RESPONSIVE SSA – RESPONDING TO NEW SPACE AND OLD PROBLEMS

Dr. Darren McKnight
Integrity Applications, Inc., dmcknight@integrity-apps.com

Chris Senio
BaskEra, LLC, csenio@baskera.com

Dr. Kevin Molloy
George Mason University, kmolloy717@gmail.com

ABSTRACT

The space environment is becoming complicated by the layering of new space system architectures and a diversity of new spacefaring entities adding to the existing derelict debris population. This dynamic situation will require more responsive space situational awareness (SSA) capabilities to efficiently respond to the changing nature of space operations without looking past the lingering hazards posed by sixty years of leaving derelict hardware in orbit. This paper will provide contrast between the exciting New Space developments and the hazards associated with literally millions of kilograms of abandoned hardware in the same orbits where large distributed constellations are being planned for deployment. A series of recommended attributes for "responsive" SSA needed to manage these two disparate populations is proposed.

BACKGROUND

Space is becoming increasingly globalized and diverse in every way imaginable. There are more countries launching satellites for the first time using new technologies in new space system designs being operated by new, potentially novice, space operators. These new space entrants will likely commit more errors than the seasoned space agencies and companies who have been operating satellites for years. In addition to new entrants, there are also constellations of satellites that are larger in number than any deployed in the past. With proposed constellations as large as 900-4,000 satellites, any systemic design or manufacturing issues that result in reduced satellite reliability may be amplified with these large constellations.

In tandem with the new satellites and satellite architectures, new launch systems are being rolled out over the next few years to service this new demand. Unfortunately, historically we know that new launch systems will be much less reliable until about the 3rd or 4th launch[*] so there will likely be some launch failures in trying to deploy these constellations.[†]

[*] Kunstadter, Chris, "Space Insurance Update", Space Environmental Anomalies and Failures Workshop, Toulouse, France, Oct 2017.

[†] In 2017, three of the six launch failures were either the first or second launch of a new launch vehicle (Spaceflight 101, 31DEC17).

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The overall result of all of these trends is that there will be more, but less experienced, space operators in space which will pose increasing hazards to operational space systems and put greater demands on existing and emerging space surveillance systems.

In addition to more, and different types of, space users becoming active in space, the cataloged debris has grown steadily over the last sixty years; there is no reason to believe that this growth will be abated. Figure 1 is a depiction of the growth over the space age as a function of time and object type for all manmade objects large enough to be tracked in Earth orbit. The total number of objects cataloged is driven by the fragment population which has recently been influenced largely by two major breakup events in 2007 and 2009. However, the primary risk comes from the part of the debris population that is too small to be sensed by ground radars and telescopes yet would likely terminate a satellite's mission if struck by one of these particles. This population is called lethal nontrackable (LNT) and includes all fragments between 1-10cm in diameter. There are an estimated 500,000-700,000 of the LNT fragments in low Earth orbit (LEO) (i.e., less than 2,000km altitude). The LNT population is important since it poses a risk that satellites cannot be warned to avoid.

In 2007, the Chinese destroyed their own satellite in an antisatellite test producing over 3,000 fragments in long-lived orbits in LEO. This was followed in 2009 by the accidental catastrophic collision between the operational Iridium-33 satellite and the defunct Cosmos

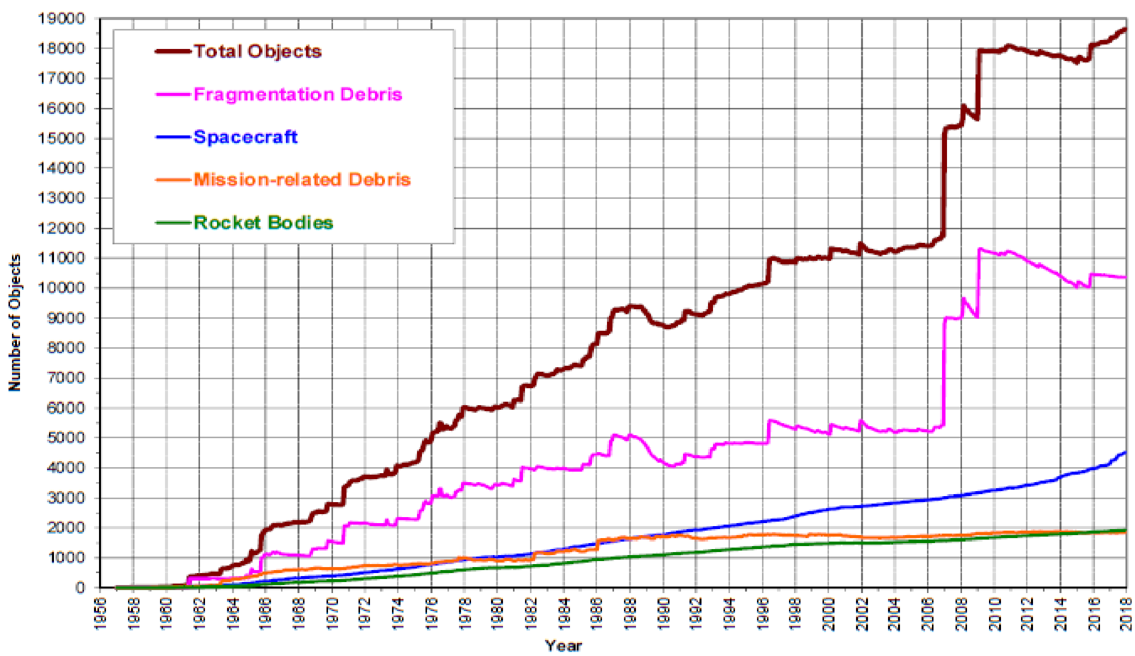


Figure 1. The cataloged population has grown steadily but sporadically during the space age. (Source: Orbital Debris Quarterly News, February 2018)

2251 payload. This event also produced over 2,000 cataloged fragments in LEO. Years of the leveling of the cataloged population from 1997 to 2007 was disrupted by these two events. In Figure 1, the number of spacecraft and rocket bodies seems small in number (i.e., totals ~6,500 of the ~18,600 total catalog) but of the ~4,500 spacecraft only ~1,700 are operational so the other ~2,800 dead payloads combined with the ~2,000 abandoned rocket bodies[‡] amount to over 7,500,000kg of space debris in only ~4,800 objects. These massive derelicts provide the potential mass for future debris-generating events since each kg of mass involved in a catastrophic collision will produce up to three trackable fragments and 30 LNT fragments.[§]

Figure 2 provides a snapshot of the distribution of the on-orbit population by number highlighting that 91% of all objects on-orbit are debris (i.e., everything except the operational payloads). This percentage has actually shrunk in the last few years (from 96% to 91%) due to the recent deployment of many 1U-3U cubesats in the 400-600km altitude range. The non-operational payloads and derelict rocket bodies that amount to 26% by number, constitute 75% of the mass in Earth orbit.

