The Aerospace Corporation's Space Traffic Management Research Program

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ABSTRACT

The Aerospace Corporation conducts extensive research regarding space traffic management (STM) and orbital debris issues, both at the behest of external customers, as well as internal, self-directed efforts. We are currently in the process of coordinating our disparate research efforts under an enterprise-wide rubric, with a goal of advancing a comprehensive research program, as resources permit. This multi-year effort will allow us to gain a synoptic view of the research terrain, with an eye towards discovering gaps in our efforts, and filling them.

Aerospace will be examining STM, debris and space safety in a holistic fashion, since these elements have a number of dependencies on each other both reinforcing and opposing. We have conducted research in this area previously [1,2,3,4,5], but are now working to integrate many of the various research threads that we find across the corporation into a more integrated program of research, which is rather a new phase for us. Initially, we will deal with technical and policy analysis, with the output consisting of a series of studies and technical demonstrations that will guide and inform our subsequent research portfolio. The idea is not to develop a completely comprehensive, all-encompassing research program, but rather to leverage some of the unique strengths and capabilities that Aerospace has. Our starting points will be to expand assessments of large-scale approaches to STM with the goal of identifying integrated policy considerations and understanding the interactions between sensing and tracking capabilities and STM and the space environment. Topic areas we have identified for initial focus include:

- Assessment of the interplay between short-term satellite safety and long-term environment evolution (see Sorge *et al*., *Interactions between Debris Mitigation and Space Traffic Safety in the Presence of Large Constellations*, this conference)
- The interplay of mitigation and active debris removal (ADR)
- The trade-offs between distributed satellite systems versus more capable, complex satellites on STM and environmental effects
- Studies to provide quantitative data to define STM metrics and thresholds to enable definition of the performance levels needed for performing STM missions

Subsequent phases of the program will investigate issues involving space tracking data integration, effective collision avoidance (COLA) system development and integration, mitigation technologies and techniques, and advanced collision prevention methods. The program will not be conducted in an entirely serial fashion, with one phase starting the various sub-elements. Although this is mainly an internal research effort, we feel the outcomes will be of interest to other researchers in the field, regulators, policy makers, and those working on relevant space safety and sustainability standards and best practices. We invite discussion and collaboration.

1 Introduction

The Aerospace Corporation [6] was established 60 years ago as a not-for-profit research and development corporation, that conducts extensive research [7] in both customer-directed, as well as self-directed, principal-investigator-led projects, in topic areas that include space situational awareness, space traffic management, and space debris. Some research is highly customer-issue focused, yet a lot of the activity is more foundational in nature and is of interest to or impacts a broad range of customers and efforts across the Aerospace enterprise [8]. We have been involved in an internal integration effort to understand the various research threads and activities across the corporation, and to pull them together, for both understanding of what investigations and activities are being conducted that are of general interest across our enterprise, but to also identify gaps and needs that we hope to fill.

If we break down the various problem areas into sets and relate them to Aerospace's various customers, both external and internal, and enumerate the elements of these sets, or 'equities', we find one possible way to display this mapping of elements into sets and sets into problem or focus areas for the customers (e.g., space traffic management, space situational awareness (SSA), space domain awareness (SDA), etc.) which may be seen in Fig. 1. We find that equities that touch on the largest number of external customers, those that are the most common, generally fall within the STM equities set. It is from this set of equities that we will choose those that will most advance our goals and that we have the necessary expertise and capability to further develop. In other words, is this research we should do internally? Can we accomplish something useful with existing available resources, and is

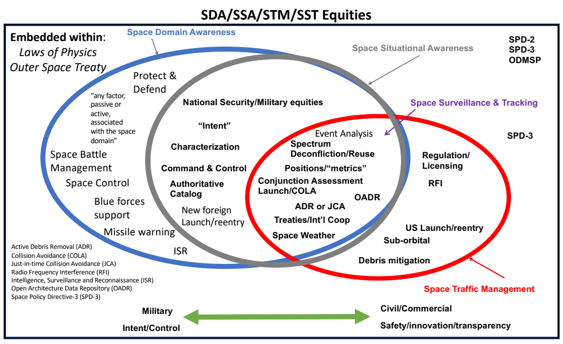

Figure 1 displays how we look at the stakeholder perspectives and the equities that fall within each set, and how the sets overlap with one another

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What we are identifying as STM research touches on several related areas. We need to consider also the space debris environment, and how data flows between SSA and STM. We note that SSA encompasses monitoring and measuring objects in space, characterizing the objects, as well as performing root cause anomaly analysis, as needed. The management of space debris (also described as space environment management (SEM)) [9] includes debris mitigation and remediation. Pertinent topics in STM include collision avoidance, regulations to enforce debris mitigation rules, and coordination with active space objects.

