Proposed Series of Orbital Debris Remediation Activities

"Monitor, characterize, and act to assure space flight safety"

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EXECUTIVE SUMMARY: Orbital debris is a growing hazard to reliable space operations and the sustainability of space-based systems that increasingly support national security and economic stability for many countries, including the United States. Short-term attention has been focused on collision avoidance for operational payloads and enhanced debris mitigation guideline compliance while long-term attention has been focused on debris remediation via active debris removal (ADR). These three activities must be continued and augmented by three new efforts that work together to provide both enhanced space flight safety and improved debris remediation activities that will contribute to long-term space sustainability and the positive reputation of the U.S. space program.

HYPOTHESIS: I propose that the spacefaring community is focused on environmental stability as the primary metric for responsible actions in space and for prioritizing investments. While preventing a runaway cascading of collision events in Earth orbit (i.e., environmental instability) is a laudable and necessary goal, I believe that we should be focusing more now on space flight safety as a relevant research, analysis, and development foundation.

The erosion of space flight safety (i.e., degradation of payload operations and reduction in operational lifetimes due to debris impacts) will occur well before the environment will manifest in outward signs of a runaway cascading effect. In addition, the means to ensure spaceflight safety will require more proactiveness in debris remediation options than is currently envisioned (e.g., five derelict removals a year starting at some future indeterminate time is a typical sequence under consideration). This is even more pronounced when considering clusters of massive derelicts that potentially have elevated[1] risk levels. A more tactical responsiveness to prevent imminent collisions of derelicts will also contribute to preemptively preventing space environmental instability.

SOLUTION COMPONENTS: I propose that there are three related activities required to grapple proactively with the future orbital debris evolution in the most responsible way to address current challenges detailed in the Hypothesis.

First, there is a significant benefit to measuring and quantifying the ensemble of spacecraft anomalies and failures that are tied to orbital debris impacts as this is a direct measure of the influence of the worsening debris environment on satellite operations. The attached paper was presented at the International Astronautical Congress (IAC) in Jerusalem in November 2015 and provides a high level summary of related research over the last 25 years.

Over the last three years, I have organized and hosted a **Spacecraft Anomalies and Failures (SCAF) Workshop** in Chantilly trying to advance the community's understanding of how orbital debris is influencing satellite operations. This workshop has been supported by and attended by NASA, NRO,

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[1] "Elevated" means higher than is predicted by the traditional statistical probability of collision equation.

NOAA, other USG organizations, U.S. industry, and U.S. academic institutions. Deliberations have highlighted that (1) most space operators do not invest significant resources to resolve the cause of unknown non-recurring anomalies; (2) attributing anomaly cause is difficult and more of an art than a science largely due to the complex space environment and lack of anomaly diagnostics on spacecraft; and (3) most space operators will not share their on-orbit anomaly and failure data due to concerns of proprietary technology, user/stockholder confidence, national security, and space insurance implications.

I suggest that an international organization such as the Inter-agency Space Debris Coordination Committee (IADC) take on the charter to plan, organize, and conduct an annual international Spacecraft Anomalies and Failures Workshop or support the expansion of the existing SCAF Workshop. It is hoped that this would help to generate an impetus for spacefaring organizations to share information that will provide a better assessment of how the manmade particulate environment has affected operational satellites in the past and support future real-time assessments of anomaly and failure trigger identification. This insight is necessary to quantify the fidelity of all of our debris environment models and to provide a measurable intermediate assessment of the evolution of the debris population. It will be the increased number of anomalies and failures to operational spacecraft that will be the best indicator of orbital debris hazard severity from the debris population too small to be cataloged (i.e., smaller than 10cm).

By measuring spacecraft anomalies and failures more carefully it will provide an early warning indicator for a worsening debris environment. If we wait for a cascading of collisions before we act in earnest, it will be more difficult and costly to remediate the debris environment (i.e., "pay me now or pay me more later"). The National Space Policy of 2010, Presidential Policy Directive-4, states that the U.S. should *"improve, develop, and demonstrate, in cooperation with relevant departments and agencies and commercial and foreign entities, the ability to rapidly detect, warn, characterize, and attribute natural and man-made disturbances to space systems of U.S. interest."*

In essence, this directive is requesting that we execute on workshops such as SCAF. Characterization of the negative influence of the orbital debris environment on operational systems provides an indirect proxy for the majority of the debris environment which is very difficult to measure directly for the size of debris that are mission-degrading or mission-terminating (i.e., 5mm to 10cm).

