conjunctions themselves.

As with existing satellites, these new satellites should be disposed at the end of their missions, and, if the constellation continues to operate, they will need to be replenished. At the end of their missions these companies plan to dispose of their satellites by moving to lower orbits to reduce their orbital lifetimes. In addition, many of these systems plan to move replacement satellites from lower temporary check-out orbits, which are beneficial in cases of early failure, to higher operational orbits. Any of these maneuver profiles will result in LLC satellites passing through the operational orbits of other satellites that do not explicitly reside at the primary operational LLC altitude, for example, the International Space Station and potentially other crewed assets. Failures among these transiting, disposal, and operational satellites may eventually add dozens to hundreds of additional dead objects to those orbits. Even if the LLC satellites have very low failure rates individually, the overall number of failures could be high due to the large numbers of satellites in the constellation or if there is a systemic design flaw. Launching all of these satellites could also place numerous upper stages into Earth orbit.

The use of CubeSats and other small satellites has also grown dramatically in the last few years. In 2017, over 400 CubeSats and other small satellites were deposited as secondary payloads by dozens of different entities. Many of the small satellite operators are new to the space business, so reliability of these vehicles is uncertain and their success in disposal could be less than the overall historical trend. The orbits for these small satellites are spread out in space and so they, like disposed or failed LLC satellites, could pose a risk to many other operators as well.[3] Collectively, these large constellations, small satellites, and launch activities are referred to as New Space.

Tracking improvements currently underway, such as the United States Air Force Space Fence or proposed commercial systems, will provide enhanced ability to track objects in LEO smaller than the current SSN limit of approximately 10 cm (4 inches). These upgrades will add many tens-of-thousands of new objects to the SSN catalog above and beyond any LLC activity. While upgraded tracking will help in reducing uncertainty of many orbiting objects, it will also add many more new objects to the catalog, some of which will be at the limits of tracking resolution and therefore have highly uncertain orbits. These objects are already in orbit now; yet they are not observable with the current USG tracking systems. Their addition to the SSN catalog does not introduce new risk to existing satellites as those smaller objects are already there, just unseen, but it will add a burden to any STM collision avoidance system.

The introduction of New Space satellites, upper stages, and upgraded tracking systems could overload STM systems. Figure 3 shows how our knowledge of the spatial density of tracked objects, the average number of objects in a volume of space, could change in the next decade given the New Space activity and improved tracking capabilities. STM service providers will need to predict close approaches of a much greater number of debris objects with a larger number of operating satellites, and this will cause a corresponding increase in the number of conjunction warnings. At some altitudes, the number of conjunction alerts could increase by a factor of ten over the current situation. Reducing this number of alerts to a reasonable level while maintaining the necessary capability to detect upcoming collisions will require an improved STM system.

Possible Solutions

There are many possible individual solutions to the STM issue, but they can be grouped into two general categories: minimizing the growth in the number of

