System of Systems Architecture: The Case of Space Situational Awareness

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The presence of space situational awareness is one approach to mitigating the long-term risks associated with space debris in low Earth orbit (LEO). As the U.S. and other nations continue to develop the space situational awareness mission area, questions arise as to how stakeholders should act to mitigate the effects of resident space objects and how our understanding of the physics of LEO inform the evolution of ground- and space-based sensors. To characterize interactions among international stakeholders, space situational awareness is modeled as a system of systems with technical and social elements. Through the use of game-theoretic cooperation archetypes and System Dynamics modeling, possible futures are explored. Extensions in space situational awareness capabilities are modeled as mechanisms to improve satellite survivability. Finally, general implications for system architecture and systems of systems are elucidated.

I. Introduction

OVER the last decade, interest has grown in how systems come together to form systems of systems (SOS). These temporary coalitions of independently operated and managed systems can meet unforeseen needs in a timely and cost-effective fashion. For example, during the Persian Gulf War an SOS was formed between Patriot missile batteries and Defense Support Program (DSP) satellites. The satellites, originally designed for strategic missions, provided the Patriot's operators with "over-the-horizon" early warning of medium-range missile launches prior to the inbound missiles being visible to the Patriot radar.[1] Combining disparate systems was not always so successful. During the lead up to the same conflict, electronic coordination could not be fully established with naval forces resulting in air tasking orders needing to be flown to aircraft carriers from Riyadh.[2] There is much attention focused today on deliberately architecting systems so that they support broader objectives of an SOS.

The purpose of this paper is to develop a descriptive model of an SOS that characterizes interfaces among the constituent systems as mechanisms for transferring value between stakeholders. The system analyzed is a hypothetical space situational awareness (SSA) network composed of ground-based sensors and command centers that characterize and monitor resident space objects (RSO). A key issue facing the future of space surveillance is the potential for international collaboration. While there are significant technical issues associated with international cooperation (*e.g.*, data representation standards, coordination of tasking), significant socio-political issues will also define cooperation (*e.g.*, military reluctance to share surveillance assets). The model proposed attempts to incorporate both social and technical considerations to better characterize the evolution of SSA under a variety of alternative futures.

II. Systems of Systems

Decomposition and hierarchy lie at the foundation of system thinking and are the basis of often-cited V-model[3] of systems engineering (SE). By the early 1990's, this notion was extended to systems composed of other systems. In a 1991 paper, Eisner[4] expresses a need for extending the systems engineering paradigm to include "systems of systems." Table 1 provides Eisner's seven criteria for using SOS methods and contrasts each to the traditional SE paradigm. Eisner's seven criteria provide an initial definition of SOS engineering as a unique class of problems

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related to, but different from, systems engineering. SOS are systems that are composed of other systems, and have some additional properties. In Eisner's list, constituents of the SOS are distinguished from subsystems by the degree of independence that they retain. For example, the national air transportation system is an SOS composed of airports with requirements imposed by both local and national authorities. In contrast, the design specifications for the wing of an airplane are derived directly from the requirements of the airplane as a whole.

Table 1 Eisner's seven SOS observations

	System of Systems Engineering	**Traditional Systems Engineering**
1	There are several independently acquired systems, each under a nominal systems engineering process.	Subsystems are acquired under centralized control.
2	Overall management control over the autonomously managed systems is viewed as mandatory.	The program manager has almost complete autonomy.
3	The time phasing between systems is arbitrary and not contractually related.	Subsystem timing is planned and controlled.
4	The system couplings can be considered neither totally dependent nor independent but, rather, interdependent.	Subsystems are coupled and interoperating.
5	The individual systems tend to be uni-functional and the systems of systems multi-functional.	The system is rather uni-functional.
6	The optimization of each system does not guarantee the optimization of the overall system of systems.	Trade-offs are formally carried out in an attempt to achieve optimal performance.
7	The combined operation of the systems constitutes and represents the satisfaction of an overall coherent mission.	The system largely satisfies a single mission.

Maier (1999) provides structure to the SOS problem by introducing the notion of *collaborative system of systems.*[5] Maier approaches the SOS problem by focusing on the decentralized control structure that Eisner observes (points 1 and 2 in Table 1). He proposes that because authority is distributed, and constituent system lifecycles are not necessarily coordinated with the needs of the SOS, traditional SE methods do not work well. Maier defines a collaborative SOS as a system composed of constituent systems that exhibit operational and managerial independence. Operational independence means that, should the SOS constituents be removed from the SOS, they still exist and are able to function as they did prior to joining the SOS. Managerial independence means that, not only can the constituents function independently, they continue to do so even while part of the SOS. Traditional systems engineering techniques are difficult to apply to SOS design where authority is distributed among constituent systems (*i.e.*, misalignment of top-down thinking of traditional systems engineering with the bottom-up authority structure of SOS). This leads to extra work for the system architect who must not only manage the development of the SOS as a whole but also ensure that the constituent's needs are met.

In analyzing these architectural challenges, Maier recommends several heuristics that may aide the architect. One of them is to leverage interfaces. Maier points out that the SOS architect is not in control of the constituent systems; rather, the architecture of the SOS is architecture of the interfaces *between* the constituents. It is through the careful design and operation of these interfaces that SOS value is generated. Traditionally, the design of interfaces has focused on the physical and functional aspect of the interface.[6] SOS interfaces have an additional role: they create the "why" of the SOS. They serve as conduits by which value is exchanged between stakeholders and, thereby synergistic relationships are formed. For example, a global SSN might have mechanisms for coordinating tasking to improve situational awareness across participating nations. If one wishes to model a collaborative SOS, capturing the exchange of value is essential to understanding the dynamics that govern the actions of the constituents and, by extension, the behavior of the SOS.