We categorized the various efforts, into "themes" or "topic areas". We identified five such topic areas:

Topic 1: STM Enterprise Analysis & Policy Justification
Examining "big-picture" issues across STM including interactions between technical and operations areas, quantification of effectiveness of space safety techniques to guide policy and best practices

Topic 2: Space Tracking Data Integration
Areas related to the integration and utilization of space tracking data

Topic 3: Effective Collision Avoidance (COLA) System Implementation
Areas addressing improvements to collision avoidance

Topic 4: Mitigation Technologies & Techniques
Technologies for improving debris mitigation and space safety

Topic 5: Advanced Collision Prevention
Farther-term techniques for reducing conjunction frequencies, collision risks, and debris generation

These five areas provide a framework for our STM-related efforts. We see them as somewhat sequential, but not rigidly so; although some things build on previous topics, there is interplay and feed-back between the topics, which may be seen in Fig. 2, which displays our phased approach to tackling these topics, in the form of a "roadmap".

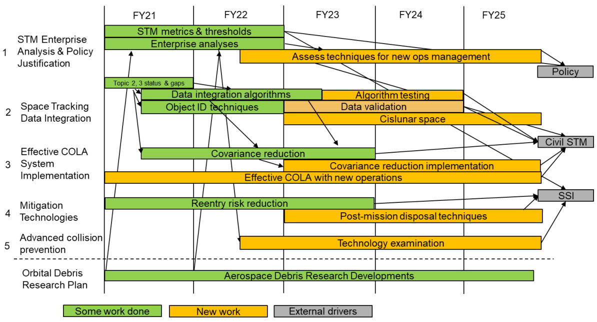

Figure 2 outlines how we see phasing research topics to fit within the framework, how this fits with existing efforts, where we identify new work to be accomplished, and identified external drivers, such as Policy considerations, support to a new Civil STM agency, and work with a nascent "Space Safety Institute" (SSI) [10].

2 STM Enterprise Analysis and Policy Justification

In Topic 1, our strategy is to assess large-scale approaches to STM with the goal of identifying integrated policy and guiding further research. This includes assessing the interplay between short-term satellite safety and long-term environment evolution, for example examining the interaction of post-mission disposal and collision avoidance frequencies, the interplay of mitigation and remediation (e.g., active debris removal), and the trade-offs between distributed satellite systems (e.g., large constellations) and more capable/complex satellites on STM and environmental effects. We will examine the interaction between sensing and tracking capabilities and STM and the space environment. This topic is a good fit with our internal capabilities and interests and leverages our modeling capabilities that enable the examination of large trade spaces, our history of examining the interplay between operations and the space environment, and our traditional role of providing technically-justified policy options. Our long experience with satellites both tempers and provides a broader cost-benefit assessment for policy options we may develop. Topic 1 will consist of not just traditional R&D, but also studies and assessments, as well as enumerating policy options.

As space operation become more complex with more actors, more varied activities and significantly greater traffic understanding the interactions between different aspects of space safety become increasingly important. With the trend toward large percentages of space activity being commercial rather than government there is less margin for overly conservative rules and behaviors. It then becomes important to be able to thoroughly understand the benefits and consequences of proposed rules and guidelines as well as their interactions. The Aerospace research efforts in this topic area are designed to do that and we encourage the rest of the community to step up efforts in these areas. Having a broad understanding of costs and benefits from both government and commercial perspectives will be critical for the international community to identify the best way forward to both encourage innovation and maintain a safe operating environment for everyone.

3 Integration of Space Tracking Data

Combining disparate sources to get a better answer

Research topic 2 involves a number of areas having to do with integrating data from various sensors and various types of sensors (examples may be seen in Tab. 1). We see this as beginning with the validation and characterization of data from sensors and networks of sensors, including data from other than US government sources (e.g., commercial or foreign sources), and the development of real-time sensor calibration techniques. We plan algorithm development for integrating different data sources and types (e.g., operator ranging and optical telescope tracking data, or operator-supplied position, navigation and timing (PNT) data with radar measurements, etc.). Questions we are considering include how to effectively integrate sensor data with different data volumes and distributions along orbital tracks, how to identify which data will improve tracking results (and which will not), and how to integrate ground sensor, space-based sensor and operator data. Challenges include how to blend SSA data from the Space Surveillance Network (SSN) and commercial vendors, how to gather and blend in owner-operator data (e.g., operator ranging data or on-board GPS data), and how to gather and employ real-time maneuver data from operators, especially autonomous maneuver plans. We will develop solutions for real-world issues with data integration that have

Table 1 shows examples of various types of relevant observational data (time-tagged positional measurements), and other useful information, such as maneuver plans. Note that positional uncertainties are not indicative of a single observation, but what may be achieved after analysis of several observations. The first three items are generally provided by third parties, the latter three items by a satellite's operator.