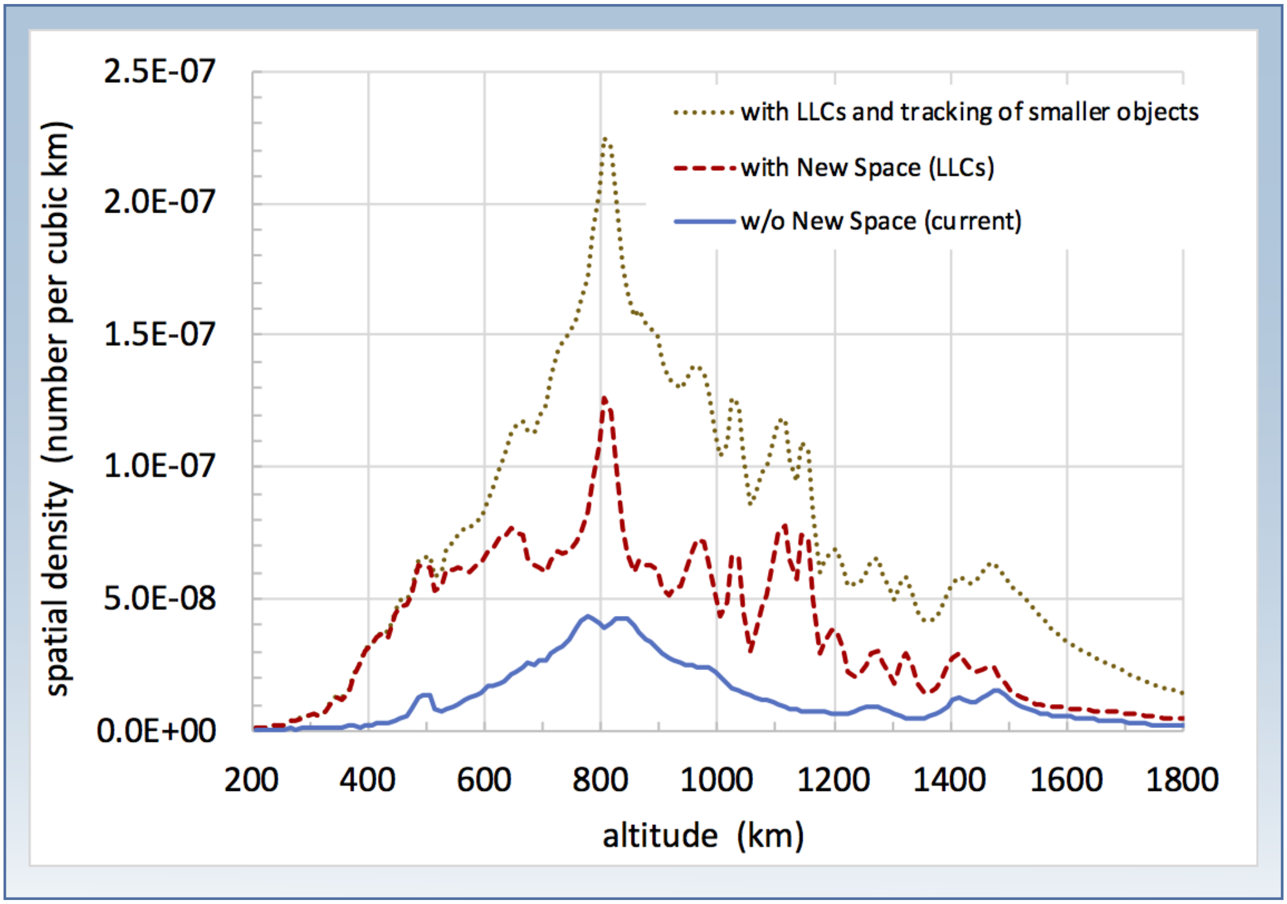

Figure 3: Spatial density of objects in LEO with and without New Space activity. Adding New Space LLCs will increase the density at all altitudes due to replenishment, disposal, and failed satellites. Adding the smaller objects that would appear with an improved tracking system could increase the density at all altitudes even more.

future objects (mostly debris) and reducing the orbit uncertainty through improved observations and additional operator data.

Minimize the future population growth. Post-mission disposal is one mechanism by which the future growth of objects in space can be controlled. The United States Government Orbital Debris Mitigation Standard Practice[4] (ODMSP), referenced in the 2010 National Space Policy[5] requires that US agencies' satellites in LEO should, at the end of their mission, be placed onto orbits that "limit the lifetime to no longer than 25 years, or be moved to a storage disposal orbit above LEO"[4] Similar rules are applied to US licensed commercial satellites through the Federal Communications Commission (FCC)[6]. Several LLC operators have realized that placing their satellites on 25-year decay orbits will still cause a substantial increase in the debris over the long term due to the large number of the LLC satellites, their mass, and the altitude regime they must transit to re-enter. Their response has been to develop disposal profiles to remove their satellites in a much shorter timeframe (months to a few years). Shortening the time to re-entry of New Space satellites will help reduce the conjunction assessment burden on STM systems to some degree, but it is even more beneficial to inhibiting the long-term growth of debris.

