# Low Earth Orbit Debris Avoidance Using Situation-Risk Assessment Modeling

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**Launch and on orbit operations for debris-field avoidance has been an issue in the community for many years. However, with the increase in commercial space traffic, the need for assessing the risk of space activities has become more important. In this paper, we used the situation-risk assessment (SRA) method contained within the intelligent situation assessment and collision avoidance (iSC) platform to develop a risk analysis of space operations. We defined the concept of a launch theater and developed a risk metric to assess the chance of collision when traveling through the low earth orbit (LEO) debris field. Then, we then used this concept to make decisions that lowered the launch risk. Finally, this method was applied to objects already in orbit attempting to make decisions on how to avoid debris while also attempting to keep the necessary orbital parameters for mission success.**

## I. Nomenclature

| | | |
|---|---|---|
| $\omega$ | = | argument of periapsis |
| $\Omega$ | = | right ascension of the ascending node |
| $a$ | = | semi-major axis |
| $\delta t$ | = | the time difference between the closest orbits (or trajectories) |
| $D_{CR}$ | = | critical distance metric for risk assessment |
| $d_{min}$ | = | minimum safe distance |
| e | = | eccentricity |
| E | = | eccentric anomaly |
| FV | = | future value |
| $i$ | = | inclination |
| $P_g$ | = | geometric risk |
| $P_t$ | = | theater risk |
| PV | = | present value |
| $P_{Xi}$ | = | collision probability with the i$^{th}$ object |
| r | = | discount rate |
| $S_f$ | = | scale factor for risk timing |
| $\vec{u}$ | = | command decision |
| $V\|_{min-d}$ | = | speed at the minimum distance |

## II. Introduction

Space traffic management (STM) is a growing concern for commercial space operations. Current estimates have a minimum of 15,000 (LEO) [1]. This is a collision danger for space flight. This danger exists for both the active carrying of humans into space, as well as the unmanned spacecraft that carry logistical supplies to human space operations.

There have been many proposals investigated in the past ten years discussing the need and the requirements for some sort of coordinated space traffic management [2-9]. These works have mainly focused on legal coordination for traffic management, as well as the challenges to developing a systematic and effective system for the safe and easy access to space. However, currently, there is little to no coordination between international stakeholders. The major issue is that space tracking is controlled by individual militaries that may or may not share their findings.

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Currently there is no set system for checking launch clearance. In [8], Cukurtepe discussed the data transfer and permission systems that are currently in use for tracking and resolving space traffic management. This method has many moving parts and is reliant upon many key individuals to assess the current space traffic situation. This paper addressed one of the bottlenecks in the space traffic management that is the debris avoidance.

Unlike all the other STM systems proposed, the Intelligent Situation Awareness and Collision Avoidance (iSC) methodology proposes a decentralized system aboard each craft that would make use of whatever resources are available at the moment. The iSC method is currently being developed at the University of Southern California (USC), which is a cognitive computing approach to situation awareness and collision avoidance. Currently this method is being applied to the task of collision avoidance in maritime applications [10]. The similarities between the STM problem and maritime problem are striking. They both involve dynamics that are stable on short time-frames, but chaotic for the long term. Both problems involve a large number of independent components that may or may not be under the control of an agent. Finally, both problems have decisions that are made at the current time that affect both the current state of the situation as well as long-term implications for the situation.

## III. Situation Awareness

Most people have a colloquial understanding of what is meant by a situation. However, from an engineering and systems engineering standpoint there are two (related) schools of thought on situation, situation awareness (SAW), and situation assessment (SA). The first is the method proposed by Dr. Endsley [11] on situation awareness. Dr. Endsley proposed that SAW is developed in through three levels. The first is determining the entities and states in the environment. The second level is understanding the relationships between those entities. Finally the third is the ability of an agent to project that situation into the future. This model is shown graphically Fig. 1, below.