Radar
• *Usually for LEO objects* • *All-weather, 24/7* • *>10-100 m positional uncertainty*
Optical
• *Usually for high orbits (>10k km): MEO, HEO, GTO, GEO* • *Usually requires terminator conditions, ~30-m positional uncertainty*
Laser Ranging
• *Requires network of laser ranging stations, like ILRS* • *Weather outages* • *~cm-m positional uncertainty (better with corner cube reflector)*
Operator ranging
• *Self-reporting by Operator when making contact with satellite* • *>10-100 m positional uncertainty*
PNT (GPS)
• *Self-reporting by Operator from telemetry, usually LEO* • *1-3 m positional uncertainty*
Other useful information: Operator maneuver plans

for deployment (this is an acute problem for CubeSats, see Fig. 3) [11]. This topic also entails the management of issues pertaining to extending object trackability range (e.g., how to deal with data from new sensors on a large number of objects smaller than 10 cm, which gives catalogs a "fuzzy" lower boundary, and catalog management of greatly increased numbers of objects, and the uncertainties in the measurements. Also, there is interest in extending SSA to cislunar space, with its vastly larger volume of space than current SSA incorporates.

The challenges of collision avoidance in the face of the increasing density and pace of operations require the use of <u>better</u> knowledge of the orbits and intentions of the resident space objects. Separate and independent orbit predictions have the potential to add confusion rather than clarity. Finding better ways of combining these various data sources into the <u>best</u> answer will have benefits for all residents, and we encourage research into this topic.

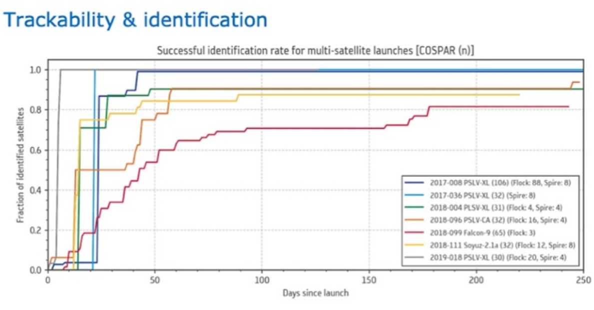

Figure 3. It can take weeks to months to identify most of

4 Effective Collision Avoidance (COLA) System Implementation

Current COLA practices are inadequate for the new large constellations and satellites using autonomous maneuvering; we need a <u>new approach</u>

The third research thrust is to implement more effective collision avoidance systems (see Fig. 4) [13]. We will develop covariance reduction and accuracy characterization techniques, including algorithms for optimizing sensor collections to improve conjunction covariance, as well as tracking enhancement technologies and implementation strategies. We will develop methods for managing new operations and techniques, including management of multi-object (large number) deployments (see Fig. 5), frequent or extended maneuvers (e.g., low thrust electric propulsion) and non-propulsive maneuvers (e.g., dynamic drag), management of large satellite constellations [14], and rendezvous and proximity operations, and other low-velocity conjunctions.

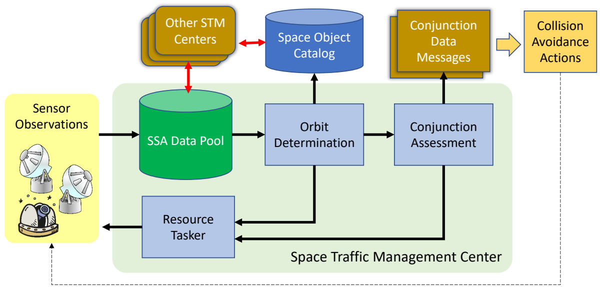

Figure 4 illustrates a notional "safety cycle" for COLA assessment, including integration and vetting of multiple data sources, sharing of data with other STM Centers, orbit determination and catalog correlation, and conjunction assessment and collision avoidance monitoring

The traditional approaches and timelines for collision avoidance as outlined in Fig. 4 will become less and less effective in the face of large constellations and automated low-thrust maneuvers. We encourage the community to re-consider how we should approach basic collision avoidance in the face of these changes.