Active debris removal has been proposed as a mechanism for "cleaning" space by directly removing debris. However, as a post-collision effort, it is of limited value simply because the debris spreads too far too fast to be retrieved effectively without interfering with other operational satellites. As a pre-collision effort, there is no crystal ball to see into the future and know definitively what objects are going to collide. As a result, any active debris removal system will have to remove objects based upon a statistical potential to add debris to the environment. This reality makes target selection difficult and will result in the removal of many objects that would not have been involved in a future collision. In general, the likelihood of an object to create debris is dependent on the size and mass of the object and the population of its immediate surroundings (i.e., how many other objects are passing nearby).[9] A large object in a dense environment has a higher likelihood of creating a lot of debris in the future and so is more desirable as a removal target. Active debris removal is more effective in reducing the long-term growth of debris, and hence helping far-future STM systems, than assisting current or near-future STM.

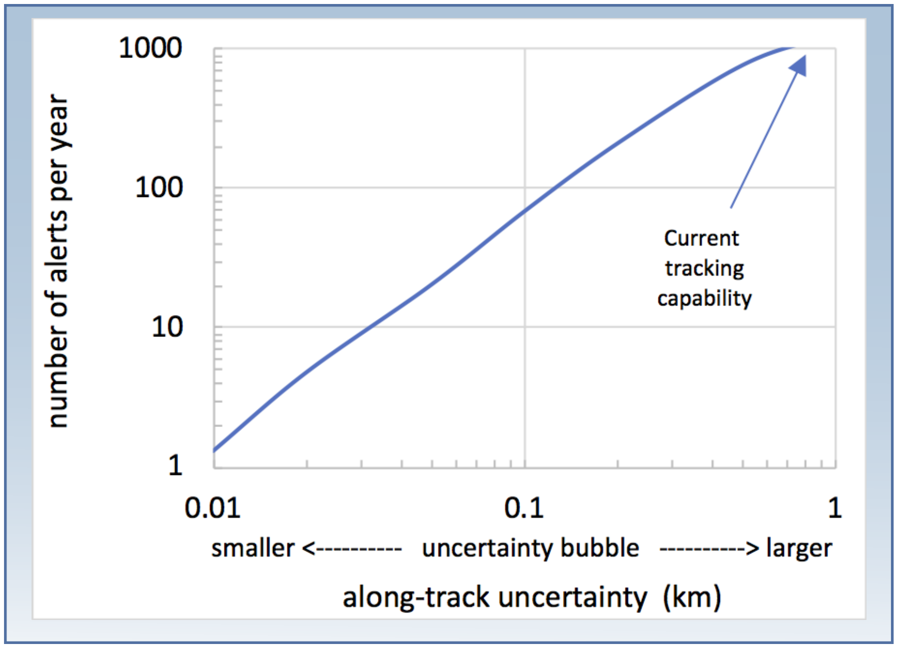

Figure 4: Annual number of expected alerts for Iridium constellation using a threshold probability of 1 in 100,000.

Improved/additional data and processing. For the near-term STM problem, the most effective mechanism for reducing false alarms while still identifying truly dangerous conjunctions is reducing the size of the orbit uncertainty bubble through improved tracking. This reduction could be accomplished by various methods: increasing the quality of observations, increasing observation frequency, ingesting operator orbit data, including satellite maneuver plans, and improving modeling of orbit evolution.

Some of these methods may be appropriate for some sub-groups of the orbiting population but not others. For example, transponders and/or retroreflectors are being proposed for satellites and upper stages[5] but would not be possible for either currently existing objects or any future fragmentation debris (which makes up the vast majority of expected future objects). By reducing uncertainty, the probability of collision for actual collisions will increase while the probability of collision for false alarms will decrease. With the smaller uncertainty bubble, we can more confidently predict where a satellite will be in the future. At some point, the truly dangerous conjunctions will consistently stand out from the background and the STM system will provide more actionable alerts and fewer false alarms. However, if any such improved system can detect smaller objects that have highly uncertain orbits, the problem will remain for those objects. The effect of lower uncertainty for many objects must be balanced against the ability to see smaller objects (with larger uncertainty) for an improved STM system to be fully realized.