If we tabulate these massive objects by orbital regime and type of object, the importance of this derelict hardware is amplified; see Table 1. As a matter of fact, the derelict hardware is ~3x

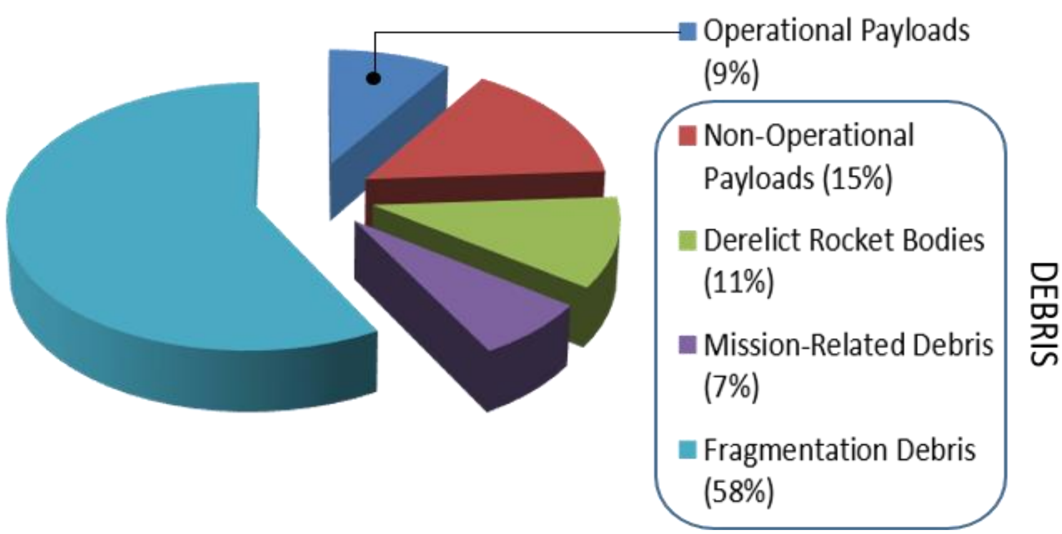


Figure 2. The vast majority of trackable objects in Earth orbit are debris and the majority of the debris are fragments from explosions and collisions.

‡ The fact that there are a similar number of dead payloads as abandoned rocket bodies is not completely a coincidence. Of the ~2,300 dead payloads there are ~500-600 occurrences where the rocket body that deployed it is lingering in a similar orbit. The remainder of the abandoned rocket bodies and payloads are not paired spatially.

§ McKnight, D.S., "Determination of Breakup Initial Condit ions," Presented at the 29th Aerospace Sciences Meeting, Jan 7-10, 1991 , Reno, Nevada; To appear in the Journal Of Spacecraft and Rockets, 1991 .

the mass of operational satellites; this is much more pronounced in LEO (i.e., ~6x). The equally large ratio of derelict hardware to operational payloads in the HEO (high Earth orbit) is due to the large number of rocket bodies in geosynchronous orbit (GEO) transfer orbits (GTO).

Table 1. The depiction of number/mass by orbital regime and type of object highlights how little operational hardware there is in Earth orbit relative to intact non-operational hardware.

	Number / Mass (million kg)			
Orbital Regime	Operational Payloads	Non-Operational Payloads	Rocket Bodies	Total
LEO	~950 / 0.5	~1,100 / 1.8	~1,250 / 1.2	**~3,300 / 3.4**
HEO	~250 / 0.3	~50 / 0.1	~300 / 1.5	**~600 / 1.9**
GEO	~500 / 1.5	~650 / 1.6	~ 250/ 0.5	**~1,400 / 3.6**
Total	**~1,700 / 2.3**	**~1,800 / 3.4**	**~1,800 / 3.2**	**~5,300 / 8.9**

As mentioned previously, the primary probability of collision is driven by the LNT population followed by the cataloged population; the current probability of collision is determined by the number of objects. However, the consequence from these events is small in comparison to collisions that might involve significant amount of mass such as the non-operational payloads and derelict rocket bodies. So, it might be said that the future debris hazard is a function of mass since it is the collisions between these massive objects that will drive the future population of cataloged and LNT debris. For this reason, we will scrutinize this small (by number) population which, unfortunately, actually largely linger in clumps due to a process whereby the rocket bodies that deployed payloads were abandoned in the same orbits as the payloads they delivered to LEO. This process is no longer employed by launching states and it was primarily used by Russian deployments in LEO.

OPERATIONAL CONTEXT

With this backdrop, it is clear that space situational awareness (SSA) will only get more difficult over time. So, in order to address SSA in a substantive way, we need to define the scope of SSA. We would like to propose that the overall construct for ensuring on-orbit space safety can be encapsulated in what we call Space Operations Assurance (SOA). SOA has three major components as depicted in Figure 3.

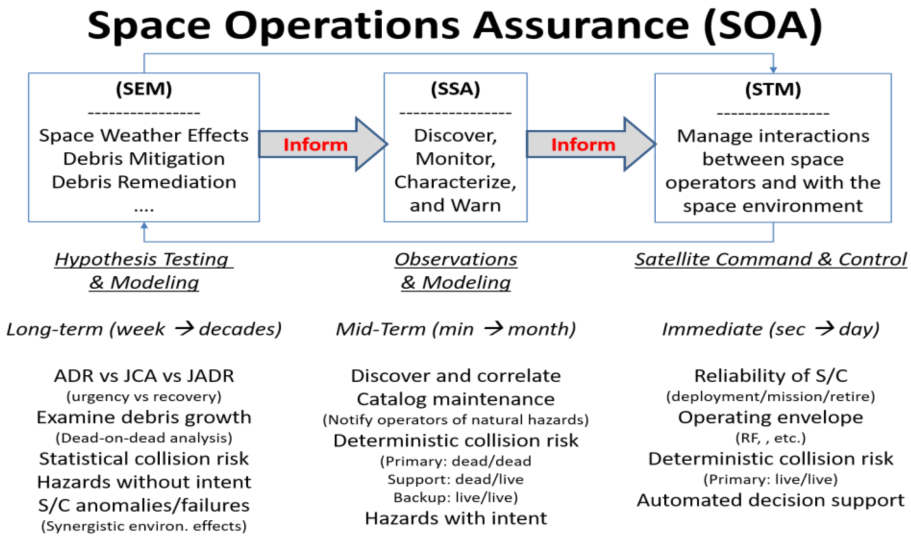


Figure 3. Space Operations Assurance (SOA) provides an umbrella under which space environmental effects, space situational awareness, and space traffic management work together.

Space Traffic Management (STM) is primarily satellite command and control to manage the interactions of and between space operators and with the space environment. STM has immediate, real-time needs such as reliability of spacecraft (deployment, mission operations, and retirement), radio frequency interference identification/resolution, defining an operating envelope (temporally, spatially, etc.), deterministic collision risk (primarily between two operating satellites), and automated decision support (covering all of the previous activities).STM is informed by the second major domain, SSA, that covers the capabilities to discover, monitor, characterize, and warn about space objects (with an emphasis on non-operational objects since constellation/satellite operators normally know the locations of their own objects better than anyone else).

The observations gathered by SSA resources produce mid-term insights (minutes to months) such as uncorrelated target processing, discovery of newly created space objects, space catalog maintenance, and deterministic collision risk (for dead-on-dead and dead-on-operational while providing backup for operational-on-operational).

SSA is informed by Space Environmental Effects and Modeling (SEM) activities that often use hypothesis testing related to research to better describe why space objects behave the way they do. This domain focuses on long-term (weeks to decades) issues such as examining tradeoffs between debris remediation options (e.g., active debris removal [ADR], just-in-time collision avoidance [JCA], and just-in-time ADR [JADR]), space weather/predictions, debris growth modeling, statistical collision risk, migration of high area-to-mass ratio objects, surface erosion, and spacecraft anomaly/failure attribution analysis.