III. Overview of Space Surveillance

A. Space Surveillance Mission

Space is a commons shared by all space-faring nations. Utilization of space leaves deposits of orbital debris (*e.g.*, dead satellites, spent upper stages, separation devices, bolts, and paint chips) behind. A "tragedy of the commons" occurs when a freely-available shared resource is overused to the point where it is no longer useful to anyone. Orbital debris is a tragedy of the commons problem in that the marginal cost of "littering" in space is nil, yet the cumulative degradation of the space environment due to debris deposits may hinder space utilization in the long-term.[7] Organizing the diverse set of space-faring nations beyond agreements to voluntary orbital debris mitigation standards is a challenge due to the lack of space environment ownership.

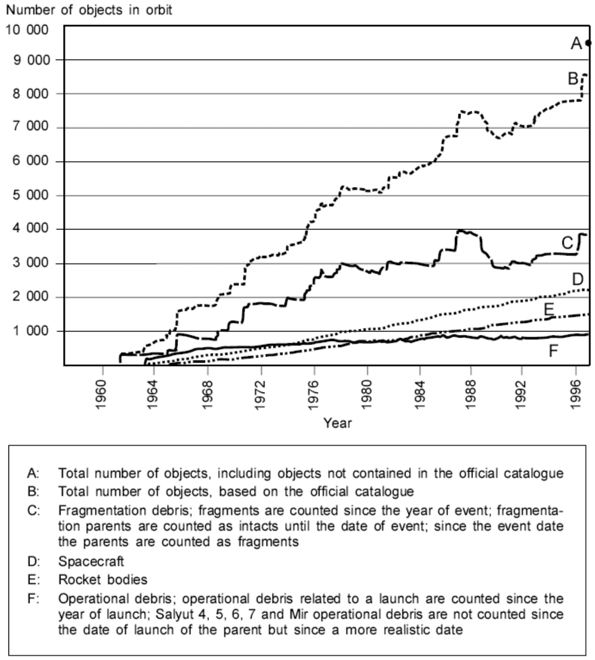


Figure 1 Number of objects in the US space catalog (United Nations 1999)

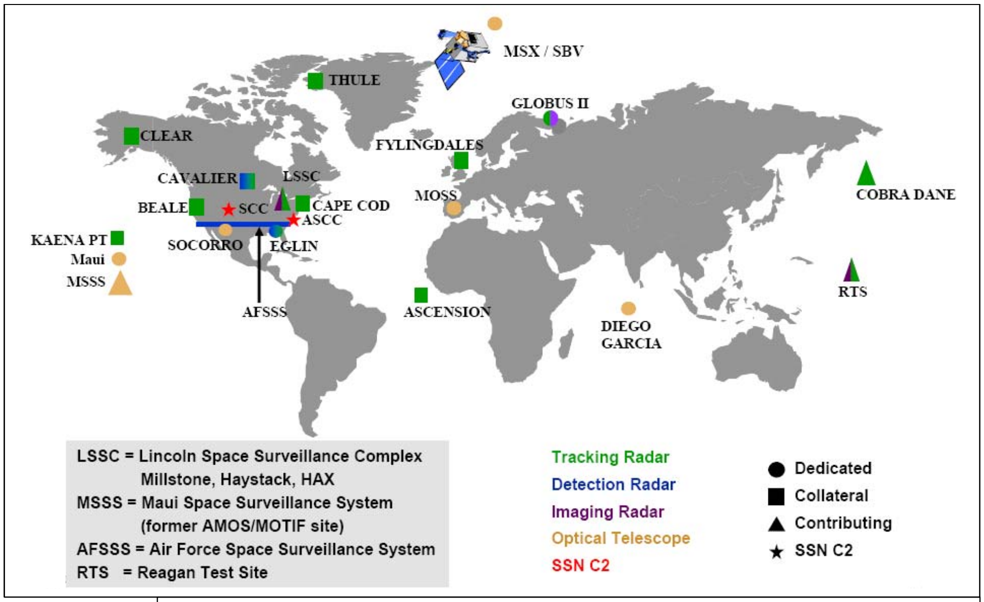
Founded following the launch of Sputnik 1 in 1957 for the purposes of ballistic missile warning and resident space object tracking, the mission of the U.S. Space Surveillance Network (SSN) is to detect and maintain a positional catalog of all detectable RSO. Using a distributed network of radar and optical sites that are operated by the U.S. Air Force, Army and Navy, the U.S. Space Command tracks more than 9,000 space objects with major axes in excess of ten centimeters. An additional 100,000 objects ranging from one to ten centimeters are estimated to be in Earth orbit (Figure 1)[8] that can only be addressed through costly spacecraft hardening and expensive avoidance maneuvers. It is estimated that the debris population continues to grow by more than 175 metric tons per year.[9]

B. Sample Space Surveillance System: U.S. SSN

The SSN consists of a worldwide network of 20 sensors and 2 processing centers (Figure 2).[10] Sensors include ground-based tracking, detection, and imaging radars and ground- and space-based optical telescopes. The processing centers provide command and control functionality to the sensors and compute RSO location, size, shape, motion, and orientation data. The primary center is managed by the U.S. Strategic Command in the Cheyenne Mountain Complex of Colorado Springs (and the backup center by the U.S. Navy in Dahlgren, VA).

