Space Traffic Safety: A New Self-Governance Approach for the Smallsat Community

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ABSTRACT

A new focus, both domestically and internationally, has been placed on the governance of orbital space traffic. Most often referred to as "Space Traffic Management", concern focuses on an increased risk of orbital collisions that can damage operational spacecraft, create interfering orbital debris, and present potential human spaceflight hazards. Small satellites are especially a focus of concern, as potential populations are increasing by orders of magnitude. There are a variety of technical and policy based approaches to address this issue. This paper will provide an evaluation of the risk presented by small satellites and various technical and managerial mitigation steps that can be applied to address the "problem". In conclusion, we provide an initial "bottoms-up" approach using a Self-Regulatory Organization model that the small satellite community can embrace to best address space traffic safety concerns, while enabling commerce and innovation.

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INTRODUCTION

A new focus, both domestically and internationally, has been placed on the governance of orbital space traffic. Most often referred to as "Space Traffic Management" (STM), concern focuses on an increased risk of orbital collisions that can damage operational spacecraft, create interfering orbital debris, and present potential human spaceflight hazards. For instance, passed into law in November of 2015, Section 109 of the "U.S. Commercial Space Launch Competitiveness Act [CSLCA]" stated,

"It is the sense of the Congress that an improved framework may be necessary for space traffic management of United States Government (USG) assets and United States private sector assets in outer space and orbital debris mitigation."[1]

The law directed assessments of relevant policy, regulations, international considerations, technology, and operations topics related to STM. Specific focus was placed on smallsat safety issues, directing "[a]n assessment of the risk to space traffic management associated with smallsats and any necessary Government coordination for their launch and utilization to avoid congestion of the orbital environment and improve space situational awareness." This study, part of a much larger STM and spaceflight safety assessment was conducted by SAIC (under NASA contract) and presented to Congress in December of 2016[2].

The 2015 CSLCA is but one example of increasing awareness and concern of spaceflight safety issues specifically focused on smallsats. As noted in the SAIC report, the perception of increased space traffic safety risk due to smallsats is a combination of the following factors:

- Increasing populations
- Limited maneuverability
- Limited operational lifetimes and suspect reliability
- Limited operator experience
- Space Situational Awareness challenges with tracking
- Operational and decay orbits in high value orbital regions (especially LEO), to include human spaceflight zones

Smallsat spaceflight safety concerns and the associated risk of increased orbital debris generation, damage to operational spacecraft, and loss of human life, must be addressed and taken seriously by the smallsat community. This paper aims to provide enhanced awareness, insight, and courses of action which can be taken by the community of small satellite developers and operators to appropriately and responsibly address space traffic safety. The approach we utilize here is

1. Quantify the spaceflight risk of small satellites, particularly in LEO
2. Examine technical approaches to mitigate the spaceflight safety risk
3. Examine policy approaches to mitigation of spaceflight safety risk
4. Provide recommendations for the technical and policy approaches best suited for the smallsat community

DEFINITIONS

For purpose of clarity, several key terms and expressions are defined here:

Smallsat

This paper focuses on developing a smallsat community of interest with similar goals, objectives, and limitations. Therefore, strict definitions of "smallsats" based on size and mass are hard to apply (although CubeSats certainly will fall into the domain of a proposed community). Of specific note, large LEO constellations will utilize smallsats, and those smallsats will present additional risks to space traffic safety. This paper will quantify this risk, but only to provide relative context to the more general hazard presented by CubeSats. The group of large LEO owner operators is small. Their operational and financial challenges are similar to each other yet distinct from the rest of the small satellite community. Technical and policy risk mitigation schemes and approaches that address large LEO constellations will therefore not be considered in this paper (although of course, many recommendations should be considered to provide relevant information for large LEO owner/operator consumption).

Orbital Debris

Orbital Debris is any object placed in space by humans that remains in orbit and no longer serves any useful function. Objects range from spacecraft to spent launch vehicle stages to components and also include materials, trash, refuse, fragments, and other objects that are overtly or inadvertently cast off or generated.[2]

Space Traffic Safety

Space Traffic Safety is freedom from those conditions in orbital space that may lead to incidents resulting in harm (death or injury to astronauts and spaceflight participants, damage to public welfare, damage or loss of spacecraft, interference to spacecraft). Incidents of specific concern are collisions or orbital breakups.[2]

Orbital Zones

Orbital Zones are orbits that are subclasses of the typical orbit types (LEO, MEO, GEO, etc.). Zones can be delineated by their mission utility to one or more spacecraft and hence overall value. Examples of specific orbits that could be designated as orbital zones include the International Space Station (ISS) orbit, a variety of sun-synchronous orbits (e.g. the NASA A-Train orbit) and the Global Positioning System (GPS) orbits.[2]

SMALLSAT SAFETY RISK ANALYSIS

Prior to providing recommendations for reducing the spaceflight safety risk of smallsats, that risk must first be quantified. Furthermore, risk mitigation schemes, or "levers" must be analyzed for their potential mitigation impact. These steps should be conducted continuously in any spaceflight safety governance approach selected to provide objectivity and effectivity. We begin this process here, with some initial modelling of a variety of future LEO orbit contexts involving smallsats. Specifically, using Aerospace Corporation tools, we provide modelling results for future CubeSat and large LEO smallsat constellations and provide metrics of future collision risk in the LEO environment. Levers of risk control (e.g. reduced orbital lifetimes, maneuver, improved SSA, and active debris removal) are analyzed and addressed for effectiveness.

Aerospace Corp ADEPT MODEL

The Aerospace Debris Environment Projection Tool (ADEPT) simulation process generates predictions of the future orbital population[3,4,5] that can be used to evaluate the long-term implications of technical and policy proposals. The model includes orbit trajectories, sizes and masses for a complete set of discrete Earth orbital objects. The following populations are included: initial population model (IPM) down to 1 cm in size, a future launch model (FLM), and debris from future collisions between the above objects (100 Monte Carlo scenarios). The IPM itself consists of several sub-populations: the unclassified U.S. STRATCOM catalog of resident space objects; currently existing Iridium, Globalstar, ORBCOMM constellations (which are assumed to be continuing their operations into the future in the FLM); a sub-trackable population based on a statistical assessment of debris generated from historical sources; an “unknown” statistical population to bring the total count of trackable objects to the publicly stated value of 24000; and a sub-trackable population based on explicit modeling of the Fengyun-1C and Iridium 33/Cosmos 2251 collisions. The IPM is augmented with the future launch model (FLM) which is based on replicating the last 10 years of historical behavior for launched objects remaining in near-Earth space (i.e., LEO to GEO). Once the IPM and FLM have been generated, all objects are propagated from initial epoch to 200 years into the future using the mean element propagation code MEANPROP[6] with operational satellites having appropriate perturbations turned off to simulated station-keeping. The 200-year timeframe is selected for two related reasons: 1) a long-time scale is necessary to appropriately understand the factors that drive long-term debris growth, and 2) policy makers are concerned with such time scales when developing policy documents such as the United States Orbital Debris Mitigation Standard Practices (ODMSP). Collisions are determined through an orbit trace crossing method (OTC) over 100 Monte Carlo samplings with debris down to 1 cm being generated for identified collisions and explosions using the hypervelocity code IMPACT[7,8].