Clusters of Massive Derelicts

Three clusters of massive derelict objects will now be detailed and compared to three constellations (one existing, one under development, and one to be deployed in the next few years) to provide context as to what risk is most important for the community to deal with: clusters or constellations. Each cluster is named by the center altitude of each cluster (e.g., C850 is a cluster centered around 850km). A cluster is defined as a set of space objects with identical inclinations and similar altitude. Note that each cluster is comprised of a set of rocket bodies (RB) and the payloads (PL) that the RBs deployed. [**] The investigation into the characterization of the conjunctions within each of these clusters is called the Massive Collision Monitoring Activity (MCMA) experiment.[††]

Figure 4 depicts the three clusters (in red font) and three constellations (in green font) plotted over Orbital Debris Engineering Model (ORDEM)-derived spatial density curves for LEO.[‡‡] Each of these collections of space hardware have a summary box that contains three characteristics of each: the first number is the number of objects in each collection, the second number is the approximate total mass of each collection, and the last number is the number of trackable fragments that would be produced by a collision between any two of each collection (i.e., cluster or constellation).

While the OneWeb constellation is largely above the fray from these events, they may still be affected by collisions in C975. However, the Iridium constellation is right in the middle of C775 and just below C850. Note that the clusters indeed have more mass and are more tightly populated than the constellations. It is also clear that the consequence of any collision/breakup in a cluster is much worse than any event in any of the constellations. The spatial density plot (number of objects of three particle size thresholds per volume plotted against altitude) shows that Spire and OneWeb have both strategically selected altitudes for their constellations out of the most debris-populated regions of LEO. For C850, a collision in that cluster would double the cataloged population, and yet has a 1/1200 (i.e., 0.08%) probability of occurring annually. Any of these inter-cluster collisions would produce significant amounts of debris that would measurably affect satellites within ±100-150km of the altitude of

[**] Rosenblatt, J., Garber, D., and McKnight, D., "Examination of Constellation Deployments Relative to Debris Mitigation in Low Earth Orbit," 68th International Astronautical Congress, Adelaide, Australia, September 2017.

[††] McKnight, D. and Bonnal, C., "Options for Generating JCA Clouds," 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, June 2016.

[‡‡] ORDEM is NASA's Orbital Debris Engineering Model that provides debris flux and spatial density levels in Earth orbit.

the event. In summary, the clusters of massive derelicts have larger aggregate masses and collision cross-sections than the three constellations, yet these derelict objects have no means to detect or maneuver away from collisions like operational satellites. However, there is little attention being taken of these objects.

So, one may ask, with constellation members with individual satellite masses orders of magnitude less than the abandoned rocket bodies and dead payloads in neighboring clusters plus the likelihood of inter-constellation collisions being near zero, what should the aerospace community be focusing their attention on: clusters or constellations?

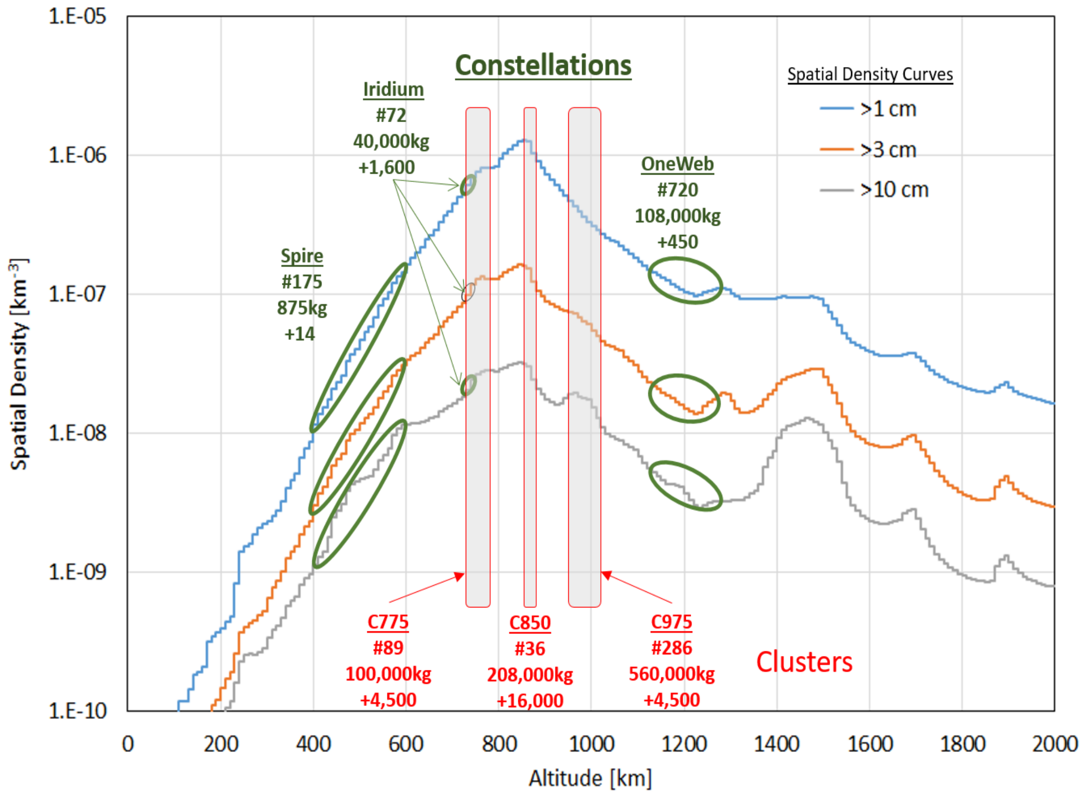


Figure 4. Depicting the cluster (red font) locations relative to the constellations (green font) shows how there may eventually be deleterious interactions between these two families of space hardware. The >10cm curve depicts the space catalog while >1cm and >3cm flux will still likely create mission-terminating event upon impact. Each cluster and constellation have three numbers to describe them: number of objects in each collection, approximate total mass of each collection, and number of trackable fragments that would be produced by a collision between any two of each collection (i.e., cluster or constellation).

Evolving SSA

While the number of objects in space, both operational and derelict, is growing and becoming more diverse, the systems to monitor these objects are also evolving. Traditional SSA, from the beginning of the space age through the turn of the century, leveraged a single government-owned global space surveillance system (i.e., USAF Joint Space Operations Center, JSpOC) which created a single unique public space catalog (available at www.space-track.org). Having a single source of SSA data resulted in limited data for a limited number of users providing limited utility beyond each operator's own knowledge of their own assets. Luckily, the number of objects in space did not require anything more.

After the turn of the century, as more spacefaring entities were born and the major catastrophic collision between an operational Iridium satellite and a defunct Soviet payload served as a catalyst for the change, the landscape of SSA was forced to evolve. First, while JSpOC continued to provide a satellite catalog to everyone, they also started providing Conjunction Data Messages (CDMs) to operators of all active satellites globally.

A CDM is issued when any cataloged object gets within a certain distance threshold to an operational satellite. Due the constituents of the cataloged population, these warnings are usually between an operational satellite and a debris fragment. In addition, commercial entities (most notably AGI's Commercial Space Operations Center, ComSpOC) started providing both SSA capabilities and command & control for operational satellites.

This current situation has resulted in a variety of new data sources, many redundant but some new, creating an increasing need to prioritize the amounts and types of data to be created, ingested, and used. This has become difficult as much of this data is maintained in independent "stovepipes" though the Space Data Association (SDA) has been perfecting the merging of satellite operator data and third-party SSA data while creating their own SSA/STM service to augment the entire process.[§§] However, the process of incorporating ephemeris data from satellite operators is tedious due to the large number of unique formats that may be used by these different operators.