Secondly, while protecting operational satellites from the trackable population via collision warnings provides a quantifiable risk mitigation mission, the primary threat to operational spacecraft comes from the lethal nontrackable (LNT) environment that will produce the vast majority of the anomalies and failures examined by the activity just outlined. LNT debris ranges from about 5mm to 10cm; these are fragments that are large enough to disrupt and terminate a satellite's mission upon impact but are too small to be cataloged. There is an estimated 500,000-700,000 LNT in LEO currently. Therefore, the cataloged population (~18,000 in LEO) that is evaded through active maneuvering is less than 5% of the lethal population.

In the future, this population will be added to primarily from collisions between large objects in orbit as the number of LNT produced is proportional to the mass involved in a collision (or explosion).[2] Cataloged debris produced from a catastrophic collision will be liberated at about 1-3 fragments per kilogram of mass involved while LNT production is around 10-40 fragments per kilogram of mass involved.

The Iridium/Cosmos collision involved a total mass of 2,000kg and produced over 3,000 trackable fragments and likely 10,000-15,000[3] LNT debris. The Feng-Yun purposeful collision yielded over 2,200 trackable fragments and likely over 30,000 LNT from only ~850kg of mass involved. While it is important to prevent these types of events from occurring in the future, the consequence of a collision (based on number of LNT produced) will be proportional to the mass involved in the collision.

The term “mass involved” implies a good coupling of the impactor mass with the target mass. For a large fragment (e.g., several kilograms) striking a typical payload (that is densely built) in its main satellite body (vice striking a solar array or other appendage) at hypervelocity speeds (i.e., above 6km/s) will result in all the mass being “involved” in the debris. However, a large fragment striking a derelict rocket body, due to the way that the mass is concentrated at the ends of a rocket body, will likely not result in all of the mass being “involved” in the liberated debris. However, it is likely that when two large derelicts, either rocket bodies or payloads, collide with each other, then all of the mass will be involved due to the likely direct physical interaction between the mass. The table below summarizes the mass involvement scenarios which highlight why the massive-on-massive collisions are the focus of our analyses.

Collision Types	Intact Payload (P/L)	Intact Rocket Body (R/B)
Large (several kg) Fragment	All mass involved	Fraction of mass involved
Intact Derelict (P/L or R/B)	All mass involved	All mass involved

Therefore, it is best to prevent the collision of the most massive objects with each other (higher consequence) and the ones that are the most likely (higher probability) since risk is probability multiplied by consequence.

Our ability to model and predict the rate of collisions is based empirically upon only one catastrophic accidental collision event and a model developed on the kinetic theory of gases (KTG). However, clusters of massive objects that have identical inclinations plus similar and overlapping apogees/perigees may indeed have a greater probability of collision than predicted by the KTG-based algorithms as they are not randomly distributed and their orbital element evolution (e.g., change in right ascension of ascending node and argument of perigee) is also similar. It is hypothesized that these similarities could result in resonances of collision dynamics that may lead to larger probability of collision values than predicted with current algorithms.

Massive-on-massive collision → potentially larger probability and definitely larger consequence

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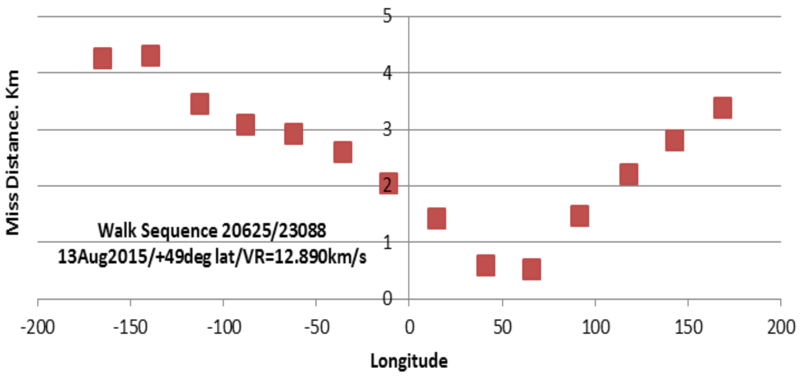
[2] Typically, catastrophic explosions create many fewer fragments per mass involved than catastrophic collisions.
[3] The LNT production is probably lower than average due to incomplete fragmentation of objects involved.