End-of-life disposal for FLM objects is based upon a “Business-as-Usual” (BAU) model where all worldwide future launched objects move to disposal orbits at end of life near their mission orbits and do nothing else to comply with any international disposal guidelines. The only change to the satellite or rocket body mission orbit at end of life is to increase or decrease mean altitude by 50 km to clear the operational altitude. The label “BAU” will be used hereafter to refer to the IPM and FLM models together with the FLM undergoing the BAU disposal profile.

CubeSats were modeled as being deployed from upper stages that were already in the FLM (simulating ride-share arrangements). They were segmented into 3 groups: those satisfying the 25-year decay requirement, those that were deployed to higher LEO such that they would not decay after 25 years, and those that were deployed from upper stages involving missions to higher altitude orbits (i.e., missions to MEO, HEO, and GEO; these CubeSats would not be expected to comply with the 25-year requirement as a matter of design although sometimes natural perturbations could combine to make re-entry within 25 years occur). These groups are hereafter referred to as LEO-compliant, LEO-non-compliant, and GTO-non-compliant respectively. The boundary line between the LEO-compliant and LEO-non-compliant altitudes is roughly 550-600 km for a 3U CubeSat, but individual configurations will vary in that value. For purposes of this analysis, all CubeSats were assumed to be of the 3U configuration with random variations in the area-to-mass ratio to reflect realistic configurations.

The CubeSat simulation model assumes 749, 385, and 588 CubeSats would be deployed for LEO-compliant, LEO-non-compliant, and GTO-non-compliant groups per year, respectively with a total average of 1722 per year, which is roughly equivalent to each upper stage that achieves orbit depositing ~20 CubeSats into the environment. This represents a significant increase over current levels, but given the rate of growth of CubeSat activity and the large deployments expected in the near future, this is not an unreasonably high rate over the long term. To place the 1722 per year number into context, the Fengyun 1C event has produced 3425 tracked debris objects, while Iridium/Cosmos collision produced 2294.

Two sample large constellations of small satellites were also included in the simulation. They will be referred to as the Future Constellation Model (FCM) and consist of a 4080 satellite constellation at 1100 km altitude and 87 degree inclination (FCM 1), and a 720 satellite constellation at 1200 km altitude and 88 degree inclination (FCM 2). FCM 1 had 48 separate orbit planes with 85 50-kg satellites each while FCM 2 had 18 planes with 40 150-kg satellites each. A launch model was assumed where satellites from a given launch were all placed into the same plane with launches evenly distributed throughout each constellation’s lifetime. Each satellite was assumed to have a 6-year mission lifetime, but were consistently replenished throughout the run duration. This implies that 800 FCM (680 FCM 1 and 120 FCM 2) satellites were placed into orbit each year.

The operational FCM satellites were constrained to the stated altitude and were propagated without drag to simulate altitude station-keeping in a manner similar to the operational FLM satellites. For disposal, satellites were placed onto orbits that would result in a 5-year time-to-decay. This represents a “good steward” approach to orbit lifetime that is more aggressive than the current ODMSP 25-year rule, but is consistent with public statements made by those considering such large constellations. In addition, a 10% failure rate was assumed for the FCM. These failures occurred either in ascent (4%) where ascent was also assumed to be low thrust from upper stage deployment to operational altitude, during operations (2%), or during disposal (4%). Failed satellites drifted as normal orbit perturbations (including drag if appropriate) required.

The CubeSat and FCM populations were added into the general ADEPT processing and treated in a manner similar to the IPM and FLM when generating collisions and debris, but book-kept separately to examine trends. The CubeSats represent a distributed smallsat population while the two FCMs represent large formal constellations of smallsats.

Simulation Results

Figure 1 shows the spatial density of >1 cm objects (including generated collision debris) at 100 years from the simulation as a function of altitude for the various scenarios: the label "Current" is for the density at the current time (i.e., 0 years to provide a baseline for comparison), "BAU only" stands for Business-as-Usual (no large constellations or additional CubeSats), "FCM+BAU" is the density when the large constellations are included with BAU, "Cube+BAU" denotes the density when CubeSats are included with the BAU model, and "Total" is for BAU, FCM, and CubeSats together. Note that these curves were generated as an average over 100 Monte Carlo runs; individual runs showed high variability.

The first thing to note is that the debris environment is going to increase noticeably in next 100 years even if there are no large constellations or high levels of CubeSat activity; in this case, the overall integrated spatial density in LEO will increase by roughly an order of magnitude, and either the FCM or CubeSat model will double that again. These values are of course dependent upon the specific models assumed here but in general the debris environment could increase substantially based on future CubeSat and FCM activity over what is otherwise expected.

Another issue to notice is the spike that occurs at ~1400-1500 km. This is caused by the Globalstar and Strela constellations. Under the FLM, the Globalstar constellation is assumed to be continuously replenished and, at end-of-life, disposed to higher altitudes. However, the Soviet-era Strela-1 and Strela-3 data dump constellations are in this higher altitude regime as well. They are older and no longer operational with the last launch occurring in 2004, but there are over 500 of them. The Russians are now launching several Strela-3M satellites every year into this altitude region as well. The Strelas are all under 300 kg and so can be considered small satellites, and their placement into a non-drag orbit altitude could cause a substantial growth in debris in the future. This is an important point: if disposal is not properly performed, then smallsats will become a significant contributor to the debris environment.

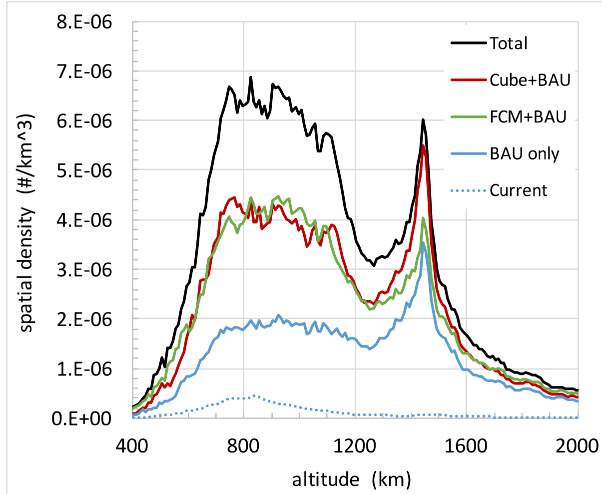

Figure 1: Spatial density projections at 100 years in LEO for >1 cm objects

Figure 2 shows the number of collisions between objects larger than 10 cm found from the ADEPT model for each of the examined scenarios. In total, the BAU model produced 21684 collisions over 200 years for all 100 Monte Carlo cases (a mean of 1.1 collisions per year) while the modelled CubeSat population caused an additional 34223 collisions (a mean of 1.7 collisions per year) and the FCM population 18787 (a mean of 0.94 collisions per year). As a side note, most of the FCM collisions are occurring for satellites that failed on-orbit and did not dispose; the shown curve thus strongly depends on the rate at which FCM satellites fail to dispose. While the modelled CubeSats are experiencing more collisions than BAU or FCM, they are smaller in size and hence each collision tends to produce less debris, resulting in the comparable increases in density observed in Figure 1.