In the future, the number and types of externally-derived SSA data (i.e., radar and telescope observations) and internally-derived telemetry, health maintenance, and system performance data (i.e., data created by space systems) will increase drastically, providing the potential for greater insights but requiring new capabilities to harness the breadth and depth of SSA data for

[§§] Oltrogge, D., Johnson, T, and D'Uva, A., Sample Evaluation Criteria For Space Traffic Management Systems, 1st IAA Conference on Space Situational Awareness (ICSSA), Orlando, FL, 2017.

the ever-expanding number of space users. In this new age, the concept of a static space catalog and a single entity issuing warnings will not suffice to assure reliable space operations for all.

We will need multi-path adaptive networks for transferring data to the right people at the right time in the right format; do not send everything to everybody all of the time. When operators get notifications constantly, they may lose their effectiveness and are likely to be ignored. The current number of CDMs issued by JSpOC relative to the number of maneuvers that are actually executed (i.e., 1000x more warnings than maneuvers) is partially due to this phenomena, but also since avoidance maneuvers may be built into other planned maneuvers and the operator usually knows where they are better than a third-party SSA provider. Future SOA needs to have fewer false alarms.

Table 2 portrays the key parameters that hint at the necessary transition in the SSA landscape from static one-way information flow to adaptive, real-time, multi-path communications that will result in enhanced space safety by minimizing debris collision risk.

Table 2. SSA has evolved in response to major trends in space activity.

Era	Number of Space-faring Entities	Number of Op Sats	Space Situational Awareness (SSA) Data	"Space Catalog"	Warning Messages for Potential Conjunctions	Info Flow	Major Players
Past (up to 2000)	~10	~200	From Ground-based Government Radars and Telescopes	Static	Only U.S. Operational Satellites	One-Way	JSpOC
Current (2000-Present)	~40	~800	From Ground-based and Space-based Government and Commercial Radars and Telescopes	Dynamic	Yes, high false alarm rate	One way & Two-way	JSpOC SDA
Future (2020's)	~100	~10,000	From Ground-based and Space-based Government and Commercial Radars and Telescopes and Onboard Diagnostic Sensors	Dynamic Mission-driven Tailored Database	Yes, low false alarm rate	Multi-Path Adaptive Networks	JSpOC SDA ???

"RESPONSIVE" SSA

As just stated, due to massive amounts of data and increasing risk from the potentially hundreds to thousands of new satellites to be launched over the next decade, the globalization of space, and the lingering clusters of massive derelicts in LEO, SSA must continue to evolve and be upgraded to continue to support on-orbit space safety and space operations assurance. Responsive SSA will span SEM and STM operations detailed previously. This requires characterizing the conjunction dynamics for derelict objects and the vibrant growth of new systems. Three main aspects of this approach are to (1) provide an automated process that leverages an activity-focused analysis framework, (2) artificial intelligence concepts such as machine learning, and (3) secure multi-path adaptive communications.

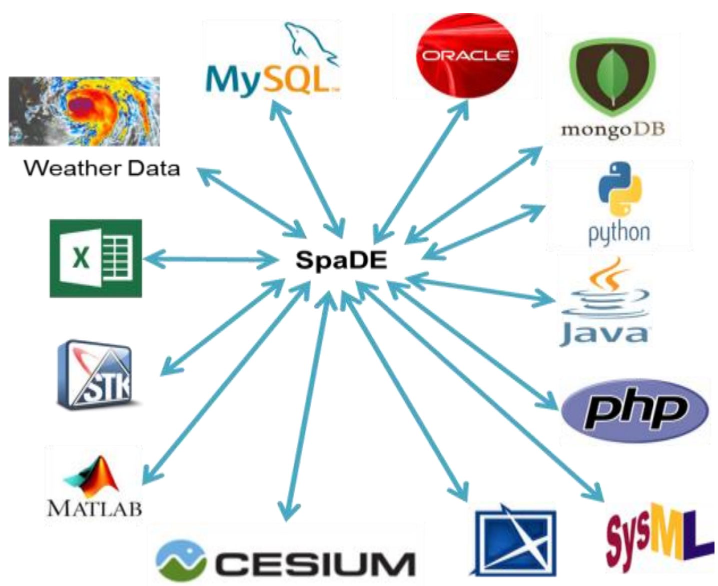
Automation via SpaDE

The existing open source information system for SSA collection and exploitation called the Space Domain Awareness Environment (SpaDE) will be leveraged. SpaDE is an IAI web-based tool for data integration/standardization, tool integration, visualization, and analytics. SpaDE is based entirely on Open Source and IAI code.

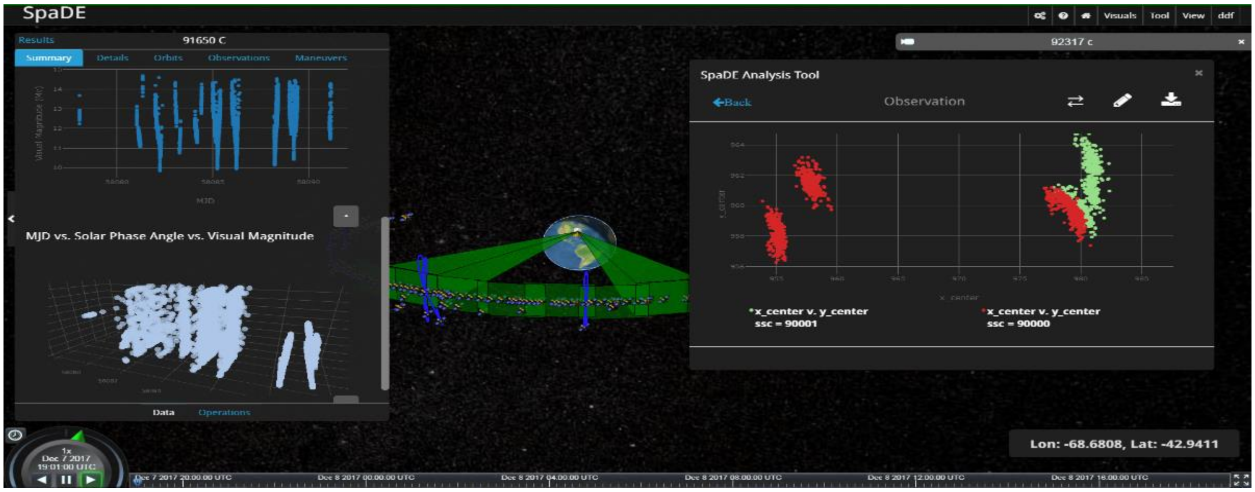
SpaDE utilizes data standardization to integrate with various tools and data sources. Data is transformed into a normalized format that allows for easy integration of additional tools.