Due to its limited number of sensors and geographic distribution, the SSN is limited in its tracking capacity. As such, space objects are not continuously tracked. Instead, debris locations are predicted by command centers, and these predictions are disseminated and tasked to sensors in the form of element sets. If predictions are close, the object is detected and the observation is sent back for processing and analysis. Command centers then update the tracked catalog, form a new prediction for the location of a particular debris object, and add that prediction to the element set for the next sensor. Regulations promulgated by NORAD prioritize tracking operations such that high-interest objects (*e.g.*, recently launched satellites, objects in unstable orbits, objects about to decay) are revisited frequently.[11]

Remote sensing in space is accomplished by detecting various sources of electromagnetic radiation from space objects. This is accomplished by the deployment of active and passive sensors. In addition to sensor type, SSN assets may be further decomposed into ground- and space-based categories. Ground-based assets include low Earth orbit (LEO) observers, such as the Air Force Space Surveillance (SPASUR) fence and phased array radars (*e.g.*, FPS-85, missile warning radars). Ground-based assets for deep space surveillance include the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system and the ALTAIR and Millstone Hill radars. Space-based surveillance is accomplished by the Space-Based Visible sensor aboard the Midcourse Space Experiment (MSX) satellite.



Graphic: G. Shepherd

Dedicated – space surveillance is primary mission
Collateral – belong to AFSPC but have primary mission other than space surveillance (e.g., launch support, early warning)
Contributing – report to another Air Force Major Command or are under to AFSPC to provide space surveillance information

Figure 2 Space Surveillance Network (Shepherd 2006)

The SSN architecture has evolved to a structurally complex state due to heterogeneity in the socio-technical composition of the contributing sensors. Not only are sensors technically diverse, integrated into legacy infrastructure, and managed and operated by independent military services; they also vary by degree of dedication to the SSN mission. Dedicated sensors are outnumbered by contributing and collateral sensors. Furthermore, the SSN provides an interesting case of how a technology originally designed for one purpose has come to assume additional mission areas. While space surveillance involves understanding the location, size, shape, motion, and orientation of space objects, the emerging mission area of SSA also includes the characterization of the broadcast frequency, ownership, command structure, and data of space objects.

IV. Model of International Cooperation for Space Situational Awareness

This paper develops a value-centric model of a relatively simple SOS, that of a hypothetical space situational awareness (SSA) system jointly operated by two nations. As space is a shared resource, there is a potential for international cooperation with regard to SSA. Such a combined SSA architecture would constitute a collaborative SOS as the control of each nation's SSA assets remain localized, yet coordination and information sharing occurs when mutually beneficial. The SOS interface in this system is the sensor data sharing between the two nations. It consists of two information exchanges. First, the tracking data for RSO is shared. Second, tracking tasks are distributed among the shared sensors to ensure that there isn't redundant tasking. For example, if Nation 1 shares 5 of 10 sensors and Nation 2 shares 3 of 20 sensors, then Nation 1's sensing capability is 10+3 = 13 sensors and Nation 2's capability is 20+5 = 25 sensors. Note that since sensors are information-generating resources, the sharing of sensor data does not preclude the owner from its use. On the contrary, shared sensors provide benefit to both the owner and receiver of the shared data.

The focus of the physics model is on the LEO debris environment. Satellites, sensors and debris are modeled using a System Dynamics simulation that allows representation of the interaction among these three classes of objects. Stakeholder decision-making, both for acquisition and operations of satellites and SSA sensors, is also represented. A mechanism for data sharing and joint tasking is included to allow the two nations to collaborate in creating an overall characterization of the debris environment.

This model may provide an example to designers of collaborative SOS, who struggle with the roles of cooperation and competition in creating and sustaining SOS. Dynamic SSA system contexts are explored by varying the parameters of the model to simulate cooperative and competitive situations. Other social dynamics can be explored, such as the impact of asymmetric power and resource distribution between the stakeholders.

Simultaneous modeling of social and technical properties of the SSA system enables end-to-end evaluation of candidate SOS interfaces in terms of function, form, and stakeholder value.

A. Stakeholders

Table 2 (adapted from Finkleman[12]) provides an overview of SSA stakeholders and their relevant issues. Each group either takes actions or imposes constraints in the model.

Table 2 SSA stakeholders

Stakeholder	**Relevant Issues**
Launch Providers	Launch safety. Resident space objects are concentrated in specific regions of space. There are only a few launch sites in the world, and space debris can persist at their inclinations.
Satellite Operators	Interference mitigation. Operators need to know the location of their satellites in order to avoid electromagnetic interference and/or physical encounters.
Satellite Service Providers	Assured service. Communications providers need to keep satellites on-station in order to fulfill service commitments. Transmit power levels are low and user antennas are small. Imaging providers require continuous, precise orbit data to evaluate access to ground targets.
Satellite Service Users	Tasks like search and rescue and environmental monitoring depend on knowledge of the location of satellites that can receive data.
Government Agencies	Protection. Need to track both cooperative and uncooperative targets to preserve the ability to operate in space and defend both space-based and ground-based assets. Emerging threats include ASAT, lasers, high power microwave weapons, jamming, etc.

Although there are many stakeholders who may stand to benefit from an SSA capability, only the governments of those nations that possess space surveillance capabilities may directly effect its deployment. Other stakeholders, such as commercial entities that make use of SSA data, may pressure their governments with organized efforts such as lobbying. Therefore, we identify two types of actors:

1) Government – responsible for sensor procurement and maintenance
2) Commercial – responsible for satellite launches and operations

The SSA model contains two of each of these actors—one for each of two modeled nations.