When examining the CubeSat model in greater detail, the LEO-compliant group experienced 1855 collisions, 31245 for the LEO-non-compliant group, and 1123 for GTO-non-compliant. So even though the LEO-non-compliant group was placing less than a quarter of the number of CubeSats into orbit relative to the other two groups (385 out of the total 1722 per year), it generated far more collisions. These results imply that CubeSats, if launched to LEO but compliant with the 25-year rule, will not participate in many collisions while CubeSats launched on GTOs similarly will not experience many events. However, CubeSats in LEO, but high enough in altitude to not comply with a 25-year decay will accumulate over time and produce an increasing number of collisions. In summary, for the CubeSat model used here, adherence to the 25-year ODMSP rule would reduce the number of CubeSat collisions by over 90%.

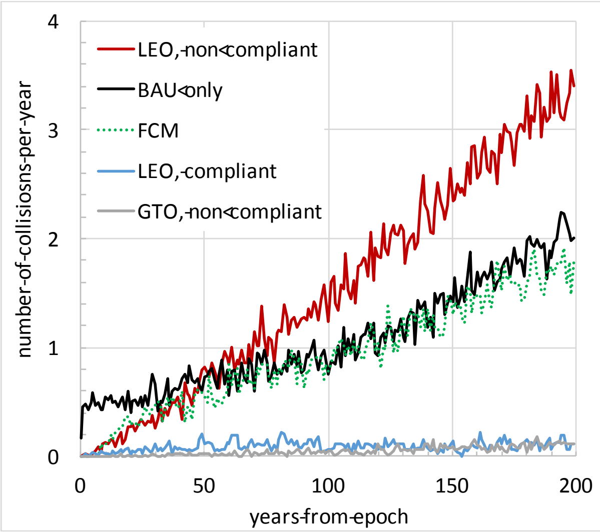

Figure 2: Number of collisions per year for BAU-only, FCM, and CubeSat Groups averaged over 100 Monte Carlos

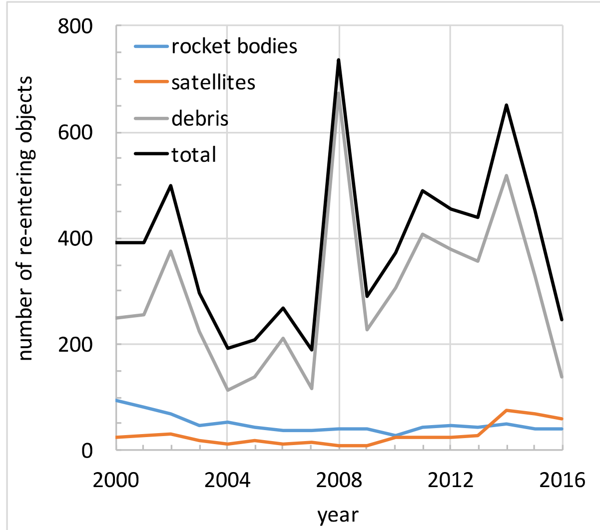

Figure 3: Historical number of re-entering objects

One issue that needs to be taken into consideration with adherence to guidelines is that if disposal by re-entry is performed for the CubeSats and FCM satellites, then they are going to come down through the altitude region where ISS and Tiangong-2 (and potentially other future manned spacecraft) currently reside (350-450 km). Figure 3 shows the historical number of re-entries from the public catalog since the year 2000. Most of these are debris with satellites and spent upper stages making up a small fraction of the overall total. Currently, ISS performs on average approximately two debris avoidance maneuvers (DAMs) per year to avoid these re-entering objects.

Assume the CubeSat and FCM model launch activity is in a steady state condition and that the CubeSats all follow the 25-year rule while the FCMs follow a 5-year rule. This means that if 1722 CubeSats are launched each year, then 1722 other CubeSats are re-entering. Similarly, if 800 FCM satellites are launched each year, then 800 are re-entering. Unless the re-entering CubeSat/FCM satellites are under control at the time of re-entry, then the burden of avoiding the objects lies with the ISS. If ~400 currently re-entering objects per year causes approximately two DAMs per year, then 2522 additional re-entering objects will likely cause approximately 12 more DAMs for the ISS per year. A too-high number of DAMs has the potential to adversely affect both human mission operations and place crew at elevated risk.

TECHNICAL MITIGATION SCHEMES

Mitigation of the debris problem is synonymous with reducing the number of collisions. Debris that does not have a risk of collision poses no possibility of human, material, or financial loss, and is therefore of no concern. It follows, that the success of any mitigation scheme must be measured not by the number of objects, but by the number of potential collisions. While these two metrics are closely related, they are not necessarily interchangeable.

To organize the potential mitigation schemes available, we have chosen to focus on four general categories of technical solutions: Knowledge, Avoidance, Prevention, and Elimination. This categorization is described in further detail below, and potential examples of each category are provided.

Knowledge

The Knowledge problem, often referred to as tracking, is a subset of the much broader domain of Situational Space Awareness (SAA), and is well understood. Namely, how accurately does the space operator community know the location of all space objects regardless of size, provenance, and operational status? In and of itself knowledge does not have any impact on the collision potentials. Rather it is an enabler for Avoidance and Elimination solutions that will be discussed later.

Impact of Tracking Accuracy

Improving tracking accuracy is often proposed as a way of helping with the collision problem. While this is effective in reducing the number of alerts to which an operator must respond, it can only help reduce collisions involving actively controlled satellites. Consider for example a smallsat under active control, and assume that any other tracked object that comes within the combined uncertainty ellipse is a "threat" that either must be avoided or additional resources must be spent to further analyze the conjunction to determine that it is not a danger. Note that the actual threshold that is chosen during operations to flag an alert is highly dependent upon orbit accuracy, acceptable analyst workload, etc. However, for discussion purposes here, it is simpler to exhibit the point by assuming violation of the uncertainty ellipsoid generates an actionable alert.

Furthermore, assume the smallsat and secondary object are tracked with either accuracy associated with the SGP4 two-line element sets (GP)[9], accuracy associated with the Special Perturbations methods (SP), or ideal high precision knowledge. GP would represent using public catalog data for the object in question, SP would represent gaining additional dedicated tracking on the object (and is here assumed to be 3 times better than GP), and ideal could represent GPS or some type of transponder (which is here assumed to be 3 times better than SP). The number of alerts can be computed as a function of the spatial density (i.e., altitude) and is shown in Figure 4.

It is immediately apparent that there is improvement to be gained in the number of alerts by improving the tracking. At ~800 km and if both objects are being tracked with GP level accuracy, then the expectation would be to have ~25 alerts per year. If one of the objects gained improved SP tracking, then the number of alerts would lower to ~14 per year. However, there is a limit to the benefit because the secondary object still has a large uncertainty; if the primary object is tracked ideally, then the number of alerts is still ~13 per year. This situation of diminishing returns could often be the case as most conjunctions are going to occur with debris which may be small and poorly tracked under the best of conditions. If both objects gained SP accuracy, then the improvement becomes more significant. This is a key point: simply improving one object's accuracy (i.e., the operational smallsat) will only yield a certain level of improvement; improving the accuracy of both objects' orbit is essential to significantly lowering the number of alerts.