SpaDE integrates:

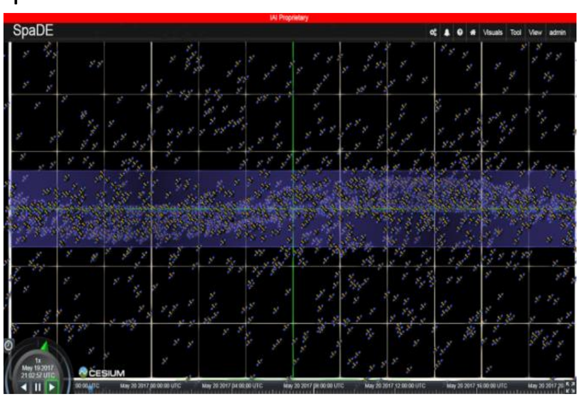
- Custom and standardized inputs/outputs
- Programming languages
- Databases
- Algorithms
- Tools/Programs
- Visualizations and models

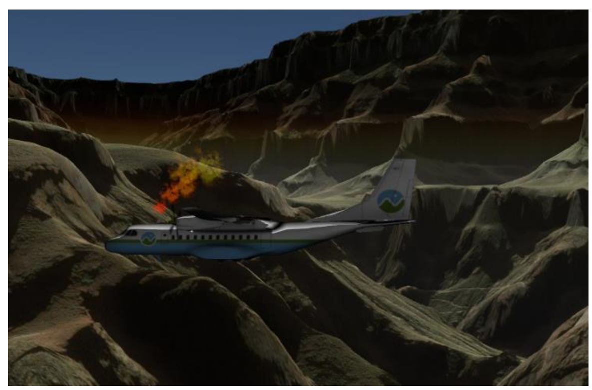


SpaDE creates a unified interface for multiple systems while maintaining fidelity and reducing licensing cost through automation and use of Open Source components. This architecture supports time-sensitive decisions through automated processing of large data sets.

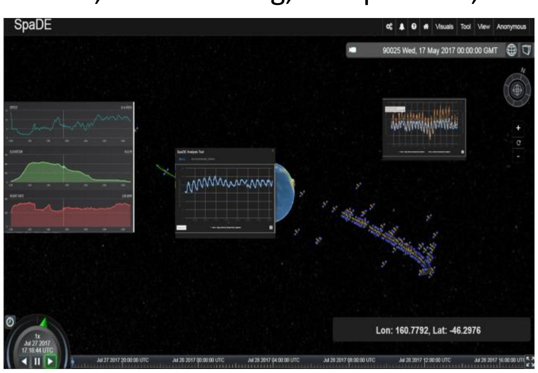


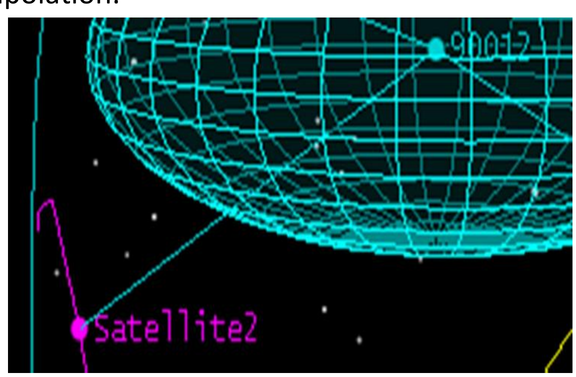
SpaDE creates custom views and data visualization to enhance information gathering by layering data in meaningful ways from a variety of analytic, operational, and geometric perspectives.





SpaDE can fuse analytical tools and data visualizations. SpaDE can do automated runs of algorithms, data trending, interpolation, and extrapolation.





Supervised Machine Learning

This congested, dynamic space environment will require many split-second decisions in order to assure space operations in the future. Focusing on the issue of collision avoidance, a similar problem to this can be found in the robotics domain, where obstacles (potentially dynamic) need to be avoided in a workspace where robot(s) will navigate between points to perform some tasks. This function is known as robotics motion planning. Algorithms in this field employ deterministic approaches for small scale problems.

For larger scale systems to be addressed while incorporating some objective functions (e.g., perform this task while balancing the goal of maintaining sufficient separation to account for uncertainty in the environment while minimizing fuel/power consumption), stochastic algorithms may be leveraged. These types of planners have been successfully deployed in many cross-domain applications including characterizing biological molecules, autonomous driving, and robotic surgery.[***]

Today, machine learning is used to model complex simulation tasks such as weather prediction and stock performance. Instead of replacing traditional models, machine learning is used to evaluate several models along with other observations to learn which models apply to varying conditions (e.g., one would guess that the same model used to predict the weather in Texas may not be well-suited for an area adjacent to the Great Lakes or the Swiss Alps).

Using machine learning can reduce the number of false alarms (or false positives) which will be required to scale reliable conjunction assessments to the increasing population of objects. Unfortunately, many of these new objects may actually have less information about their location due to their simple design. Machine learning models potentially give up interpretability for more accurate predictions and ingest a wider range of inputs—text, images, and unstructured data. Machine learning can learn from experience using regression, decision trees, and artificial neural networks.[†††]

Today, performing reliable conjunction assessments (i.e., close approach calculations) is a difficult task that is not automated well. The existing automation that is in place, which utilizes Kalman filters, often requires manual review and generates a large percentage of false alarms

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[***] Qing Li, Nanning Zheng and Hong Cheng, "Springrobot: a prototype autonomous vehicle and its algorithms for lane detection," in *IEEE Transactions on Intelligent Transportation Systems*, vol. 5, no. 4, pp. 300-308, Dec. 2004.

[†††] "The Evolution of Analytics: Opportunities and Challenges for Machine Learning in Business" by Patrick Hall, Wen Phan, and Katie Whitson, O'Reilly Media, Sebastopol, CA. 2016.

with respect to conjunction warning messages (i.e., close approach between an operational satellite and some other object).

While newer satellites may incorporate components that enhance positional characterization (such as Global Positioning System [GPS] receivers), the ever increasing population of derelict objects and lower functioning satellites will mandate sensor measurements (much like the air traffic control system which utilizes both primary (radar) and secondary (transponder) data). Many features that impact the orbital dynamics of a space object, such as solar radiation pressure, atmospheric drag (as function of altitude, object geometry/orientation, solar activity, etc.), and mission events (e.g., outgassing, routine operations, etc.) are largely ignored in these models due to lack of availability or in order to keep them from becoming intractable.

Machine learning enables computers to automate the building of analytical models that use algorithms to learn from data interactively and iteratively. These models can then be used to produce reliable, repeatable decisions.[‡‡‡] As stated previously, information about the evolving representation of the orbits of space objects has not been merged into one model with rotational dynamics, solar activity, and inertial characteristics. Machine learning holds promise for doing exactly that. The unique database of three years of conjunction data between the hundreds of massive derelicts studied in MCMA provide the foundation for a machine learning demonstration to enhance the accuracy of conjunction predictions.

The data used in the MCMA experiment are enhanced General Perturbation (eGP) two-line element (TLE) sets provided by the Joint Space Operations Center (JSpOC) via the web site space-track.org. These descriptions of the orbits of the derelict objects are of moderate accuracy; Special Perturbations (SP) orbit propagation would provide more accurate results. However, the eGP is sufficient for the statistical analyses performed in MCMA. It has been shown that five days before a conjunction, the accuracy of the eventual miss can be made to within 6-14% (compared to final eGP assessment of the miss distance).

A potential pathway to improved conjunction assessment is to incorporate machine learning into the predictions. Data relevant to the conjunction such as event characteristics, solar activity, and object characteristics can be used as training data for a machine learning process to achieve the objective of predicting the conjunction 5-7 days out to within 1% of the final miss distance (i.e., determined after the event using eGP data).

[‡‡‡] "Statistics and Machine Learning at Scale" by SAS, 2017.

Figure 5 provides a basic concept of operations for this supervised learning exercise being executed to enhance the fidelity of conjunction accuracies between massive derelicts 5-7 days in advance; this might be sufficient time for precautionary actions to be taken if the miss distance accuracy can be improved sufficiently.