5 Debris Mitigation Technologies and Techniques

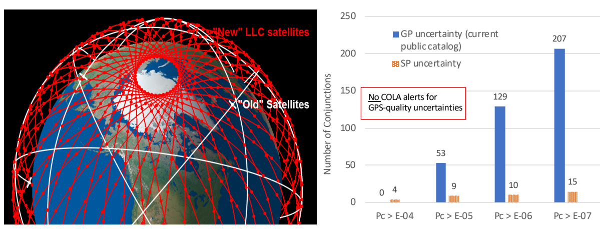

Figure 5 illustrates one of the problems that large LEO constellations may incur. In this example, a constellation consisting of 1225 satellites has them distributed in 35 circular orbit planes at 1000 km, 98° inclination. There are also 6 satellites pre-existing at the same altitude and 63° inclination. Using SPG4-quality uncertainty and a probability of collision (P_c) with a 10^{-7} threshold, these systems will see more than 200 conjunctions in 30 days. However, if GPS-quality uncertainty is assumed, there

"First do no harm"

In an effort to help prevent more space debris from being created, we plan to look at various mitigation technologies and techniques for improving debris mitigation and space safety. We recognize the large research effort underway in many institutions, e.g., the European Space Agency, with designing satellites for demise during atmospheric break-up, and plan to look at improving post-mission disposal techniques, especially for satellites that are disposed of in-orbit (e.g., the geosynchronous "grave yard" orbit [15]). For example, retiring a satellite to the graveyard orbit can be a complex process, and could be made simpler. Also, we note that satellites that are disposed of in-orbit do not necessarily remain intact, and they may shed surface layers (e.g., multi-layer insulation) that may be the source of the high area-to-mass ratio (HAMR) debris population, see Fig. 6. Objects that are disposed of in-orbit need to be passivated by having all of their stored energy sources depleted, which to date may not be as effective as it was thought. We want to avoid having the burgeoning CubeSat & nanosat population become a source of orbital debris by being "dead on arrival" and will look at de-orbit devices for use at higher LEO altitudes [16].

The international community has already set broad principles and guidelines for debris mitigation, including preventing collisions and explosions, and calling for effective post-mission disposal. The rate of successful compliance with these guidelines and principles is less than it should be, even when the clear intention is to comply. We encourage further research into how and why these failures occur, and into better approaches to compliance.

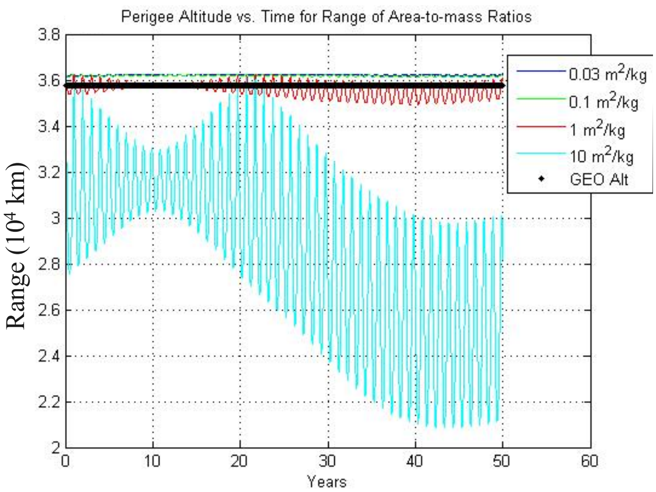

Figure 6 shows how four objects having area-to-mass-ratio (AMR) values of 0.03, 0.1, 1, and 10 m^2/kg, respectively would evolve over a 50-year span if shed from the same retired GEO satellite at the graveyard orbit altitude at the same time. Note that the higher airmass object almost immediately dips below the GEO altitude, and over time may interfere with PNT satellites at lower altitudes

6 Advanced Collision Prevention

Research the net environmental impact of debris and <u>justify debris remediation approaches</u> with cost-benefit analyses

The advanced collision prevention research topic will investigate methods to prevent collisions between uncontrolled space objects (debris on debris collisions). This includes gaining a thorough understanding of what we are trying to accomplish and then using these goals to drive solutions. It is our observation that much of the current ADR research is very 'siloed' or narrow in its applicability. It is likely that there is no 'silver bullet' single solution, but through research an optimum solution can be used for a subset of debris, and thus a set of optimal solutions can be identified that, taken together, represent a the best-in-class solution to deal with the full range of debris challenges. Some of the alternatives include attaching small "sticky" modules with some propulsive capability on large debris, to rather move the debris out of the "active driving lane" and onto the shoulder, and to disperse massive, dangerous clusters. Additionally, we will also examine just-in-time-collision avoidance (JCA), which could be quite effective at preventing actual collisions, but could require very high accuracy knowledge of objects' orbits [12]. Fig. 7 illustrates some of the options to be examined.