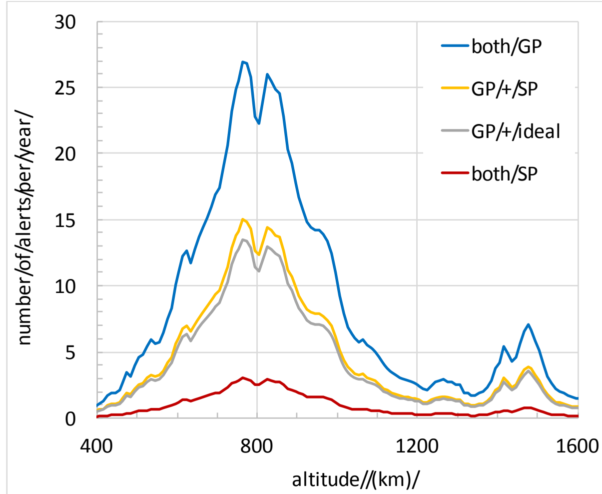

Figure 4: Effect of improved tracking accuracy on number of alerts for current (year 0) environment

Improving the tracking accuracy can also help reduce the cost of maneuvering in case that becomes necessary. To avoid a dangerous conjunction, the active object must not only move enough to physically miss the other object, but given the uncertainties, move such that the two uncertainty ellipsoids no longer touch (to the chosen sigma level). Larger uncertainties require both a greater number of maneuvers and a higher delta-V for each maneuver. In the sample case discussed here, the GP+GP conjunction solution would require approximately 300 m/s/year of delta-V to alleviate, the GP+SP would need ~112 m/s/year, while the GP+ideal would require ~86 m/s/year. By contrast, only ~11 m/s/year would be needed if both objects were being tracked to the SP level.

It is important to acknowledge that improved tracking accuracy reduces potential workload on organizations and their personnel responsible for space traffic safety. This has not only a cost impact but also a safety impact by reducing cognitive burdens and allowing focus to be maintained on true high risk situations. Additionally, added tracking accuracy adds to transparency of operations and in effect promotes national security and international stability in the space domain.

Onboard Solutions

Improving the tracking accuracy of active objects is relatively easy through modern onboard equipment such as GPS. GPS receivers for satellites are broadly available. In Figure 4, this further brings us into the "ideal" domain; namely the accuracy is high enough to be statistically equivalent to perfect knowledge for purposes of determining collision probabilities. This is especially true when the raw GPS position and velocity solution is combined with filtering methods such as least-squares or Kalman filters. In these instances, position accuracy can be improved to single-digit meters on a continuing basis, with no growth in errors due to propagation.

The advantage of onboard solutions cannot be understated. The 2013 launch of the ORS-3 mission onboard a Minotaur I included a record number (at that time) of secondary payloads, most of them CubeSats. Approximately half of them, mostly of government of commercial origin, had onboard GPS. The other half, mostly of university origin did not. Working with the individual satellite owners, the Joint Space Operations Center (JSpOC) was able to identify and tag GPS-bearing satellites within one week after launch. On the other hand, for those satellites that did not have GPS or were inoperative after launch, tagging took as long as two months. That does not necessarily mean that the JSpOC did not have TLE-level tracking information for these satellites, but rather that it was not confident enough on which solution applied to each satellite. This metaphorical "fog of war" is common in launches with high number of satellite payloads, of which there has been an increasing number.

Unfortunately, GPS solutions are often out of reach for smallsat manufacturers due to size, cost, or technical complexity. For many universities and developing country manufacturers, GPS units are prohibitively expensive and difficult to implement. For CubeSats, especially those utilizing the 1U form factor, addition of a GPS unit is also not feasible due to mass and volume constraints. Developing cost-effective technical solutions such as incorporating a low-cost GPS receiver directly on the on board computer or primary telemetry and command radio could increase the number of satellites utilizing GPS.

As we previously discussed, however, onboard GPS is only beneficial as long as the satellite is operational and its operator is able to share its data or use it internally for its own COLA assessments.

Tracking Enhancements

For the thousands of resident space objects that do not have GPS or are not actively controlled, we must rely on ground and space-based tracking. Space object tracking faces two major challenges, both of which reduce the accuracy of publicly available solutions. First existing assets are limited in the size of objects that can be tracked; second even when an object can be effectively tracked, limited resources mean that tracking may be infrequent.

The first problem is of primary importance to the smallsat community. Today, the primary source of published tracking data is derived from the work done by the U.S. Space Surveillance Network (SSN), part of the United States Strategic Command (USSTRATCOM). Tracking solutions obtained by the SSN are published by the JSpOC through web-based interfaces. These solutions are sometimes referred to as "NORAD two-line element sets". While the exact performance limits of the SSN are not publically available, the traditional rule of thumb has been that a 10 cm (softball-sized) object can be easily tracked at LEO and a 30 cm (basketball-sized) object can be tracked at GEO. One can quickly see that these dimensions are comparable to smallsat dimensions, especially CubeSats and the newer batch of sub-CubeSat spacecraft (Pocketsats, femptosats, Chipsats, etc.). The tracking problem is further exasperated by the standard form factor that has led to the CubeSat's success – to a first order, all of the satellites following the standard look the same.

A number of potential technical solutions exists to help improve the tracking accuracy for small satellites. For instance, in 2006 a set of post-launch guidelines were suggested by members of the Space Analysis branch of the Air Force Space Command that would significantly improve the tracking ease during the initial object identification period. These included:

1. Coordinate launch trajectory and initial orbit information.
2. For multi-satellite launches information regarding deployment sequence, separation timing, and object shape and size is extremely beneficial.
3. Sequential satellite deployments should be separated by at least 20 seconds.
4. Separation velocity between the satellite and the launch vehicle should be at least 5 meters/second or more.
5. Report problems identified in two-line element sets.
6. Notify tracking authorities if assistance is desired with issues regarding satellite anomalies and/or loss of contact. [10]

Refinement and addition to these recommendations has since been made and incorporated in the JSpOC Recommendations for Optimal CubeSat Operations publication[10]. Additional techniques have also been proposed that enhance the ability of the SSN to track smallsats. Some, like transponder-based tracking, in which the target satellite receives a RADAR signal and retransmits an amplified return, have the same disadvantages of GPS in that they require power, mass, and more importantly an active satellite. Other techniques involve increasing the RADAR cross-section of the vehicle through coatings, geometry, retroreflectors, and other features. These methods could be further enhanced if a unique RADAR return-signature can be generated by the satellite. Similar features can be utilized to support optical tracking in addition to RADAR tracking. Such passive techniques have the advantage of being very low mass and complexity as well as not requiring an active satellite. Increasing the RADAR cross-section will be critical for some of the newest satellites such as Chipsats, especially if they have mission life times of more than a month or so. A third potential option is a hybrid "tag" similar to those found in toll collection systems such as EZ-Pass. In this scenario the satellite may produce some active response to being queried by the tracking stations. However the tag would be an independent, low-power circuit, completely isolated from the primary spacecraft. This way, the tag can continue to operate even in the event of a failure.