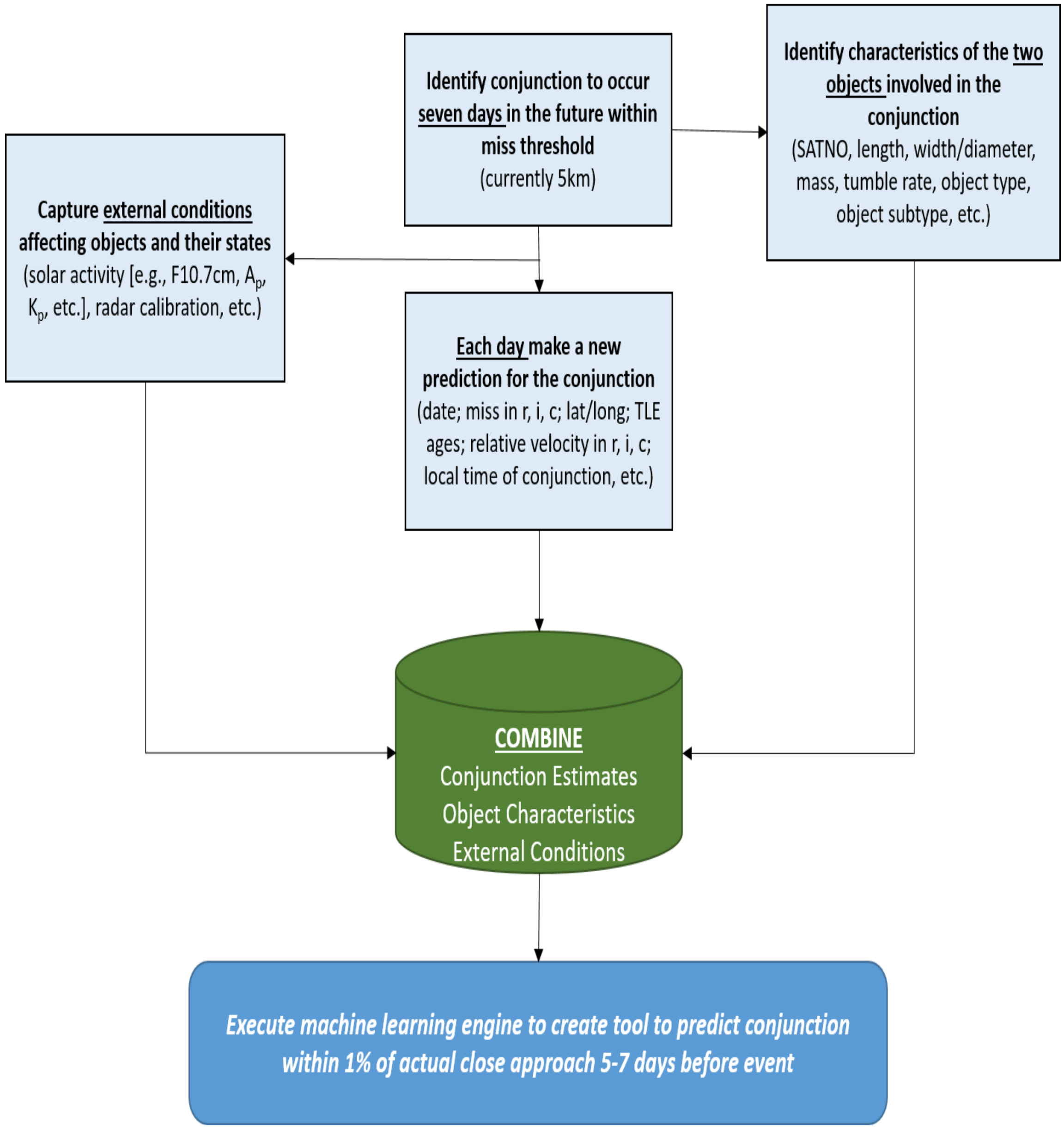

Figure 5. The collection of data for the machine learning application to enhance conjunction warning accuracy temporally requires aggregating event, object, and space environment data.

Figure 6 shows space weather parameters that might affect the drag profile for these massive derelict objects and illustrates how they can vary in a complex way. This sort of data will be ingested into the machine learning engine to test the hypothesis that variation in space weather may be partially responsible for the uncertainty in conjunction assessments.

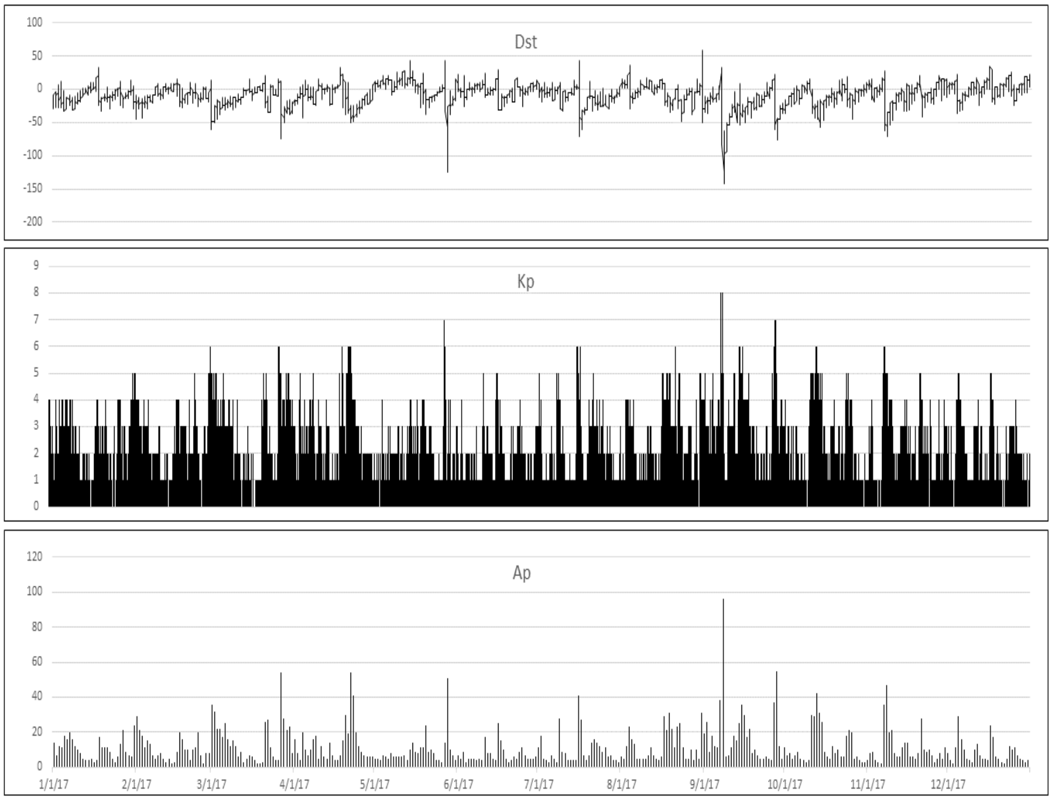

Figure 6. Space weather parameters have a complex and time-dependent effect on the atmosphere that creates the drag on massive objects in LEO. [Source: Dr. William Cade, Baylor University]

The critical thresholds from the ongoing MCMA effort consider conjunctions less than 5km and examines these events starting seven days before the predicted conjunction. Under the current framework, it is estimated that we have nearly 200,000 conjunction data sets per year to train the machine learning application. It is possible that these thresholds may need to be modified to generate sufficient data for more reliable prediction algorithms to be generated. For example, possibly starting to look at predictions of a conjunction less than 5km 14 days in advance may provide needed data to create the hoped-for 1% accuracy goal. In addition, it is in question how many early predictions will be needed in order to achieve the objective 1% miss distance accuracy.