B. Modes of Stakeholder Interaction

In determining interactions between the two nations, five different types of interactions are considered. The five strategies, based upon innovations in evolutionary game theory, represent archetypes of ways in which nations may choose to interact with one another.[13]

1) **Always Cooperate (ALLC)** – This mode of interaction models the case wherein each nation shares all of its sensors and data. In this case, each country allows all of its data and tracking capacity to be used by the other nation regardless of need or national security concern. In effect, each nation contributes to a collaborative system.
2) **Always Defect (ALLD)** – This mode of interaction models the case wherein each nation keeps its sensors and data proprietary. In this case, each country allows none of its data and tracking capacity to be used by other nations, resulting in two disparate networks.
3) **Partial Cooperation (C+D)** – This mode of interaction models the case wherein each nation chooses to share a fixed proportion of their sensors. In this case, each country attempts to strike a balance between economic/political and national security concerns, using an *ex ante* strategy.
4) **Tit-for-Tat (TFT)** – This mode of interaction models the case wherein each nation modulates the number of sensors that are shared based upon the actions of the other nation. If one nation reduces/increases its number of sensors on the common grid, the other will follow suit.
5) **Win-Stay-Lose-Shift (WSLS)** – This mode of interaction models the case where in each nation changes the number of sensors that it shares in response to the outcome of its previous action. Whereas Tit-for-Tat examines the other nation's previous action and mimics it, Win-Stay-Lose-Shift nations examine their own previous action. If this action resulted in a favorable outcome, they will repeat it. If, on the other hand, an unfavorable outcome was the result, the opposite strategy is attempted.

In this paper, results from the first three modes of interaction are presented. Subsequent work will address the latter two cases. In a given simulation run, a government actor chooses a level of cooperation. Aggregate metrics tracked include growth of debris, satellite revenue, and SSA sensing capability.

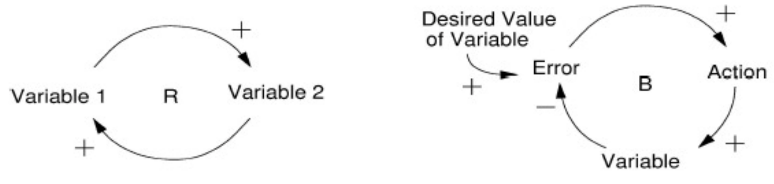
C. System Dynamics Model of SSA

Most models of the space debris problem (*e.g.,* NASA's EVOLVE or ESA's MASTER) have focused on the technical aspects of characterizing the highly complex interaction among RSO. These models are useful for making detailed predictions about the environment and providing designers information regarding the hazards in various orbits. Such models, however, tend to be computationally intensive. Since this study concerns a large variety of cooperation strategies, such detailed models of the physical interaction were not within the computational resources available to the authors. Similar situations arise with many SOS. Therefore, the authors built a model of the debris problem based on a set of feedback loops in which debris generation exhibits increasing returns—eventually ruining LEO without policy intervention. A natural tool for modeling feedback in system problems is System Dynamics (SD).

System Dynamics was created at MIT in the 1950s by Jay Forrester. Its theoretical basis comes from control systems and non-linear dynamics. Complex systems, whether they are technical, organizational, or some combination, often exhibit highly non-linear behavior where the relationship between cause and effect is not intuitively obvious. According to Martinez-Moyano (2005):

> System Dynamics is a computer-aided approach to policy analysis and design that applies to dynamic problems arising in complex social, managerial, economic, or ecological systems. Dynamic systems are characterized by interdependence, mutual interaction, information feedback, and circular causality.[14]

System Dynamics models are composed of a combination of positive (reinforcing) and negative (balancing) feedback loops in addition to state and rate variables.[15] At its lowest level, an SD model is a mathematical system of coupled, first-order, non-linear, ordinary differential equations presented in a graphical form accessible to policymakers.



a. A Reinforcing Loop

b. A Balancing Loop

Figure 3 Feedback loops[16]

The SSA model consists of several interacting feedback loops. At the heart of the model, there is a simple physics model of LEO that produces impact events among RSO. Aggregation is used to reduce computational complexity: all satellites, debris, and sensors are treated as identical "stocks." This simplification allows the model to track the number of each of these entities rather than concern itself with the state of individual satellites or sensors. Within the environment described in the physics model, government and commercial stakeholders make decisions whether to purchase sensors and satellites, respectively. The consequences of these decisions are then fedback to the stakeholders as capacity to track RSO and satellite revenue. The following sections describe the major loops in the model.

1. Physics Model of LEO

The simulation begins with two satellite companies, one for each nation, each company owning 160 satellites and ten sensors. Each sensor can track up to 500 objects with a major axis of at least 10 cm. The model is restricted to debris objects of this size for simplicity as objects of the 10 cm or larger class will nearly always result in destruction of the satellites they impact. By assuming that all impacts are catastrophic, modeling of individual satellite health is not needed.

LEO is defined as the region between 400 km and 1250 km around the earth. This forms a spherical shell of volume 5.54×10^{11} km^3. Within this space, debris and satellites interact. Initially, the space is filled with debris with a spatial density of 2 x 10^{-8} debris objects/km^3.[17] Satellite cross sections are assumed to be on average 40 m^2. The effect of debris hitting debris is relatively negligible so we only model the impact of debris with satellites. Satellites are assumed to operate for eight years and are de-orbited after this period if they have survived without a collision. We assume that each satellite-debris collision results in 1000 fragments with a major axis of at least 10 cm. To model the actual impact dynamics, it is assumed that debris objects move as an ideal gas through the space (*i.e.,* they exhibit Brownian motion).

The *average* impact rate between debris and satellites is based on the probability of a potential collision, P_{pc}. This parameter is dependent on spatial debris density (SPD), satellite cross sectional area (AC), observation time (T), and debris relative velocity (VREL):

$$P_{pc} = 1 - e^{-SPD*AC*T*VREL} \tag{1}$$

Not all potential collisions occur. Depending on the tracking capability of a given nation, only a fraction of the potential collisions will result in the loss of spacecraft. As modeled, the actual rate of collisions, P_{pc}, is reduced by the fraction of debris tracked (*i.e.*, avoidance of tracked RSO is assumed to be successful 99% of the time). Finally, actual collisions in the simulation are modeled as a Poisson process:

$$P_r(N_t = k) = \frac{e^{\lambda t}(\lambda t)^k}{k!} \tag{2}$$

where λ = Average Impact Arrival Rate. The model runs for a period of 100 years.