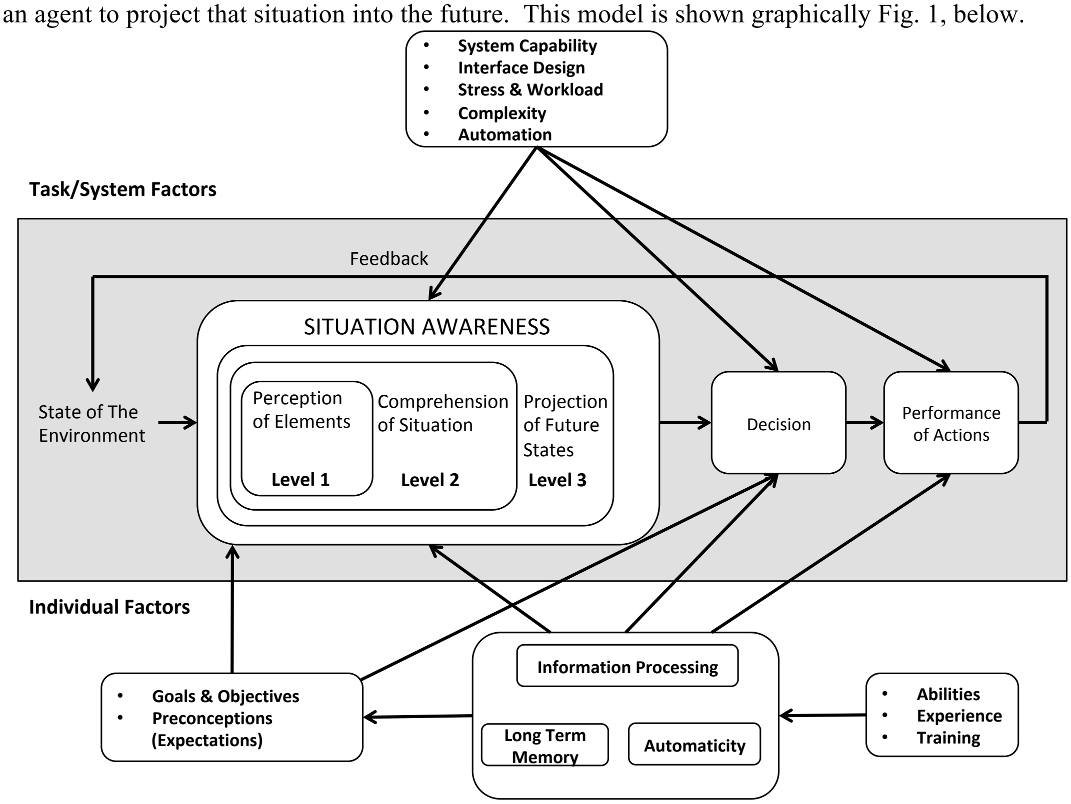


**Fig. 1 Endsley's model of situation awareness.**

It should be noted that Endsley's model was initially developed for human cognition, and not necessarily for autonomous systems. Although it should be noted that Dr. Endsley and others have updated this cognition method to include multiple agents and system situational awareness [12-13]. As was noted in [10] Endsley's model resembles the standard guidance, navigation, and control loop. The main difference is that SA views allow for a broader scope of data, beyond standard navigation state and sensor data.

The second direction comes from the ontological build up of SAW and SA through the sensor fusion community. This begins with the work of Barwise and later Devlin on the philosophical basis of situation and situation awareness [14-15]. The ontology based SAW [16] was developed as an object orientated data model completed with a UML based diagram. The use of predicate calculus and infons through the use of object orientated data development allows for the development of autonomous SA methods to be developed.

In both of these methods it is assumed that the situation is known a-priori, and that the data that arrives is either in or out of the situation. In the situation-risk assessment (SRA) portion of iSC we make note that an agent's goals specifically create a situation. Our goal defined situation then uses data infons to determine what data are relevant to that user-defined situation. With this we now look to define what our goals/objectives are. In this paper we look at two sets of goals/objectives. The first set of goals is for maintaining an asset that is already in orbit:

1) Do not collide with anything
2) Maintain our orbital parameters
3) Use the lowest amount of energy (fuel)

The second set of goals is for placing an object in low earth orbit:

1) Do not collide with anything
2) Provide our object with the correct orbital parameters
3) Use the lowest amount of energy (fuel)

We note that these are similar, but the subtle differences in our goals/objectives make for different results as we will see later. In this work we specifically make use of the model based SA method that defines the entities and the relationships between those entities. By doing this we can set up a systematic process to identify what is happening to our situation and to make decisions to achieve those goals/objectives that we have set forth. The basic computational loop is shown in Fig. 2, below.