The not well-known fact is that many of the most massive objects are in tightly clumped clusters that will likely produce greater probability of collision than estimated by the KTG approach (see attached paper) and with the much larger consequence (i.e., creation of catalogued LNT fragments). The attached paper that studied this possibility shows some initial indications that this may indeed be true but much more analysis is needed to provide this conclusively.

Objects / Mass (kg)	Number of Objects	Total Mass (kg)	Cluster Center / Inclination
SL-8 rocket body / 1,434kg	~150	~215,000	950km/83°
SL-16 rocket body / 8,300kg	~20	~100,000	850km/71°
SL-8 rocket body / 1,434kg	~65	~90,000	1,500km/74°
Assorted Int’l payloads and rocket bodies / ~2,000kg	~40	~80,000	825km/99°
SL-8 rocket body / 1,434kg	~50	~70,000	750km/74°
Meteor payload / 3,250kg	~20	~65,000	850km/71°
SL-14 rocket body / 1,407kg	~30	~42,000	1,500km/73.6°
SL-3 rocket body / 1,440kg	~30	~40,000	900km/81.2°
Cosmos 2-3 payload / 1,295kg	~25	~35,000	950km/65°
Meteor 1-X4 payload / 1,200kg	~20	~25,000	850km/81.2°
SL-14 rocket body / 1,407kg	~10	~14,000	950km/82.6°
CZ-4 rocket body / 2,000kg	~5	~10,000	920km/99°
Ariane 40B rocket body / 1760kg	~5	~9,000	780km/98°
TOTAL DERELICTS IN LEO	**~480**	**~810,000kg**	-----

This table of clusters represents well over 50% of the total derelict mass in LEO. However, no one is currently monitoring these potential events. It is proposed that it would be a prudent risk management approach for space flight safety to monitor and characterize this inter-cluster collision risk. The **Massive Collision Monitoring Activity (MCMA)** is proposed whereby the encounters between members of these clusters are constantly monitored and close encounter information collected, plotted, analyzed, and shared. This would provide a rich research base for scientists and a predictive service for spacefaring countries. I am currently executing a subset of this proposed activity in an ad hoc fashion in conjunction with JSpOC. I have been monitoring the interaction dynamics between the SL-16 population in the 820-865km altitude region for the last nine months.

The figure to the right shows an encounter sequence on 13 August 2015 as two SL-16s passed within 5km of each over 14 orbits in a row with the closest pass being 526m. Between 11May2015 and 11Feb2016, there have been 8 passes within 1km (closest pass was 425m on 1Aug2015) and 175 passes less than 5 km.



One might ask, so what if we see an impending collision between two massive derelict objects, what can we do about it? Do you want to be sitting at the console watching the miss distance between two SL-16s closing in orbit after orbit knowing that this one collision (that has at least a 1/400 chance of occurring in the next decade) that would likely double the debris population in a single event cannot be prevented? This leads us to the third and final research area being proposed to be raised up for increased activity – **Just-in-Time Collision Avoidance (JCA).**

The concept of JCA is to use a sounding rocket on a ballistic trajectory releasing a cloud of gas or very small particles in the path of one of the two potentially colliding derelicts to deflect its path to prevent the imminent collision (or widen the predicted miss distance to an acceptable level). The attached paper provides details of the JCA concept as it currently stands. It should be noted that JCA is not proposed to replace ADR but, rather, would contribute to determining the best combination of ADR and JCA that would minimize the chances of the future deterioration of the space environment with high confidence and maximum cost-effectiveness. More importantly, it provides a timely means to prevent a significant imminent debris-generating event between two massive uncontrolled objects in space. JCA would cost about $1-3M per launch and even with a few false alarms a year would be 1000x less expensive than ADR operations (~$140M per mission[4]) as measured by cost per collision prevented but still leaves the derelict in orbit.[5] It is expected that JCA and ADR operations will eventually be performed in tandem, reinforcing each other with ADR operations removing "frequent JCA offenders" and JCA creating risk statistics to make more relevant decisions about removal of the derelicts. The table below summarizes ongoing and proposed efforts under the banners of short-term and long-term foci.