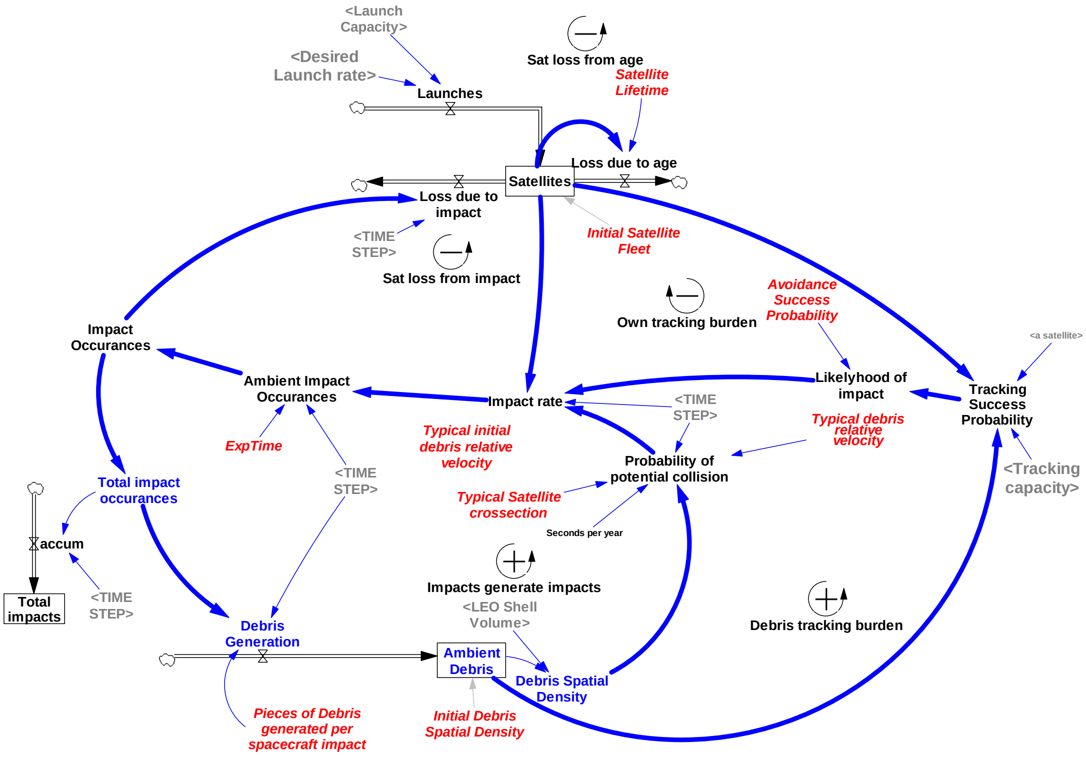


Figure 4 Physics model of LEO debris environment

The physics model of LEO debris, displayed in Figure 4, has four major loops: *Debris Tracking Burden*, *Own Tracking Burden*, *Satellites Lost from Impact*, and *Impacts Generating Impacts*. The first and last are reinforcing loops, while the middle two are balancing loops. *Impacts Generating Impacts* models the increased number of collisions given increases in the debris population. Debris generation leads to more debris generation—hence the loop is a reinforcing loop. As another reinforcing loop, *Debris Tracking Burden* also presents a problem. As debris levels increase with a fixed tracking capacity, the probability of successfully tracking a given piece of debris declines. Decreased tracking success leads to even more debris, which will further decrease tracking success.

To test the model against more sophisticated space environment models, the assumptions were adjusted to match those of Walker's DELTA 2.0 model, documented in Klinkrad's recent volume on space debris.[18] Walker's model includes both collisions between non-debris objects (*e.g.*, satellites, rocket bodies) and collisions with debris objects. DELTA predicts that there will be 21 catastrophic collisions between debris and spacecraft over the next 100 years. Under similar assumptions for initial RSO population and launch rate, the present model predicts, on average, 23 collisions over the next 100 years with a standard deviation of 10 (computed using 1000 Monte Carlo trials). DELTA predicts, on average, 50,000 fragments (>10cm) generated over 100 years with a standard deviation of 15,000 fragments. The present model produces, on average, 23,000 fragments. The lower count is due to the present model's exclusion of non-debris object collisions, which constitute half of the collisions in the DELTA model.

2. Satellite and Sensor Economics

Satellites are modeled as revenue generating entities. Increases in satellite revenue occur as the result of new spacecraft launches. Over the last 15 years, the number of transponders per satellite has almost doubled. Therefore, the model incorporates a marginal revenue growth rate to capture this rate of technology growth. The difference between actual and desired revenue produces goal-seeking behavior to close the gap. Capacitated by the maximum launch rate supported by the national space launch vehicle infrastructure, the firms seek to launch satellites to meet revenue goals. Revenue is balanced by costs associated with satellite procurement and operations (assumed to be $171M and $1M/year, respectively). Relevant financial accounting is provided, such as computing the present value of the net cash flow less the initial investment to acquire a satellite, to inform the commercial stakeholders regarding their economic performance. Sensor economics are treated separately from satellite revenues as government stakeholders are responsible for sensor construction and operations. As with satellites, sensors are very expensive to build and relatively cheap to operate (assumed to be $171M and $1M/year, respectively).

3. Sensor Building and Operations

The nations attempt to keep sensor capabilities at 20% in excess of need. Therefore, sensor construction is triggered when observed RSO exceeds this margin. Sensor construction is also triggered by the loss of a satellite, a sign of inadequate tracking capacity. Nations are permitted to order sensors at a maximum rate of one per year. Each sensor is assumed to take three years to construct.