It is worth noting that smallsats can also contribute to the state-of-the-art for tracking capabilities. As an example, two university satellites developed under the auspices of the AFRL University Nanosat Program were developed with just this mission in mind. The Oculus, developed by Michigan Tech aims to improve determination of spacecraft attitude using unresolved ground imagery. Ho'oponopono from the University of Hawaii was designed to provide a calibration and known tracking target to RADAR stations in the SSN.

The second tracking problem is one of frequency. With limited ground resources available, it is not possible to continuously track the thousands of monitored objects. This problem, of course, affects not just smallsats but the entire satellite community. The United States government is actively trying to expand the SSN resources with new programs such as Space Fence. More recently, commercial entities have started to step in to augment the services provided by the SSN. AGI's Commercial Space Operations Center (ComSpOC) utilizes a commercial network of optical and RADAR tracking stations to provide a catalog that is "on par" with the JSpOC's. [12] As smallsat developers find ways to improve their satellite's trackability, working with these commercial providers will be key.

Propagation

Although TLEs are the *lingua franca* for disseminating tracking information on objects, we have already seen they have significant uncertainties, especially when propagated with the standard SGP4 propagator. Alternatives to the TLE standard, or even broader adoption of enhanced techniques in the use of TLEs, have the potential to yield significant improvements in positional knowledge. In Figure 4, these allow us to move from the GP domain to the SP domain.

For instance Levitt and Marshall set out to study alternatives to the TLE/SGP4 accuracy with the goal of increasing "the predictive accuracy for orbital objects, using only historical TLE data, such that it enables operational conjunction assessment for collision avoidance." In their results, they postulate that use of a batch least-squares differential correction on publically available TLEs could reduce propagation errors to an average of 150 m/day compared to 1,500 m/day. A roughly ten-fold increase in accuracy[13]. A number of other similar enhanced techniques have been proposed over the last two decades. The exact implementation is not as important as broader adoption of such techniques.

Data Dissemination

Improved accuracy of tracking solutions are only as good as their availability. Even when an improved solution exists, it is often of limited distribution due to proprietary and commercial constraints.

Due to the use of previously discussed GPS and ranging systems, operators of many active satellites often have tracking knowledge for their own spacecraft that is significantly superior to what is publically available. This data, however, is often not made public due to proprietary concerns. A sharing framework for smallsat and especially CubeSat enhanced tracking data has the potential to improve overall community awareness leading to lower costs of COLA and reduced risk of collisions. However, even perfect sharing of this data is still only limited to active satellites.

For inactive debris objects, commercial entities with enhanced catalogs such as the ComSpOC currently requires a subscription. These commercial services can be of significant benefit to large operators in assessing collision risks, but smallsat owners with limited resources may not be able to utilize these services. On the other hand it is likely that such small operators will have satellites with limited or no maneuverability so that this enhanced data would be of no benefit, even if freely available.

For both operator and catalog providers the question exists on whether there should be certain best practices and guidelines that would encourage free and public release of data in specific circumstances such as imminent collisions.

Avoidance

When sufficiently good tracking data exists, it becomes possible for a spacecraft to perform collision avoidance maneuvers (COLAs) in order to reduce the probability of impact against another object. Provided the owner's spacecraft has propulsive capabilities, its orbit can be changed to protect against impending collisions. As previously discussed, however, this is a balancing act. High uncertainty in monitored objects can lead to a large number of false alarms that precipitate an unnecessary maneuver. Unfortunately most smallsats may not have the required propulsive capability, and even when they do, they may not have sufficient delta-V capacity to perform a large number of COLAs.

The ability to perform COLAs can also reduce the number of collisions that might occur but its effectiveness in limiting the long-term growth in debris is limited. Consider the LEO non-compliant number of collisions from Figure 2 and reproduced in Figure 5. This assumes natural decay for however long it takes for decay to occur. If COLA is performed during mission operations, then a certain number of the collisions depicted in Figure 5 will not happen. The 3-year curve in Figure 5 shows the number of collisions occurring in the simulation during the first 3 years of a CubeSat's lifetime; the number of collisions in this case is much lower than the no-COLA case. For comparison purposes, a 25-year curve is shown as well (i.e., a CubeSat somehow performed COLA during the first 25 years it was in orbit). What this figure depicts is that most of the collisions are occurring for CubeSats that have been aloft for a very long time, decades or more.

Logically, this follows: since most objects on orbit now and in the future will be inactive, it is more likely that the future debris environment will increase because of dead-on-dead collisions rather than active-on-active or even active-on-dead collisions. This does not mean that COLA is not useful for protecting an operator's vehicle from either having a mission ending event or from liability in case of hitting someone else; it simply means that COLA as a mechanism for reducing long-term debris growth is minimal.

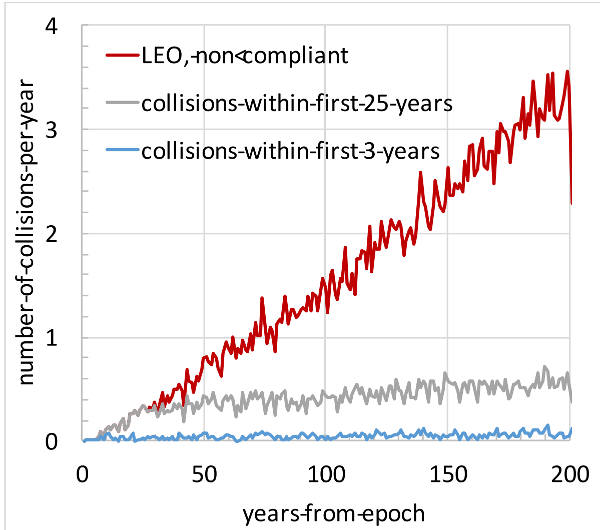

Figure 5: Effect of COLA on LEO, non-compliant CubeSat collisions

Prevention

Today, the primary means of collision prevention in the smallsat community is through the use of the 25-year rule set out in the ODMSP. Broadly summarized, this rule dictates that any satellite in LEO should re-enter the earth's atmosphere within 25 years after it ceases operations. Depending on the spacecraft's ballistic coefficient and solar activity, this effectively places a cap on a satellites End of Life (EOL) altitude between 550 km and 650 km.

Meeting this goal presents several significant challenges to smallsat designers:

- Smallsats, on average, tend to be more densely packed than their larger counterparts and therefore have a higher ballistic coefficient. This puts the "25 year" altitude threshold lower than for larger satellites.
- Smallsats are usually launched as secondary payloads, and therefore have a limited choice of potential orbits.
- When placed above the 25-year altitude, the satellite must have a means to deorbit itself, which adds mass and complexity and is often unfeasible to implement in a smallsat.
- The satellite must remain operational and under ground control long enough to execute any orbit-lowering maneuvers. This can present a challenge for smallsats which are often meant to have lower reliability than their larger counterparts.