As an example, a simulation was performed for the Iridium constellation to determine how many conjunction alerts occurred above a probability of collision threshold (1 in 100,000) with the space catalog population during the years 2000-2018. Recall that there was one actual collision during the time frame of data used: with the Cosmos 2251 satellite in 2009. The orbit uncertainty for all objects was fixed as an oblong bubble representative of existing public catalog uncertainties. The uncertainties were then scaled downward in size while keeping the shape of the bubble constant to see how many alerts above the threshold occurred. This simulated the effects of improved tracking. The results are shown in Figure 4. For these assumptions, to get the number of false alerts to be fewer than 1 per month, tracking accuracy uncertainty would need to be improved by a factor of 30. Larger constellations, larger populations of debris or operational satellites in orbit, and the tracking of additional objects will all affect this result. Studies such as this can assist in determining practical requirements for a future traffic management system.

Good-quality data may also be available from other data sources, including tracking systems of foreign nations and private entities as well as high-quality orbit information from satellite operators. Nations operate tracking systems and satellites of their own, and it would be beneficial for any STM system to be able to incorporate this data and process it in a timely manner. However, there are challenges in incorporating data from other sources: integration process, standardization/understanding of formats, policies to allow sharing of data, observation integrity, maintaining reliability of data delivery, etc. In any event, some nations may not want to share all of their data for specific satellites, so they will desire access to the best data to perform their own STM protection of these private satellites. Consequently, a high priority for any STM provider would be to protect proprietary information to address these privacy or security concerns.[10] The Department of Defense has been working on developing mechanisms and identifying tall poles on the data sharing issue through various efforts for several years.[15]

How do we get there?

The following are possible steps in setting a course for an improved STM service:

Assign and define responsibility. Space is an inherently international regime, and improved STM services are required to allow space-faring nations sustainable use of space. Currently the US Air Force 18th Space Control Squadron provides conjunction advisories to virtually all space operators worldwide. There is current debate within the US Government as to whether the Department of Defense will continue to provide this service or if it will be transitioned to a civil government agency. Non-profit or for-profit STM entities may be possible solutions in the long-term. All of these options have advantages and disadvantages that must be weighed. Without a decision on how future responsibilities for STM and the associated data gathering will be organized, it is not possible to effectively move forward with the other necessary changes to accommodate the changing space operations environment.

An additional consideration for the agency or organization chosen to provide STM services is **the nature of those STM services.** Should a new STM system provide only basic tracking data and alerts for predicted conjunctions, requiring the operators to make decisions and plans about how to manage the situation? Should the STM system offer higher level services such as providing additional data to reduce uncertainties and refine the conjunction estimate, suggesting what type of maneuver should be performed, or even tasks such as assistance in assessing risks from recent fragmentation events or assistance in satellite anomaly resolution?[10] Providing these additional services would make the system correspondingly more complex. There is also the question of freely providing or charging users for some or all of the services; liability questions would also need to be addressed. The choices of service provisioning and how to deliver is related to the choice of governance (e.g., who provides oversight and which structures are more conducive to providing certain sets of services). Once a decision is made on STM governance and the organizational structure for future STM, there are a number of other issues to be addressed to make an effective STM system. The USSTRACTCOM SSA sharing program implemented by the Department of Defense provides an example of the type of organization that can fulfill this role and the services it could provide.[15]

Enhance SSA data collection, services, and tools. As discussed previously, the ability to conduct effective collision avoidance in the new space environment is driven by the availability of sufficient quality data. Current capabilities will be challenged to meet the demands of future space operators. Without sufficient data quality, the false alarm rates will be too high for an effective STM system to function. There are several approaches to improving tracking information on all or a subset of the orbital population.