Sensor owners have the capability to share assets. Sharing provides satellite operators an economical way to close the gap between the apparent number of RSO and tracking capacity. When a sensor is shared, the model assumes perfect coordination with no redundant tasking. Thus, mutual sharing leads both nations to have an effective network of their own sensors, plus those being shared by the other nations, thereby increasing their tracking capacity and reducing the number of losses due to collision.

4. Sensor Buying Decision

The model tracks the number of apparent space objects as revealed by sky surveys. It is assumed that the sky surveys are able to estimate the approximate number of RSO (even when they exceed *tracking* capacity). As mentioned above, when a desired tracking capacity margin of at least 20% is lost, sensor construction begins with a desired time to recover the margin of three years.

V. Model Results

This section presents several sample runs of the model. Note that since it is stochastic model, these runs only illustrate one of many possible outcomes. A Monte Carlo analysis follows the sample runs.

A. No Cooperation

Initially, as a baseline, we present the behavior of two actors who do not cooperate. The graph in Figure 5 captures the tracking success probability and tracking capacity for one nation as well as the ambient debris. In order to track all RSO (which includes spacecraft and debris), Tracking capacity (green line) needs to exceed ambient debris (red line).

Initially, there is very low tracking success probability because the initial sensor set is inadequate to detect the initial ambient debris. The nation responds by building additional tracking

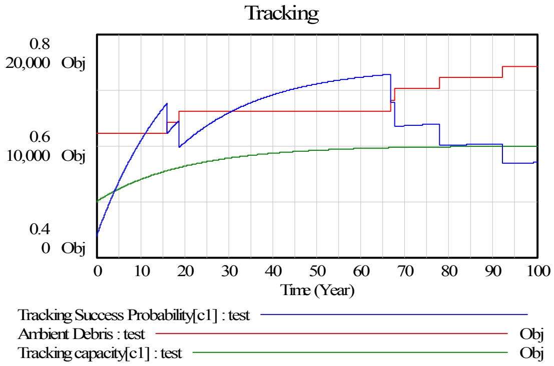


Figure 5 Tracking without cooperation

capacity. This, however, is a losing battle as impacts quickly raise the ambient debris to well above the maximum possible tracking capacity. Initially, tracking success improves but soon succumbs to debris generation as the nation reaches it maximum sensor capacity and tracking success decreases with subsequent impacts (time = 60yrs). Further improvement in tracking success will require access to additional sensor resources.

B. Full Cooperation

When the two actors cooperate by fully sharing their sensor networks, a very different dynamic emerges. As observed in Figure 6, the initial combined sensor network is nearly sufficient to meet needs (*i.e.*, tracking capacity is just under ambient debris). Within five years, enough sensors are constructed such that the gap is closed. After 15 years, a 20% margin exists, approximately 3,000 RSO. Since all RSO are tracked, collisions will be rare; and in fact, none are observed in this sample.

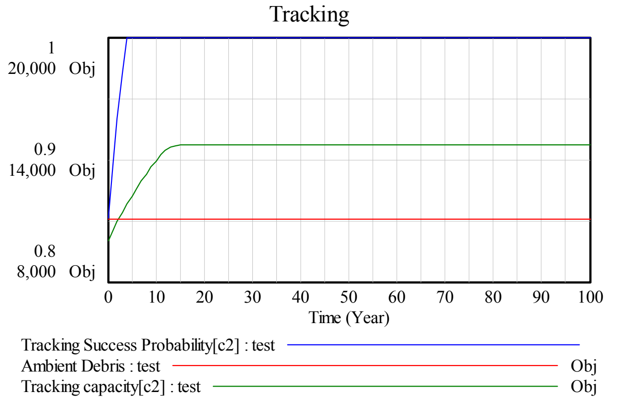


Figure 6 Tracking with full cooperation

C. Partial Cooperation

Another important scenario to consider is the situation where actors share only a portion of their sensor resources. As observed in the sample run depicted in Figure 7, each country begins with a different number of sensors: C1 has 10 sensors while C2 has 2 sensors. C1 agrees to share 70% of its resources while C2 shares 80%.

This particular run was quite unlucky for the two actors in that several early collisions occurred before adequate tracking capacity was available. After 20 years, tracking success reaches a peak, followed a gradual decline as debris generation outpaces sensor construction. The loss is gradual enough, however, that overall average mission lifetime is not affected by the rising debris population. Impact events remain rare enough such that the average satellite survives its full design life. Generosity does pay off in this example, as actor C1 maintains a higher tracking success probability (blue line) than C2 (red line).

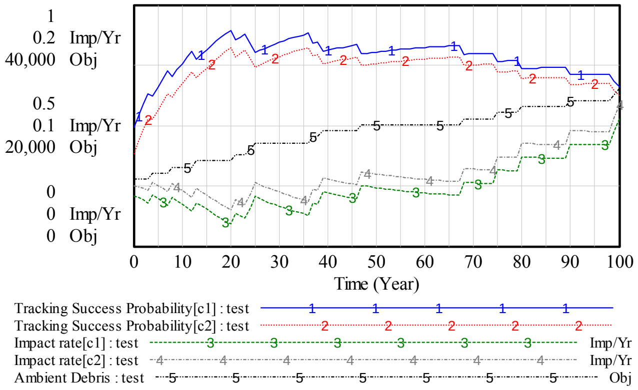


Figure 7 Tracking with partial cooperation

D. Monte-Carlo Results

While the individual sample runs describe possible futures of the space debris environment, to account for the probabilistic, path-dependent nature of the simulation, a Monte Carlo analysis was performed to extract general conclusions. The following two figures show aggregate SSA performance in terms of a physical metric (*i.e.*, debris accumulation) and a value metric (*i.e.*, stakeholder utility).