To move a satellite to an appropriate disposal orbit a number of techniques have been proposed. Most common is the use of a propulsion capability to lower or raise the orbit as required. Propulsive techniques have the advantage of using well known hardware and are available in any orbital regime, LEO, MEO, GEO, or HEO. If a satellite already requires propulsion to complete its primary mission, then adding additional delta-V capability for disposal is relatively trivial as long as mass is available. However, for satellites that do not already include propulsive capabilities, the addition of such hardware can significantly complicate the design as well as the approval process when launching as a secondary. For this reason a number of non-propulsive deorbit techniques have been proposed through the years. While these eliminate the inherent costs and risks associated with propulsion systems, they have the disadvantage of only working within the LEO environment. Non-propulsive techniques in general work by increasing spacecraft aerodynamic, electromagnetic, or photonic drag forces.

All methods of increasing aerodynamic drag utilize some sort of deployable that significantly increases the cross-sectional area thereby decreasing the ballistic coefficient of the spacecraft. These devices can be large sails, booms, or spheres. One such example is Towed Rigidized Inflatable Structure (TRIS) proposed by Ball Aerospace and L'Garde Inc. in 2004. As way of comparison it was estimated that for a 300 kg spacecraft at 700 km a 15-m deorbit device would provide the same capability as 16 kg of hydrazine fuel, but at a reduced mass and cost penalty. Researchers estimated a system cost approximately 10 times lower for the inflatable than for a propulsion system, assuming the satellite didn't otherwise have a propulsion system. [14]

Electromagnetic drag devices utilize a conductive material, usually in the form of a tether that is set up to carry a current that is generated by the interaction of the tether with the magnetic field and ionosphere of the Earth. The current in turn interacts back with the magnetic field setting up a drag force that can be utilized to change the altitude of the spacecraft.

An example of a tether device, the nanoTerminator™ was specifically designed to be used on 1-10 kg satellites. The nanoTerminator included redundancy features to increase the probability of survival during the deorbit phase. The developers estimated that such a device could potentially increase the permissible orbit altitude of the spacecraft up to 1000 km while only adding 100g to the mass of the host spacecraft.[15]

Other techniques that have been proposed include utilizing solar sails that can serve to increase atmospheric drag while also creating some amount of propulsion capability utilizing photonic energy from impinging sun light.

It is interesting to note that although many of these deorbit techniques were proposed over 10 years ago, none are widely used today. The reason for this is not clear. It could be due to inherent immaturity of the technologies (since they first have to be flight tested), higher than expected implementation costs, or lack of a perceived need. If there is to be a reduction in the "non-compliant CubeSat population" or if stricter guidelines than the 25 year limit are to be implemented, it would be important to understand why such deorbit systems have not been utilized.

An aspect that is not often considered in developing such deorbit techniques is that they must, by definition, work at the end of the mission, when often times the satellite may be crippled or suffer from reduced capabilities such as available power. Furthermore, utilizing such devices assumes that the spacecraft is operational to begin with and has not suffered a mission-ending anomaly. To be effective, then, deorbit systems must have an increased reliability that ensures they will properly operate at EOL, perhaps even autonomously. This might involve selective redundancy, independent systems, and other fail-saves. For instance, a deployable drag system might be setup to utilize an independent power supply, and rather than be deployed using a ground command, deployment could be based on some sort of watch-dog timer that is pinged by the main flight computer. Were contact to be lost with the spacecraft due to a computer issue or a short in the power subsystem, the independent deployment circuitry would kick in, deploying the drag device even as the spacecraft is otherwise defunct.

While disposal guidelines are fairly well understood, if not always followed, by smallsat designers and operators, there are other aspects of prevention that are not as widely implemented. Of particular importance is the concept of "passivation." Not only is it important that the spacecraft be moved to an appropriate disposal orbit, it is key that during its time in that orbit (up to 25 years in LEO, infinite in GEO) the spacecraft does nothing to contribute to the debris environment. The process of passivation is removing as much stored energy that could lead to catastrophic breakup of the spacecraft. Such passivation techniques include depressurizing all pressure vessels such as propellant tanks, discharging batteries, and removing all kinetic energy stored in reaction or momentum wheels. Until fairly recently smallsats did not often have pressure vessels or momentum storage devices. However as the complexity of these satellites has evolved, these features are now more prevalent, and passivation techniques must be adhered to at EOL.

Elimination

An additional method for reducing the growth of debris related to smallsat is through Elimination utilizing active debris removal (ADR) systems. The difficulty with any ADR systems is that the space community has no crystal ball to know which specific objects are truly going to collide, and therefore removal targets must be selected based on their statistical likelihood of adding debris to the environment. One parameter commonly utilized to evaluate ADR targets is the probability-severity (P-S) metric[16], which is a combined value consisting of the likelihood that the object will be hit (i.e., probability of collision) times the amount of debris that a collision involving that object would create. In specific terms, the probability of collision is the background flux that the object faces times its cross-sectional area while the amount of debris is a function of the expected relative velocity and the object's mass (i.e., the energy of collision). The P-S value for each object in the simulation can be computed and a ranking established determining what the "best" targets to remove are.

Figure 6 shows the P-S value of potential ADR targets that could be targeted by a mitigation system. In the simulation, every object had its P-S value computed; the objects in Figure 6 are those that yielded the highest values. ENVISAT, ALOS, and ADEOS are Earth observing satellites with large buses, solar panels, and, in the case of ENVISAT and ALOS, large extended synthetic aperture radar antennas. The SL-16 rocket bodies (of which there are many) are approximately 11 meters in length and have a mass of ~8300 kg. They are depicted in Figure 6 alongside a Dove-like 3U CubeSat in lower LEO (500-1000 km), and FCM 1 and FCM 2 satellites. Note the orders-of-magnitude difference on the y-axis scale. Therefore, it would roughly require 100-200 CubeSats (or ~500 FCM 1s or ~800 FCM 2s) to be removed to get the same benefit from removing the singular satellite ENVISAT. While it may be technically easier to design a system that can scoop up a smallsat, the system would also have to be able to move between multiple targets to influence the long-term growth of debris.

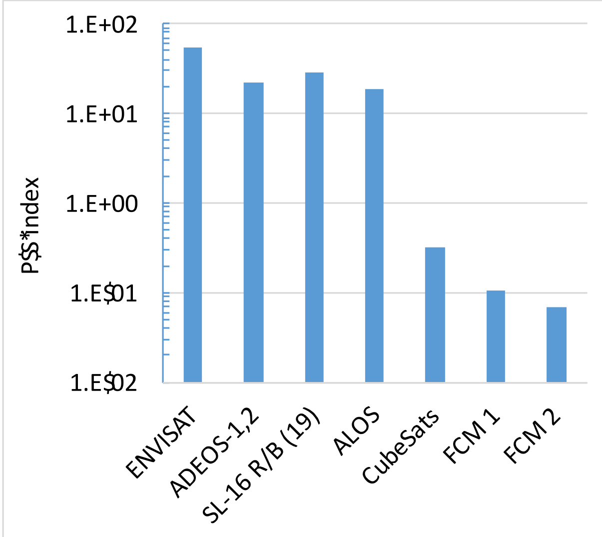

Figure 6: Relative effectiveness of potential ADR targets

Although ADR of very large objects such as ENVISAT is clearly beyond the domain of smallsats, smallsats may still be able to play a role in removing extremely small objects, especially objects that cannot be effectively tracked such as collision fragments, and separation and deployment debris. One such concept is a deployable Multi-Layer Sphere (MLS) that would focus on purposely breaking up 1-10 cm class debris into <1 cm debris particles that can be shielded against [17]. Other potential solutions have been proposed including scoops filled with absorbing gels that would "clean" a path in the sky. For all of these solutions, further study is required to assess their capture/removal effectiveness and ensure that they are not exasperating rather than decreasing the collision risk problem. Methodologies need to be developed that can help determine whether these methods actually decrease the probabilities of collisions, given the low P-S of the small objects that would be targeted.