Aerospace believes that minimizing debris mass on orbit is the most critical parameter in controlling the growth of the debris environment and is a much more useful metric for debris growth than is the simple number of objects. ADR should thus focus on removing or reducing collision risk from massive debris objects. Sweeping small debris objects is likely to be very difficult and probably will not be cost-effective, and it must be coupled with massive object removal – one large breakup could undo years of efforts sweeping small debris. Targeted deorbit of massive objects may be needed for due to minimized reentry risk, which would place higher demands on ADR system capabilities. In any event, any approach to ADR must have extremely high reliability; i.e., we should never make more debris while attempting a cleanup.

Overall, we encourage the community to conduct research and advance the technology of active debris removal. It should do so with clear goals and a holistic, cost-benefit approach to evaluating alternatives.

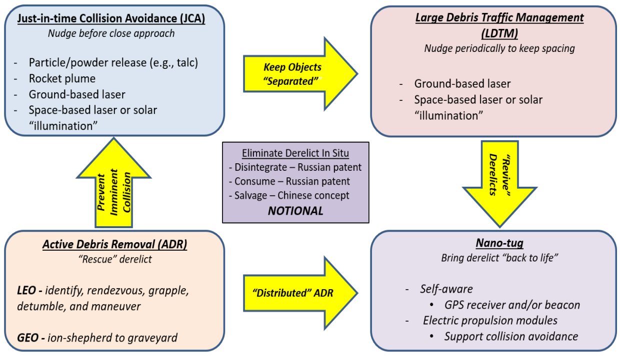

Figure 7 shows some of the options under consideration for debris remediation in addition to traditional active debris removal (ADR). From [17], used by permission.

7 Comparison to US National Orbital Debris R&D Plan

There is good consensus on the prioritization of research efforts.

Earlier in 2021, the US Office of Science, Technology and Policy (OSTP) released the "National Orbital Debris Research and Development Plan," which had been assembled and written by the Orbital Debris Research and Development (ORAD) Inter-agency Working Group (IWG). In many ways, the two plans are very similar, see Tab. 2. That there is similar conclusions as to the way forward. Additionally, many experts at Aerospace provided input and opinion to the National R&D Plan. That there are differences between the two can be ascribed to Aerospace's prioritizing research efforts that we feel we can provide the largest impact, based on our experiences and resources.

Table 2 lists the three core elements and fourteen prioritized topical areas for US National R&D activities for orbital debris risk management [18].

1. Limit debris generation by design. Deliberate spacecraft design choices can limit the generation of new debris. • Reduce debris during launch • Improve resilience of spacecraft surfaces • Improve shielding and impact resistance • Develop designs that will reduce or limit fragmentation processes • Improve maneuverability capabilities • Incorporate end-of-mission approaches to minimize debris into spacecraft and mission design
2. Track and characterize debris. Debris tracking and characterization are critical to enabling effective mitigation measures and safe spaceflight operations. • Characterize orbital debris and the space environment • Develop technologies to improve orbital debris tracking and characterization • Reduce uncertainties of debris data in orbit propagation and prediction • Improve data processing, sharing, and filtering of debris catalogs • Transition research on debris tracking and characterization into operational capabilities
3. Remediate or repurpose debris. Remediation activities, also called active debris removal, could in the long-term substantially reduce the risk of debris impact in key orbital regimes. Repurposing may also contribute to reducing risk and removing debris. • Develop remediation and repurposing technologies and techniques for large-debris objects • Develop remediation technologies and techniques for small-debris objects • Develop models for risk and cost-benefit analyses

8 Conclusion

We have outlined an internal multi-year research effort that we plan to embark on across the Aerospace Corporation. This phased approach begins by looking at the bigger picture of debris, space safety and space sustainability, rather than jumping immediately into narrow research threads. The conclusions we draw from the initial effort will guide subsequent phases of our research program, including examining how to combine different types and sources of space tracking data to arrive at a better answer as to where things are and where they are going, how to deal with some of the new modes of operation in space (large constellations, autonomous and/or continuous maneuvering), investigating how best to prevent debris from being generated in the first place, and which approaches make sense if remediation is relevant space safety and sustainability standards and best practices. We invite discussion and collaboration.

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