Figure 8 depicts a histogram of the frequency of debris accumulation. To gauge the impact of debris accumulation on a government stakeholder, a utility function was defined that consisted of two equally weighted components. The first component reflected national security concerns

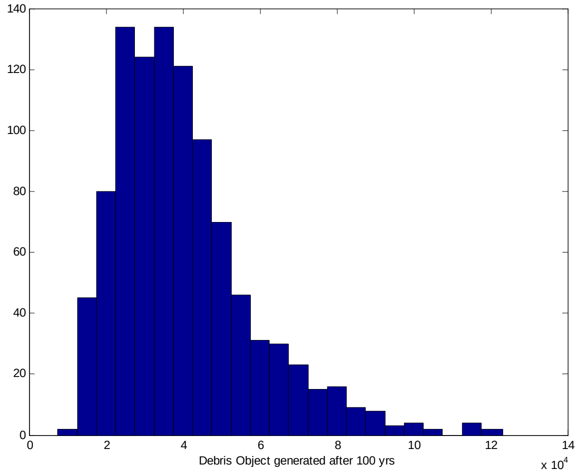


Figure 8 Histogram of debris accumulation

related to sharing the sensor network. It was defined as the proportion of the debris population that could be tracked without the aid on the other country. A greater reliance on sharing leads to lower national security utility. The second component relates to the economic interests of each nation. It was defined as the ratio of annual revenues earned by a satellite operator and the maximum possible revenue given the technological limitation of the spacecraft, launch rates, and the debris environment. Figure 9 shows a histogram of this additive multi-attribute for the 1000 runs depicted in Figure 8.

Monte Carlo analyses were also run for a range of partial cooperation values with the intent of determining, for each nation, which cooperation strategy might be a best-response to the set of strategies available to the other nation. This concept is known as a *Nash Equilibrium* in Game Theory.

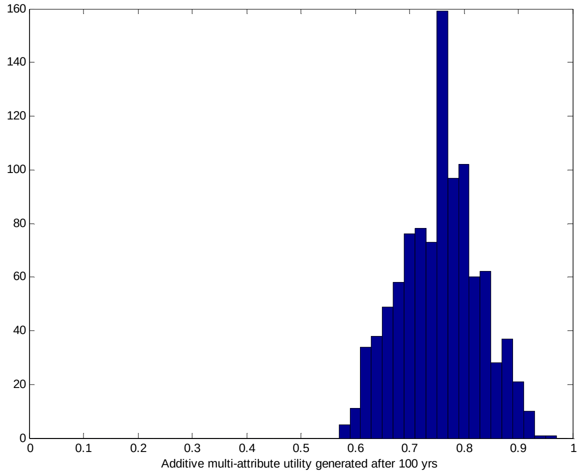


Figure 9 Histogram results of additive utility

In order to determine potential Nash Equilibria, a joint-strategy space was plotted, shown in Table 3. Each entry in this matrix represents the mean utility achieved by each player over 100 Monte Carlo runs given a particular level of cooperation by each nation. Each axis ranges from 0 (no cooperation) to 1 (full cooperation). The upper number in each cell is the utility realized by Nation 1, the bottom number corresponds to Nation 2. Entries highlighted blue indicate a utility maximizing response for each level of cooperation that the other nation may choose. For example, if Nation 1 chooses to share 30% of their network, then Nation 2's best response is to share 70%. The Nash Equilibrium constitutes the case in which both parties select their best response to the other's strategy.

Table 3 Mean utility values for each nation's cooperation strategy

Nation 1 - Proportion of sensor network shared

Nation 2 - Proportion of sensor network shared	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0.5663 0.5663	0.5732 0.5732	0.5838 0.5838	0.5881 0.5881	0.5912 0.5907	0.5936 0.5898	0.5955 0.5839	0.5962 0.5752	0.5962 0.5661	0.5962 0.5571	***0.5965*** 0.5495
0.1	0.5777 0.5777	0.5858 0.5858	0.5947 0.5947	0.5982 0.5983	0.6007 0.5998	0.6023 0.5962	***0.6035*** 0.5882	0.6033 0.5783	0.6031 0.5681	0.6029 0.5590	0.6030 0.5513
0.2	0.5838 0.5838	0.5939 0.5939	0.6013 0.6013	0.6047 0.6047	0.6067 0.6055	0.6090 0.6005	0.6096 0.5913	***0.6098*** 0.5814	0.6094 0.5711	0.6091 0.5622	0.6091 0.5545
0.3	0.5886 0.5886	0.5987 0.5987	0.6054 0.6054	0.6091 0.6091	0.6112 0.6099	0.6126 0.6032	0.6137 0.5930	***0.6138*** 0.5825	***0.6138*** 0.5731	0.6135 0.5643	0.6137 0.5570
0.4	0.5903 0.5908	0.6007 0.6015	0.6072 0.6085	0.6105 0.6119	0.6120 0.6120	0.6141 0.6037	0.6149 0.5931	***0.6152*** 0.5826	0.6150 0.5733	0.6150 0.5651	***0.6152*** 0.5579
0.5	0.5893 0.5934	0.5967 0.6031	0.6004 0.6095	0.6026 0.6127	0.6035 0.6141	0.6038 0.6038	0.6074 0.5932	0.6111 0.5825	0.6144 0.5734	***0.6162*** 0.5654	***0.6162*** 0.5583
0.6	0.5839 0.5950	0.5883 ***0.6035***	0.5910 ***0.6097***	0.5925 0.6130	0.5929 0.6144	0.5931 0.6070	0.5935 0.5936	0.5972 0.5833	0.6018 0.5735	0.6054 0.5653	***0.6086*** 0.5583
0.7	0.5749 ***0.5955***	0.5781 0.6032	0.5805 0.6088	0.5821 ***0.6131***	0.5824 0.6147	0.5824 0.6106	0.5833 0.5972	0.5838 0.5838	0.5867 0.5743	0.5921 0.5654	***0.5964*** 0.5584
0.8	0.5662 ***0.5955***	0.5685 0.6028	0.5708 0.6085	0.5729 0.6128	0.5733 ***0.6149***	0.5733 0.6138	0.5734 0.6018	0.5743 0.5867	0.5751 0.5751	0.5774 0.5662	***0.5825*** 0.5584
0.9	0.5569 ***0.5955***	0.5592 0.6023	0.5616 0.6078	0.5641 0.6123	0.5650 0.6146	0.5653 ***0.6156***	0.5653 0.6053	0.5654 0.5921	0.5662 0.5774	0.5673 0.5673	***0.5693*** 0.5588
1	0.5486 ***0.5955***	0.5512 0.6021	0.5543 0.6078	0.5566 0.6122	0.5578 0.6143	0.5582 ***0.6156***	0.5583 ***0.6084***	0.5583 ***0.5964***	0.5584 ***0.5825***	0.5587 ***0.5693***	***0.5602*** ***0.5602***