POLICY AND RULES RELATED RISK MITIGATION APPROACHES

Awareness and analysis of small satellite space traffic safety risk are necessary steps that must be taken to mitigate the likelihood of on-orbit collision and orbital debris generation. Awareness ensures the smallsat community is cognizant of growing risk – both real and perceived. Analysis, like that presented here, provides a rational approach to quantifying the seriousness of the safety problem both now and in the future. In addition, analysis must be done to understand the costs and value of a variety of technical mitigation approaches, many of which were discussed in the previous section.

Awareness and analysis alone are not sufficient to have a significant impact on enhanced smallsat space traffic safety. There must be an element of management for such an effort, to include the development and implementation of policies, processes, and procedures that are embraced (by either requirement or consensus) by the smallsat community in order for safety practices to be truly effective. There exist a wide variety of policy related courses of action that can be taken to mitigate smallsat related space traffic safety risks. Such policy type approaches are manifest in "rules of the road" and engineering related specifications to be followed by smallsat developers and operators. Before discussing what such rules and specifications could be, it is important to note there are a variety of ways in which such rules and specifications are developed, implemented, and enforced. There is often much confusion in this arena, with a lack of consistent well-defined terminology leading to misunderstandings of intent and actual implementation process. We therefore begin with a model of rules development presented in the SAIC Orbital Traffic Management Report[2]. This policy domain "stack" provides a hierarchical depiction of the range of possible rules-based control mechanisms. This stack is shown in Figure 7. Going up from the bottom of the stack, compliance requirements become more stringent and the bodies creating the rules more formal. Lower level elements of the stack are typically subordinate to higher levels.

Figure 7: The Policy Domain Stack Model

The following is a description of each layer, with relevant examples provided.

Policies

Policies are high-level principles adopted or proposed by a governing body, typically a nation-state and/or an intergovernmental organization. Note that such policies are higher level abstractions and are not legally binding (i.e. cannot be enforced as though they were law). An example is the United States National Space Policy.

Laws, Rules, and Regulations

Laws, rules, and regulations are specific directives created to accomplish policy established by public entities (governments). These are literally the law or carry the force of the law. Assumed to be included in this subset are self-executing international treaties (i.e. do not require further legislation to be implemented and followed by a nation-state). An example law is Title 10 U.S. Code 2274 (USSTRATCOM SSA Data Sharing Program). An example of regulations are 47, CFR Parts 5, 25, and 97, which are used by the Federal Communications Commission to regulate radio communications from space stations (i.e. satellites).

Standards

Standards are a set of directives created and or adopted through consensus by a private entity. They are codified documentation describing requirements, specifications, or characteristics that can be used consistently to ensure that materials, products, processes, and services are fit for their purpose. Standards must be measurable and verifiable. These are voluntary, but, for example, "Federal agencies may incorporate standards developed by non-governmental entities, thereby forming a quasi-governmental regulatory mechanism."[18] An example is The Consultative Committee for Space Data Systems (CCSDS) Space Data System Standard for Conjunction Data Messages (CDM).

Guidelines

Guidelines are a codified set of recommendations or advice provided by one or more public or private organizations. These do not carry the force of law and compliance is voluntary. Examples include Interagency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines and JFCC Space, JSpOC Recommendations for Optimal CubeSat Operations.

Best Practices

Best practices are a technique or methodology that, through experience, has proven to reliably lead to a desired result. These can be written or unwritten. Promulgation is typically limited and compliance is voluntary. An examples is the Space Data Association (SDA) maneuver notification practices for GEO operators.

Note that missing from the stack list are "norms of behavior" which are often brought up in discussion of procedural rules based controls mechanisms for space traffic safety. "Norms of behavior", which are informal understandings of what is acceptable to society, include political, social, psychological and cultural elements and evolve over long periods of time. Because of the complex forces involved, "Norms of behavior" are very difficult to become universally accepted, especially in short time periods (years). Thus, we do not consider that "norms of behavior" provide a timely and reliable means of risk control and therefore do not include them as part of this discussion. Furthermore, "norms of behavior" are most often informed and influenced by best practices, guidelines, etc., and not vice versa. It is often differences in value propositions which present the greatest challenge in implementation of "norms of behavior". Safety focused best practices, guidelines, and standards (especially when based on analytically based risk analyses), provide a common value proposition of freedom from potential space operational hazards for international actors and hence are more likely to be embraced globally.

Both explicitly and implicitly noted within the hierarchical policy and rules model is the role of governments versus private entities. For clarity, the range of organization responsible for development of rules and process is described in more detail, with membership and authority ranging from fully governmental to fully private.

Federal Agencies

"The most prominent means by which the federal government controls the conduct of private entities is through a congressional delegation of regulatory power to a federal agency".[18] Such power is then manifest in development of rules and/or the grant of licenses. Most often rule-making and licensing are complementary actions. A relevant example is the granting of a Federal Communications Commission license for a space station defined under FCC rules.

Federal Advisory Committee

Typically referred to as a "FACA", Federal Advisory Committees are established under The Federal Advisory Committee Act, Pub.L. 92-463, 6 October 1972. Their memberships typically consists of both private and public individuals; the FACA reports to a federal organization, providing recommendations for future policy and legislative action. A relevant example is the Commercial Space Transportation Advisory Committee (COMSTAC), which provides information, advice, and recommendations to the FAA administrator within the Department of Transportation (DOT) on issues regarding the U.S. commercial space transportation industry.

Congressionally Chartered Non-Profit Organization

Also referred to as "Title 36 Corporations", these are private non-profit organizations with a patriotic, charitable, historical, or educational purpose. "Chartered corporations listed in Title 36 are not agencies of the United States, and the charter does not assign the corporate bodies any governmental attributes. For instance, the corporation's debt is not guaranteed, explicitly or implicitly, by the full faith and credit of the United States. The attraction of Title 36 status for national organizations is that it tends to provide an 'official' imprimatur to their activities, and to that extent it may provide them prestige and indirect financial benefit."[19] A relevant example of a Title 36 Corporation is The National Council on Radiation Protection and Measurements (NCRP). NCRP "seeks to formulate and widely disseminate information, guidance and recommendations on radiation protection and measurements which represent the consensus of leading scientific thinking."[20] The National Academy of Sciences and the National Academy of Public Administration are both Title 36 Corporations that later also became FACAs.

Standards Bodies

Standards bodies are private organizations that create voluntary consensus standards through common processes that include consideration of a wide variety of inputs from individuals and industry. Some form of internal governance is practiced. Relevant examples include The International Standards Organization (ISO) and the American Institute of Aeronautics and Astronautics (AIAA). Note that AIAA also publishes guidelines ("Guides") and best practices ("Recommended Practice") that may evolve later into standards.