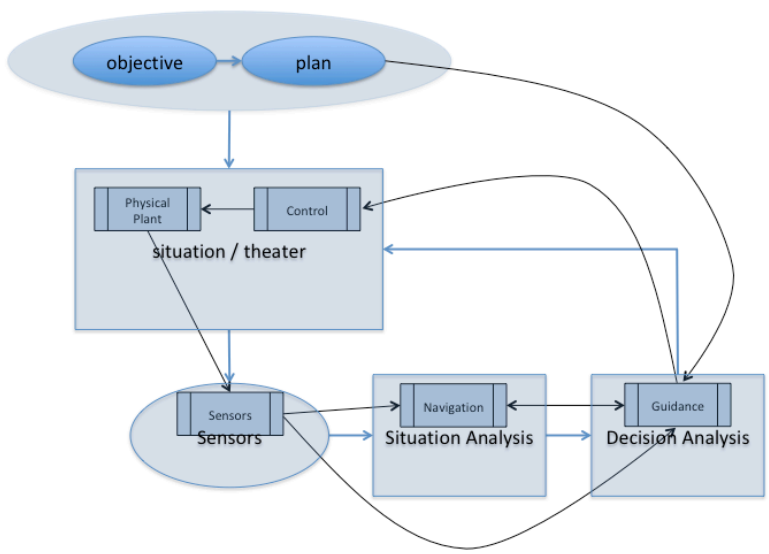


**Fig. 2 Comparison of traditional guidance, navigation, and control to situation assessment.**

## IV. Risk Analysis

The definition of risk is more nuanced than the definition of a situation. Like the word "situation", the word "risk" is commonly understood when used in casual conversation. However, for us to appropriately use the concept, we must define clearly what is meant by risk as different industries and individuals have differing definitions of the word. For our purposes risk is the probability that events in our future situation will cause us to not be able to achieve our goals or objectives. The cause of that risk is defined to be a threat.

To identify what a threat is we need to go back to our definition of a situation. If an object, entity, or agent is a part of a situation (that is defined by our goals/objectives), and it has the potential to act contrary to those goals/objectives it is a threat. By projecting the states of those threats into the future through some model (cognitive, mathematical, or otherwise), we can determine the likelihood that the threat will cause harm to our goal.

This is generally how humans assess the world around us, however, in this formalized method, we can use this method to control our own system to minimize our risk. To do this we employ a method that was described in [17] of using a Poisson process with the miss timing differential denoting the arrival time to obtain the probability of an incident.

## A. Collision Risk Calculation

We start by assuming we know the positions of each of the objects within the situation (for this problem the objects within LEO) with a high degree of accuracy. Such that we can calculate the positions of the objects out to a few days ahead in time. Errors in the current (t=0) navigation state are currently outside the scope of this work. For each debris cluster, we determine either from the orbital parameters or the objects' ephemeris table, two values. The first is the current distance between "us" and the other object, d(t). Notice this is a function of time and thus will change from t=0 until $t_f$ (defined later).

The second value is the minimum time difference at the closest orbital distance, δt. Meaning that one object will be at the point where the orbits are closest at some time, $t_1$. The other object will then be at the point in that object's orbit of closest orbit distance at some time, $t_2$. The difference between $t_1$ and $t_2$ is δt, and is defined in Eq. (1). We must be clear to note that the value of δt assumes a specific trajectory with a specified set of control inputs that we provide.

$$\delta t = \left| t_1 - t_2 \right| \tag{1}$$

Like was used in [10], we define two risk components. We look at the risk that comes from the theater itself. This is the component that uses the current distance between the two objects. We then use this in a Poisson distribution simulating arrival times. This distance is then scaled by a critical distance parameter, $D_{CR}$. This value is specific to us. Typically this value would be filtered from some training data to scale the risk. This component of the risk is given in Eq. (2), below.

$$P_t\left(t\right) = e^{-\frac{d(t)}{D_{CR}}} \tag{2}$$

The second of the collision risk component is the geometric component. This is also a Poisson arrival distribution shown in Eq. (3). Like in the theater risk component we need to scale the value δt by a scale factor; this is denoted by $S_f$. We note that while Eq. (2) is a function of time, Eq. (3) is not. Since the value δt is the minimum time difference between t=0 and $t_f$ it is independent of time, and is only a function of a given trajectory.