Adaptive, Multi-Path Secure Communications via Blockchain

A critical part of "responsive" SSA is the sharing of SSA and STM data with a wide variety of stakeholders at the appropriate time sequencing and fidelity for their needs. This is complicated by the fact that co-users of space may also be business competitors or even geopolitical adversaries. In the past, the concept of sharing and refreshing a catalog of space objects was seen as a key aspect of SSA. However, it is not sufficient to just discuss a catalog of entities; activities such as conjunctions, maneuvers, and emissions must also be shared. It is also essential that all parties have confidence that the data is shared reliably and securely to enhance space operations assurance without eroding "business safety" (which might also include national security issues). While the discussion has often been about the tradeoff between centralized and decentralized solutions,[§§§] it also requires a discussion about security, terminology, and formats.

As the number of players actively launching and operating satellites continues to expand, not only does the risk of catastrophic events increase, but so does the volume, velocity, and variety of data that is generated by both ground-based and satellite-based systems. This presents both challenges and opportunities for the growing number of international actors who have a vested interest in the successful cradle-to-grave management of space assets: countries, international governing bodies, space agencies, academia, operators, manufacturers across the supply chain, insurance providers, launch companies, investors, citizens, and space enthusiasts. While this collective of entities has diverse motivations, each can benefit from more complete, accurate, timely, and predictive information.

At the highest level, a decision needs to be made as to whether or not the existing mode of sharing a common space catalog of objects will persist. In the current JSpOC-centric concept of operations, they provide a space catalog of objects globally but do not pass along the raw or even processed observations that generate these TLEs. This is sufficient for many applications, however, when there are very close conjunctions this approach may not provide data of sufficient accuracy to serve as a risk mitigation mechanism to inform potential operational responses such as orbital maneuvers or alterations to satellite orientation. As a result, in order to gain a more comprehensive understanding, one must access numerous standalone databases for object dynamics generated by academia simultaneously with solar weather measurements/predictions from commercial/civil organizations in addition to either the radar data from JSpOC and/or telemetry data from operational satellites. To permit the accessing and

[§§§] Gehly, S. and Bennett, J., Distributed Fusion Sensor Networks for Space Situational Awareness, IAC 2017, Adelaide, Australia, October 2017.

assimilation of this data, a different data communications schema needs to be used that is both "centralized" and "decentralized."

We look to leading edge commercial finance applications for inspiration. One can hardly escape the frenzy surrounding Bitcoin, a digital crypto-currency that made its debut in 2009, but only recently broke through to mainstream America as the price of a single bitcoin skyrocketed over 1000% approaching a high of $20,000 USD in 2017 (but tumbled somewhat in early 2018). Beyond the hype of the massive growth in Bitcoin's value, Bitcoin, and similar crypto-currencies, offer their users a unique value proposition: a peer-to-peer network where value (via the digital currency) can be exchanged across borders securely, anonymously, and near instantaneously with complete trust between individuals or organizations that do not know one another. This is accomplished without the need for a third-party (such as a bank) to settle transactions or central government to back its value (as with fiat currencies) and with nominal transaction fees. Bitcoin has empowered individuals in countries where governments and banking are corrupt and banking services are only available to the upper class. For the first time, entire groups of people who have otherwise been locked out from traditional banking, getting credit, and owning property, are able to benefit from a trustworthy, worldwide adopted store of value and actively participate in commonplace economic activities. Digital currencies are leveling the playing field for many people around the world and major institutions are accepting crypto-currencies for regular purchases.

While Bitcoin and other digital currencies continue to improve the daily lives of many, the underlying blockchain technology is the true breakthrough capability that promises to have an even larger impact on the world in the coming years. Similar to how e-mail was the first major innovation to leverage the potential of the internet back in the early 1990's, Bitcoin was the first implementation leveraging the capabilities of blockchain technology. And we have only scratched the surface of what's possible. Today, blockchain and distributed ledger technologies continue to gain momentum. With nearly all of the major banking institutions in the world experimenting with these technologies; governments attempting to utilize them to increase transparency, increase efficiency, and improve services for its citizens; and consortia of industry leaders coming together to drive standards and concept of operations (i.e., conops) for their industries, it has clearly captured the attention of the masses. However, before proceeding, it is instructive to explain four key attirbutes about blockchain technology:

- <u>Distributed/Decentralized Database</u>: Blockchain's shared ledger creates one version of the data "truth" for the players in a peer-to-peer network. One can think of it as a shared spreadsheet with predefined format that everyone can trust has accurate, up-to-date information. Each party in the peer-to-peer network has a copy of the distributed database with no single party owning, controlling or governing the database, its contents or interactions between the parties. Flexibility is achieved through subchains, sometimes called channels, where users can subscribe to information on and post information to a specific channel with the ability to define what information they are comfortable sharing, with whom, and when. It becomes a trusted repository of events, actions, and data. For example, the data required to perform machine learning of conjunctions between massive derelicts, described in the last section of this paper, could be integrated into a distributed ledger rather than be posted to a public web site.

- Immutable: A blockchain leverages public key cryptography and digital signatures and is formed by stacking transactions sequentially with time stamps into a block of transactions and chaining the blocks together (hence the name blockchain). New blocks are added through the consensus of the peers in the network who are able to approve or deny the transactions in a block. Whenever a new block is added, the updates to the blockchain are propagated to the entire network, such that each node is in sync. The result? It is nearly impossible to rewrite history once added to the shared ledger. Unless a majority of peers in the network agree to recreate all transactions up to the current point in time and quickly approve those transactions without the knowledge of other peers, it cannot be done. Additionally, since everyone has a record of the historical data created, transparency alone serves as a deterrent to malicious attempts to rewrite history.

- Smart Contracts: Smart contracts are similar to traditional contracts in that they represent the agreement between parties (in this case peers in a network) on what will happen when certain conditions are met. What makes smart contracts so useful is that they are self-executing computer code installed into the blockchain itself, triggered and enforced based on a pre-defined set of criteria and/or trigger events and they execute without the need for human intervention or approval. They simplify and automate routine and repetitive processes ensuring that actions are executed as agreed by the stakeholders in advance. This automated capability is ideal for notifying SSA stakeholders when critical events occur or are predicted to occur in the future.

- Component of Solution: While blockchain itself has many valuable capabilities, the creation of a functional business network leveraging blockchain technology requires several additional components: membership and enrollment services (leveraging PKI for enrollment and transaction certificates), a user interface (front-end software for user interactions with the shared ledger, alert notifications, collaboration, and reporting), APIs to existing data sources to extract and post information to the blockchain (JSpOC etc.), data extraction utility to pull data used to inform analytics, predictive modeling and AI applications.

In short, blockchain can provide a self-adjudicating distributed append-only database application. Blockchain potentially provides the capability for achieving the needed multi-path distributed communications that are required to optimize responsive SSA. When a set of organizations, partners, companies, regulators, or other group of known entities wish to join forces to share information and interact leveraging distributed ledger technology, a permission-based (or private) blockchain is the ideal solution. Whereas anyone can join Bitcoin's public blockchain without restrictions, permission-based blockchain users must be enrolled and accepted in the network prior to performing transactions. To add to it, shared governance of the permissioned blockchain defines membership privileges including what types of actions they can perform, and what type of information they can access. These characteristics make it a suitable match as a foundation to enable responsive SSA.