Timeframe	**ONGOING**	**PROPOSED**
Short-term	*Collision avoidance for operational satellites and enhanced debris mitigation guideline compliance*	
		Characterize current space flight safety degradation from debris impacts (via Spacecraft Anomalies and Failures, SCAF, Workshops)
		Characterize cluster dynamics for massive objects (via Massive Collision Monitoring Activity, MCMA)
		Just-in-time Collison Avoidance (JCA) concept development
Long-term	*Prevent environmental instability*	
		Ensure continued operational space flight safety
	Active debris removal (ADR) study	ADR demonstrations and operational testing
		JCA demonstration and operational testing leveraging MCMA data

The combination of these three tasks (i.e., SCAF, MCMA, and JCA) will provide (1) an advanced SSA perspective for the international community and (2) a more defensible, proactive debris remediation stance that will position the U.S. as a global thought leader in space technology and space environment sustainability that will also catalyze ongoing discussions on space traffic management. This proposal assumes that continued pressure and resources will be applied to (1) increase the worldwide

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[4] Wiedemann, Carsten**, "**The Cost-Effectiveness of Post-Mission Disposal Maneuvers**,"** Technische Universität Braunschweig, 65th International Astronautical Congress, Jerusalem, IS, October 2015.

[5] The current approach to ADR is that of a long-term statistical cleanup effort that prevents one collision for every 35-50 derelict removals which produces a cost of approximately $1-3B per collision prevented. ADR solutions are currently not operational and even as envisioned are not responsive enough to react to MCMA Warnings.

compliance to existing debris mitigation guidelines, (2) move ADR concepts to an operational state, and (3) continue conjunction warnings for operational satellites; these three activities are essential complementary work that must be continued along with the three new proposed activities.

Augment ADR study, enhanced debris mitigation guideline compliance, and the focus on preventing environment instability with (1) more focus on space flight safety via quantification of debris-induced anomalies worldwide, (2) characterization of clustered massive-on-massive encounter dynamics, and (3) development of tactical response to imminent massive-on-massive collisions between derelicts that can work cooperatively with ADR capabilities.

<u>SUMMARY</u>: I would like to encourage the immediate application of resources (diplomatic, operational, engineering, and new funding) to increase efforts in the three proposed areas. There is some question how to best "divide and conquer" globally in the execution of these activities. The table below provides a strawman of how to best to proceed, however, it is likely that this draft approach will require significant tweaking as it is exposed to interested parties. The primary motivation for this white paper is to advance the space community's position on orbital debris response well past a philosophy of "study, wait, and hope" to "monitor, characterize, and act responsibly."

"Study, wait, and hope" → "Monitor, characterize, and act"

The table below summarizes the three topical areas and issues related to their transition into real initiatives.

Activity	Current Status	Proposed Lead Organization	Issues
Spacecraft Anomalies and Failures (SCAF) Workshop	Ad hoc support from NASA and NRO over the last three years and wide participation from across USG spacefaring agencies, industry, and academia.	IADC – make this an international effort to start to bring spacefaring countries together to emphasize how data sharing and joint analysis will contribute to space flight safety for all countries.	Already have difficulties getting people to share in a U.S.-only environment (first day unclassified and second day classified); these issues will only be worse in an international venue.
Massive Collision Monitoring Activity (MCMA)	Support from JSpOC for a small demonstration since May 2015 of this type of activity but needs to be expanded in scope of analysis and determined how to best provide artifacts to spacefaring organizations.	JSpOC or temporary operational partner will transition to wherever the space catalog migrates. It is not a battle management issue.	The staffing required to make this analysis real is minimal (one full-time position) so possibly an intermediate solution of a USG agency getting data from JSpOC under the current arrangement is sufficient for for 18 more months then reexamine next step.
Just-in-Time Collision Avoidance (JCA)	JCA work has been all on paper thus far with no government acceptance as a part of the USG debris remediation strategy though through the IAA it has been accepted as a viable debris remediation adjunct.	IADC – make the development of this capability an international effort to spread out costs and support its ability to be seen as non-confrontational. USG should seed with initial funding for international (jointly with CNES and UKSA) demonstration within 18 months.	This process may be seen as a potential antisatellite weapon. However, the fact that it uses existing launch systems and even if it "misfires" the encounter cloud produced may be seen as the equivalent of a non-lethal countermeasure as used in law enforcement is good.

Attachments: Anomalies paper, Jerusalem 2015; Clusters paper, Toronto 2014, and JCA paper, Krokaw 2015