$$P_g = e^{-\frac{\delta t}{S_f}} \tag{3}$$

The value $S_f$ is mostly analytically derived. We assume that at some specified minimum safe distance our risk tolerance is 95%. So we can derive the value of $S_f$ through the use of this through Eq. (4). In Eq. (4), $d_{min}$ is the minimum safe distance, and $V|_{min-d}$ is our orbital speed at the time of closest approach.

$$S_f = -\frac{d_{\min}}{\ln\left(0.95\right)V\big|_{\min-d}} \tag{4}$$

With this we can now calculate what the collision risk is. We notice that regardless of the orbital miss distance, if we have a 100% theater based risk the distance is 0 and thus our total collision risk is by definition 100%. Similarly, if we have a 100% geometric risk but we are "far" away from the object our risk is only the current distance from the object. This is similar to a logical AND function. Thus our total risk can be calculated by Eq. (5).

$$P_X\left(t\right) = P_t\left(t\right)\left(P_g + \left(1 - P_g\right)P_t\left(t\right)\right) \tag{5}$$

The topology for Eq. (5) can be found in Fig. 3, below. Note that this satisfies how we need the collision components to be combined to provide a logical risk assessment.

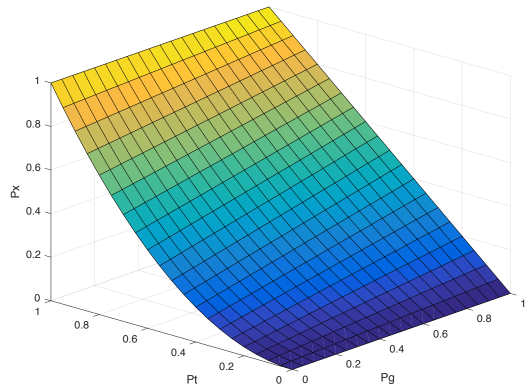


**Fig. 3 Collision function risk components**

With Eq. (1) – Eq. (5) we have a way to categorize the risk of us colliding with another object. How then do we determine what our risk is for an entire set of objects? We first note that on any given trajectory we can collide with one object, or we can collide with many objects, so collisions are not independent events. However, missing all the objects requires us to calculate the chance to miss one then another object and these are independent probabilities. With this in mind we can calculate the chance to collide with any object by using Eq. (6). In Eq. (6), the value, $P_{Xi}$, is the probability that we will collide with object *i*.

$$P_X(t) = 1 - P_{miss}(t) = 1 - \prod_{i=1}^{n}\left(1 - P_{X_i}(t)\right) \tag{6}$$

## B. Energy Risk

We wish to use the least amount of energy for both our launch and in-orbit station-keeping operations. For the launch problem. we assume that the amount of launch energy is set and the final system orbit is determined to be the optimum orbit for the mission success. However, in the in-orbit debris avoidance problem, we look at the risk of the energy usage.

For the determination of this risk, we assume that we have a system specified maximum $\Delta$v budget. Any use of propellant is a risk to the objective of minimal energy expenditure. We initially assume we have a maximum of 450 m/s to spend on our fuel budget for debris avoidance. So the calculation of the fuel risk is given in Eq. (7).

$$R_{fuel} = \frac{\Delta v^2}{\Delta v_{\max}^2} \tag{7}$$

## C. Combining Two Risk Components

Returning to the definition of risk, we notice that it is the probability that a goal or objective of ours will not be met; meaning that if we fail on any of our goals or objectives we have failed in our intent. We can then use this to determine what our overall system risk is. Much like in Eq. (6), where we combined the miss probabilities, we do that with the individual risks.

We combine the risks in Eq. (8), where *m* is the number of risks/objectives that we have. Equation 8 shows us the total risk at a given time. It is not the entire risk along a given trajectory, but is an instantaneous value of risk.

$$R_{isk}(t) = 1 - \prod_{j=1}^{m}\left(1 - R_j(t)\right) \tag{8}$$

## D. Total Trajectory Risk

Up until now, we have looked at the risk of our object at a specific time. However, for us to compare different trajectories we must see what the changes occur given guidance decisions. How should we compute the entirety of our trajectory? We start by employing a standard technique in financial computations by looking at the present value of “something” and comparing that to the future value of “something”. This is done through the future valuation and some discount rate, r. This is shown in Eq. (9). This standard equation says that some value in the future is worth less to us now. Similarly, value that we hold currently will be worth more to us in the future through the use of interest.