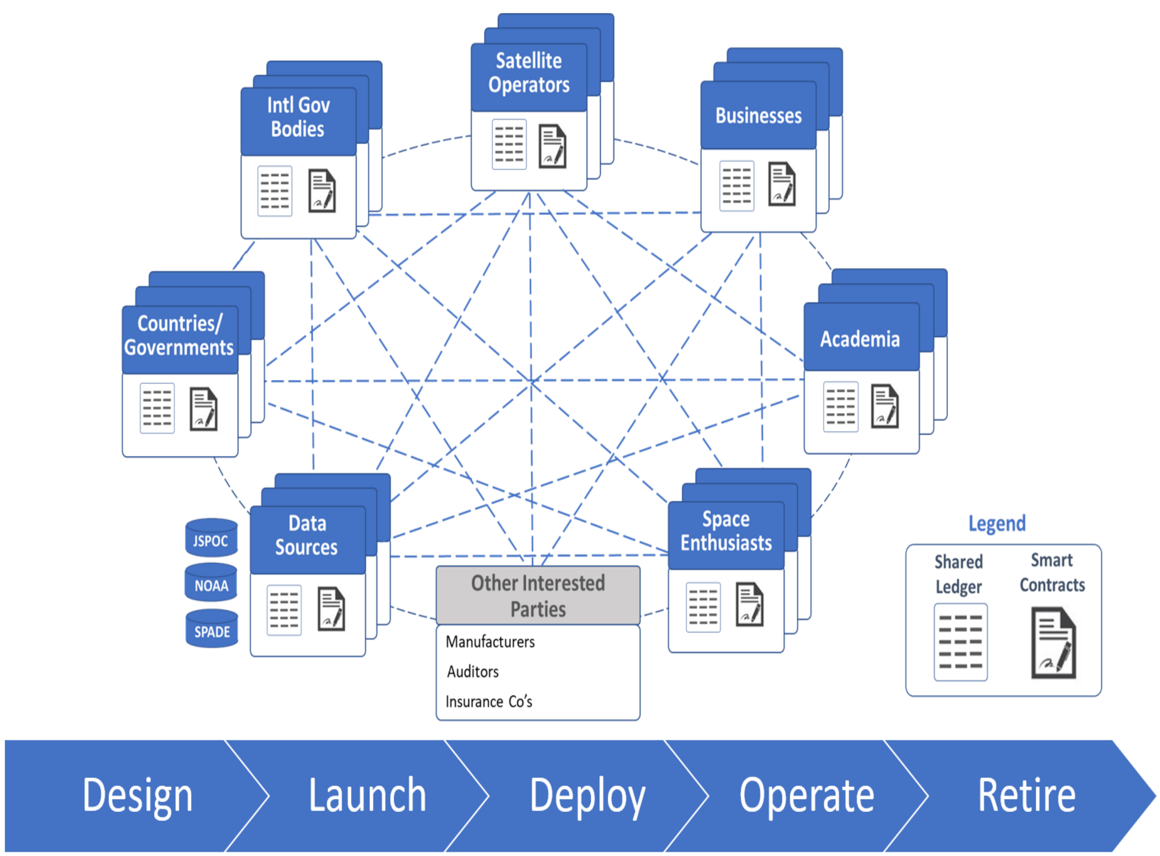

Figure 7. The blockchain-enabled solution can be applied across the entire life cycle of a satellite from design through being retired.

A blockchain-enabled “space data value chain” will provide greater transparency, mobility, accuracy, timeliness, and efficiency of access to relevant and accurate information. We propose to implement a blockchain-enabled solution in a phased approach yielding incremental gains to the community at large as each phase is rolled out.

Demonstration - Use Blockchain to Enable Machine Learning of MCMA Conjunction Predictions: This application of blockchain will create a single centralized registry of conjunctions occurring between members of the constituents of MCMA. This will require data streams from NOAA (for solar activity data), third-party SSA providers (with tumble rate for objects), SpaDE (conjunction data), etc. This instantiation will simplify our ability to perform the machine learning exercise. It will serve basically as a limited “responsive SSA” brassboard (i.e., before prototype) demonstration. Further potential use of blockchain in larger, more demanding SSA applications could be seen to develop potentially in the following three phases:

Phase 1 - A Single Synchronized Distributed Ledger of Transactions: (situational awareness): In this phase, it is proposed that we create a shared registry of all known operational assets, non-operational assets (space junk and debris), and trackable non-human created debris and/or relevant space events utilizing a decentralized ledger technology. All parties are given the chance to validate that the information is correct and once validated through consensus algorithms agreed to by all parties in the private peer-to-peer network, the validated information will be appended to the blockchain. As it is an immutable record of transactions, cataloging who and when records were posted, incentive mechanisms to reward those who post to the single distributed ledger might motivate people to update the blockchain with pertinent information to improve efficiency, compliance, security, data privacy, and speed. Standardized, detailed historical information along with metadata would be used to inform statistical models and artificial intelligence (AI) methods. AI might include machine learning for predicting collisions then in turn, prescribing potential approaches and corrective action to minimize these events.

Phase 2 - Smart Contracts with Economic Incentives: The logical development and deployment of blockchain to enhance the current space operations assurance operations could have the following characteristics:

- Alert System - Automatic notifications to all parties when a relevant event occurs that could impact their operational assets or those of neighboring assets that could impact their operations.
- Peer-to-Peer, Machine-generated Prescriptive Maneuvers - Like the Internet of Things on the blockchain – using smart contracts direct communications can be established

between the satellites themselves to share critical information that will trigger maneuvers thereby eliminating risk without humans being involved at all.

- Incentives - Smart Contracts can also be used to reward and penalize participants. For example, SSA data providers could be compensated when their data is used.
- Extend Limited Access to Larger Audience - Access may be extended to non-traditional, but interested, third parties (satellite manufacturers, supply chain, insurance companies, other countries, etc.) with economic incentives in place for those who choose to share their information for the benefit of others.

Phase 3 - Democratize/Socialize Space: However, blockchain has the potential to completely change the approach to SOA. This ultimate potential can only be attained through the radical change of many current treaties, best practices, and common perceptions of space operations. Blockchain could potentially enable voting on who can launch what, when, and where or who must maneuver. These decisions will be based on historical performance and willingness of the space community at large to assume risk and to explore new approaches to the economic and governance aspects of space utilization. Everyone can be incentivized to do the right thing while simultaneously creating new modes of value and value transfer.

It is still early in the evolution of blockchain technology and many hurdles must be addressed in order for blockchain solutions to reach their full potential. Architectural and implementation decisions will profoundly impact performance (transaction processing speed), scalability (amount of data to be stored on the blockchain vs. in external systems), security (applications that access the blockchain must follow stringent security protocols and operating procedures as they are the weakest link in the cyber chain), and standards must be created and agreed to for the collection and dissemination of specific information to/from those who need it, when they need it. Even with potential limitations to be overcome, blockchain holds much promise as a foundational component for creating a space value chain and analytics solution moving forward.

SUMMARY

Responsive SSA is a bridge between space environmental effects & modeling and space traffic management. Due to the complex combination of dynamic and perplexing space environmental effects with the fast-growing, by number and diversity, satellites operating in space, SSA must have major functions automated. This automation will help to handle the increased bandwidth that will be needed due to more sensors coming on-line producing vast amounts of SSA data and a rapidly growing number of operational satellites slated for deployment over the next 5-15 years. Open source software, machine learning, and blockchain technologies will be applied to create a flexible data ingestion, sharing, and analytical infrastructure in support of SSA.