There are several approaches to improving tracking information. One of the shorter-term approaches to improving tracking information is **to better utilize the data that exists.** Other nations and commercial entities have or are developing space tracking capabilities. Enhanced data sharing and inclusion of additional tracking data from civil, commercial, and allied sources has the potential to increase the frequency and/or accuracy beyond the current existing capabilities. There are a number of issues associated with this approach, including national barriers to sharing data, developing standard data sharing formats, and integrating diverse data types; however, the issues, particularly the technical ones, should be workable. The Consultative Committee for Space Data Systems has performed pathfinding work in the area of data-sharing.[12]

Another approach is to **acquire orbit data from satellite operators.** Satellite operators generally have very high-quality orbit data on their own vehicles. The operators also have satellite maneuver plans, which would enable an STM organization to account for the effects of orbit changes in near-real time rather than having to wait for sensor systems to detect the changes. Operator data will be critical as satellite operations become more autonomous and as the number of active satellites significantly increases. Information of this type can be of very high quality but is only available for a subset of the population in orbit: the active satellites that are willing to cooperatively participate. This approach is currently being used by the Space Data Association (SDA).[7]

Tracking can also be improved by requiring **tracking aids on satellites and upper stages.** These aids could take the form of passive systems such as a laser or radar reflector to improve a sensor's ability to detect the object, or they could be a more active system such as a transponder that broadcasts or can be queried to broadcast position information.[8,11] Both approaches can significantly increase the location accuracy for tracked objects. Also, both types of tracking aids have the potential to operate beyond the active life of a satellite and potentially through post-mission disposal and reentry. They suffer from a restriction similar to the operator data in that they can only assist with the tracking of active or formerly active objects (versus debris) and they can only be applied to future systems since they must be built into the design of the satellites and upper stages.

An approach that would enhance tracking information across all objects would be to improve the government's tracking capabilities. There are potential plans to do this including building **a second Space Fence radar** site in addition to the one scheduled to be activated in 2019. Another option is to enhance the telescope-based tracking generally used for higher orbits above LEO. Cost remains the greatest barrier since tracking systems are quite expensive to build, operate, and maintain, and they require a long-term commitment of resources.

Enhanced tracking and conjunction prediction tools, some from newly emerging data providers and sources, need to be tested and validated. Then, their data can be merged with data used for current on-orbit interference prediction services. The amount of data being processed will be large, and available web services, cloud/distributed computing, and commercial software could provide the ability to expand capabilities quickly to adapt to rapidly growing needs. Any tool or system that is developed will need to be re-evaluated at periodic intervals to ensure operator needs are still being met.

There are also other concerns for operating an STM system in the New Space environment including how to **keep track of the proliferating number of satellite operators.** In order to provide timely alerts of impending conjunctions, the STM system must know who the operators of active satellites are and that the satellites are active. It must therefore maintain an accurate and up-to-date global database of active operators, orbit information, and spacecraft physical data, such as that partially provided by the United Nations Office for Outer Space Affairs.[13] Maintaining this type of information is not a trivial task, especially with large numbers of operators, but it is essential for providing the actionable and timely services that will be critical for assuring the safety of space operations. All owner/operators should be encouraged to join the effort to build this master database. This database should be shared with entities (e.g., governments, national defense agencies), who for valid reasons, require access to the full set. An additional future challenge will be how to manage rendezvous and proximity operations, where one satellite is maneuvering close to another such as for on-orbit servicing. This activity will require coordination with any STM system to facilitate tracking the objects and to avoid difficulties with conjunction identification.

Conclusions

New Space activities could increase the number of operational satellites by an order of magnitude over the current situation. This has the potential to affect the space environment for generations and push any space traffic management system beyond its limits. At the same time, the United States is considering a transition in who will provide the service and how STM will be performed. The US Department of Defense has been examining this issue for several years and lessons learned from this effort are valuable to the development of any future system. To facilitate the envisioned New Space activity and maintain a safe operating environment for everyone in space, the issues of establishing an effective next-step STM conjunction assessment system must be addressed as soon as possible.

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