In this case, full cooperation by both nations is the only pure strategy Nash Equilibrium. Indeed, even when one nation is completely uncooperative, the other nation's incentive is to cooperate. This is because cooperation by one nation creates a disincentive for the other nation to build new sensors, essentially granting control of the network to the cooperator. Counter-intuitively, the national security implications of SSA lead each nation to engage in full cooperation with one another so as not to be dependent on the other's capability. The conclusion is sensitive to the assumptions made about the relative importance of national security *vis-à-vis* the economic portions of the utility function. The Nash Equilibrium is not socially efficient. There may be other strategies that might deliver greater value to both nations. These are not chosen since they are not mutual best responses. For example, if Nation 1 chose to share 30 %, Nation 2 would choose its utility maximizing response of sharing 70%. In response, Nation 1 would choose its best response to Nation 2's 70% sharing by sharing all its sensors. Nation 1 would then respond in kind, maximizing its utility by also sharing all of its sensors, bringing the game to the Nash Equilibrium. In order to realize the socially efficient strategies that benefit both nations, a coordination mechanism (such as a treaty or international organization) may be required to ensure that both nations choose the socially-efficient level of cooperation. Although only one pure strategy Nash Equilibrium is identified, a mixed-strategy (*i.e.*, probabilistic) Nash Equilibrium may also exist. This would occur if each player randomized across strategies. Further study is required to fully understand the strategic implications of cooperation.

VI. Future Work and Conclusions

A. Future Work

Future work will involve improving the fidelity of the SSA physics model as well as exploring new modalities of stakeholder cooperation. For example, the DELTA debris model (to which the results of the present model were compared) includes several additional types of collisions that were not included in this model (*e.g.*, satellite and rocket body explosions and collisions not involving debris fragments).

Additionally, there are many conceivable cooperation strategies that will be tested in the future. Next steps include implementation of the Tit-for-Tat and Win-Stay-Lose-Shift strategies. Indeed, there is no end to the set of strategies that one may conceive of testing. For example, one might consider adding a "correlation mechanism," such as an outside stakeholder, who receives information from both nations and then aggregates the data to draw inferences regarding the likelihood that the nations need to cooperate given the total tracking capacity and number of RSO to be tracked. We may also test variations in the utility functions such that sensor maintenance costs outweigh national security benefits.

B. Implications for SSA Architecture

The methods described in this paper offer insights into the representation, design, and analysis of SSA. While the simple model utilized in this study is by no means comparable to formal architecture descriptions (*e.g.*, the Department of Defense Architecture Framework), it may offer insights to improving the current paradigm. Social, economic, and technical domains are fully integrated into the simulation. The System Dynamics representation is inherently dynamic and internally consistent as enforced by the differential equations. Architecture design is another area addressed by the SSA simulation. In developing an executable model based on decades of empirical data, a decision maker may use the tool to investigate outcomes across technical, political, and economic domains. Finally, and perhaps most importantly, the SSA simulation is a first step for architecture analysis. Although the physics model of sensing capabilities would require higher-fidelity for a credible trade study, the framework is well-suited for evaluating future candidate ground- and space-based architectures.

C. Implications for Systems of Systems

As stated in the introduction, the objective of this paper was to model an SOS from a value perspective. Decision making was modeled for key stakeholders and the dynamics of their decisions were observed. The metric used in decision making was composed of a component that favored SOS cooperation—the economic component—and one against cooperation—the national security component. By looking beyond the functional and technical aspects of SSA, a significant insight was revealed in creating a socio-technical SOS model. An essential characteristic of this SOS is the level of cooperation between the two nations. If a nation only considers the benefits received by participation in the SOS, it would opt for full cooperation. However, as observed in Table 3, the resultant utilities are not socially efficient, and better utility can be obtained by both nations cooperating less. This reflects the dissatisfaction of the nations with not meeting their national security objectives despite having access to a superior joint sensor network. Furthermore, since this socially optimal solution is not a Nash Equilibrium, a control mechanism to ensure that the constituents don't give *too much* to the SOS may be required.

Indeed, systems composed of components that are themselves systems are increasingly common and present a challenge to system architects. In particular, collaborative SOS stands out as a class of problems that may require extensions from traditional SE methods. A key issue facing collaborative SOS is the presence of diverse objectives of constituent systems and of the SOS as a whole. The challenge facing the system architect is to be cognizant of the effect of SOS value generation on the constituent systems and to make adjustments to encourage continued participation. In doing so, the SOS architect needs to understand the effect (either positive or negative) of SOS interfaces on each constituent's ability to meet its own objectives. As demonstrated by the model of international SSA, cooperation among nations to form an SOS may reduce the incidence of debris collisions and growth of RSO. However, the model also indicates that successful implementation of SOS requires striking a balance between both local and global concerns in order for each nation to achieve a utility-maximizing result.

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