Self-Regulatory Organizations (SROs)

SROs are largely private organizations. "Although there is no formal definition of what constitutes an SRO, these organizations are generally viewed as private entities formed by members of an industry in an effort to 'self-regulate,' either because traditional governmental regulation is impractical or because the industry wishes to deter governmental regulation by demonstrating that the industry can effectively supervise itself."[18] SRO activities can include development of standards, guidelines, and best practices. In addition, SROs can truly provide oversight functions. A prominent example is the Institute for Nuclear Power Operations (INPO), which establishes safety standards and certifications for the operation of commercial nuclear power plants. INPO, a not-for-profit organization, was created shortly after the Three Mile Island incident. INPO's charter was bolstered by the recommendations of the presidential commission established after the nuclear incident:

"…the [Presidential] Commission recognizes that merely meeting the requirements of a government regulation does not guarantee safety. Therefore, the industry must also set and police its own standards of excellence to ensure the effective management and safe operation of nuclear power plants …. The industry should establish a program that specifies appropriate safety standards including those for management, quality assurance, and operating procedures and practices, and that conducts independent evaluations. The recently created Institute of Nuclear Power Operations, or some similar organization, may be an appropriate vehicle for establishing and implementing this program." [21]

Recently the Defense Advanced Research Projects Agency (DARPA) initiated an effort that is, in part, inspired by INPO. Referred to as the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), the effort is meant to kick-start a SRO led by a private entity:

"Through CONFERS, DARPA aims to establish an industry/government forum composed of experts from throughout the space community. Participants would leverage best practices from government and industry to research, develop, and publish non-binding, consensus-derived technical and safety standards for on-orbit servicing operations. In doing so, the program would provide a clear technical basis for definitions and expectations of responsible behavior in outer space."[22]

The rule-making approaches and examples discussed here provide a good cognitive framework from which to begin a discussion within the smallsat community and to answer the question "how do we want to control smallsat space traffic safety risk from a policy (vice purely technical materiel solution) perspective?"

A SMALLSAT COMMUNITY OF INTEREST

The control of Smallsat safety can be top-down, from government regulations. These could prove to be slow to evolve on one hand. On the other hand, they could be enacted relatively quickly, especially after a serious space traffic safety incident involving a small satellite. In either case, they could prove to be incredibly burdensome and greatly impact the rapid innovation, informative experimentation, and business development capabilities that are the history and future of the smallsat community. Furthermore, as stated in the presidential commission report in the aftermath of Three Mile Island, "merely meeting the requirements of a government regulation does not guarantee safety."

The alternative is a SRO approach that is coherent, collaborative, and community-wide using a "bottom-up" processes and based on technically informed, operationally relevant, and cost effective development of best practices, guidelines, and potential standards. This SRO approach would be appropriate, not only to avoid regulatory burdens, but to take responsible actions to truly enhance space traffic safety. Furthermore, if regulatory action is later desired, rules and regulations can be derived from the informed best practices, guidelines, and standards that have been developed. Given the desirable attributes and outcomes of such an approach, details on a membership, governance approach, funding (including possible sponsorship), and initial focus should be of immediate consideration. Recommendations for the "Smallsat Space-Traffic Safety Consortium", or SSSC (pronounced "triple s c") are follows:

Membership

The membership of SSSC, as consortium, should consist of international university researchers and industry (to include start-ups, their funding partners, and government contractors) partners. Private individuals should also be included. To avoid any misinterpretation of the nature of the consortium (i.e. as a SRO), consideration should be given to the specific nature of the membership of government employees. These employees bring a rich set of experience, concerns, lessons learned, and understanding of smallsat safety problems, so therefore must participate and collaborate in the SRO.

Governance

Some governance and structure of the consortium will be required. An elected board – appropriately representing the interests of all stakeholder members – should be created, to include a designated leader. Technical committees, each focused on a key area of safety concern or solution space (e.g. "Smallsat SSA"), should be created. To be most effective, a central sponsor's location and facility should be selected as the recognized "home" of the consortium. One possible approach is for the consortium to be headquartered at the chair-person's own organization. In this respect, the headquarters would rotate from time to time as leadership is changed. Another approach would be to create a not-for-profit entity responsible for consortium governance. Overall, the governance process and procedures must be codified in some way through bylaws or articles of incorporation.

Financing

Financial sponsorship should be explored for full consortium effectiveness, especially if the not-for-profit model is to be utilized. A SDA model, which bases dues on a per satellite basis could be informative. Such dues of course should consider the funding limitations of the satellite owner/operator. The DARPA CONFERS program, where a government agency provides initial consortium start-up funds, offers another alternative model for initial consortium development. At minimum, safety focused research, motivated by consortium risk concerns, should continue to have the same funding opportunities available today from industry internal research and development and government grant and contract sources. Regardless of funding possibilities, financial sponsorship should not become a pre-requisite for initiation of the consortium.

Initial Focus

Based on the technical analyses provided in this paper, the following areas of space traffic safety risk concern should be often top priority to the SSSC.

1. Development and/or reiteration of best practices and guidelines that minimize total time on-orbit. As shown in our analysis, total time on orbit is the fundamental driver to the integrated probability of collision for a small satellite. This is an issue for spacecraft of all sizes, but the limited lifetime and maneuverability of smallsats, especially CubeSats, amplify this risk.
2. Development of best practices and guidelines that minimize probability of collision with a crewed spacecraft during decay through the habited orbital zone. Again, this is an issue for spacecraft of all sizes, but smallsat limitations amplify risk in this area.

The consortium should also develop key focus areas of academic research and analysis in these areas should be motivated by both what is known and what is unknown. As a starting point for guideline development, the consortium should use as a baseline the JSpOC Recommendations for Optimal CubeSat Operations. This document provides an initial approach to address the orbital lifetime and human spaceflight safety risk areas noted.

CONCLUSIONS

Domestic and international emphasis is growing to create mitigation plans and possible management approaches to limit space traffic safety risk. Smallsats, in particular, are a particular focus of that concern. Preliminary analyses have been presented which show that, in particular, growing CubeSat populations do not significantly add to collision risk over time relative to future launch models of other spacecraft into LEO. However, there exists additional safety risk from CubeSats that do not adhere to the 25 year IADC guideline. In addition, growing populations of smallsats placed into orbit above human spaceflight zones (e.g. the ISS orbit) do add to the total number of possible orbital conjunctions with crewed spacecraft. There are a number of technical approaches to mitigate these smallsat safety risks. These solutions can be categorized in the areas of Knowledge, Avoidance, Prevention, and Elimination. All come with varying degrees of costs and value. Ultimately, to be most effective, a community-wide approach to raising awareness, conducting analyses, and management of smallsat safety should be implemented. Suggested is a bottoms-up process, to include formal development of a Self-Regulatory Organization devoted to smallsat space traffic safety. It is hoped that, at minimum, this paper serves as a catalyst in the initiation of a more wide-spread culture of safety within the smallsat community.

DISCLAIMER

References to specific products, technologies, or services are provided as examples only and do not constitute an endorsement by the authors or the author's organizations.

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