$$PV = FVe^{-rt} \tag{9}$$

We take this concept and use the future value of risk. The present value of an instantaneous risk is worth less to us the further that system state is out from us. Equation (10) shows this. We use the prime on the risk to denote that this is an instantaneous value.

$$R' = R_{isk}\left(t\right)e^{-rt} \tag{10}$$

Our discount rate, r, is set by arbitrarily saying that at our final projection time, $t_f$, the value of that state is 1% of the value of our current risk state. This is given in Eq. (11).

$$r = -\frac{\ln\left(0.01\right)}{t_f} \tag{11}$$

Returning to Eq. (9), is should be obvious that we will then integrate this risk value along some trajectory to get our entire system trajectory. This is done in Eq. (12). The coefficient outside the integral ensures that the risk along the entire trajectory’s maximum value is 1.

$$R_{\vec{u}} = \frac{r}{1-e^{-rt_f}}\int_{\tau=0}^{t_f} e^{-r\tau}R_{isk}\left(\tau,\vec{u}\right)d\tau \tag{12}$$

**E. Decision Making Loop**

Now that we have a method to analyze a specific trajectory we create a system that uses risk and is consistent with the use of SA as discussed earlier. At this point, there are a few options available to us, the first is to minimize the value of $R_u$ by utilizing a gradient based or some other formalized optimization based approach. We can also minimize $R_u$ by enumerating the potential decisions for $u$ and then selecting the lowest value of $R_u$. Finally, we have the ability to utilize data driven pattern recognition to determine the best risk assessment. This final piece is currently being developed and worked on as a part of the iSC system.

With this we can now see how the entire loop works. Our system receives infons from the theater that are interpreted through our situation definition. These infons are converted to data through our sensors. That then begins our situation assessment loop. This system loop is shown in Fig. 4, below.

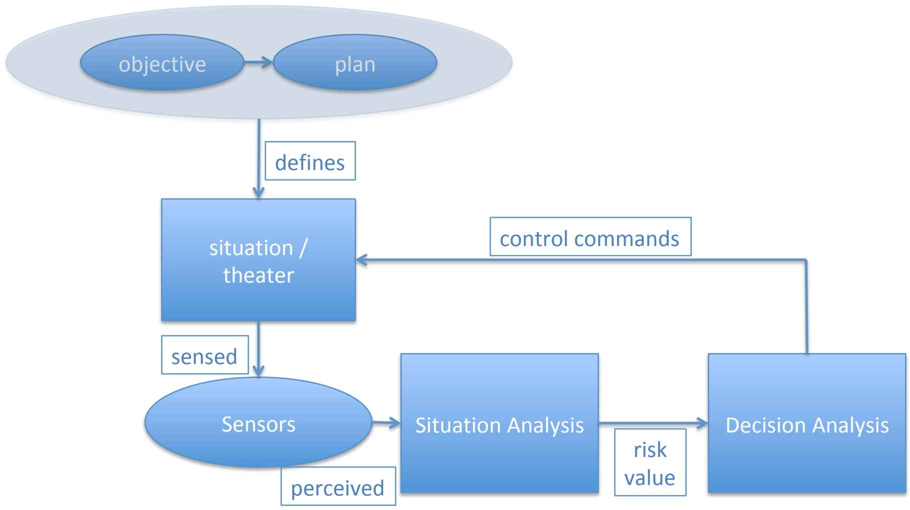


**Fig. 4 Risk assessment decision loop**

As was alluded to in Fig. 2, this loop is similar to the traditional GN&C loop. However, there are some subtle differences. The first is that there are no implicit constraints. Any constraint that exists is only seen as a risk to a goal/objective and therefore becomes intrinsic to the situation itself. The second is that by removing implicit constraints the system can adapt to be more concerned about one risk vs. another risk by the evolution of the situation alone; we do not need to develop specific logic to adapt the objective if there is a conflict. Third, by using infon based data we have the potential to make decisions that are outside traditional sensor data, thus allowing for more data based modeling and decision-making.

## V. Results

For this analysis, we are using basic two-body orbital mechanic properties [18] for simplicity of calculation. It must be noted, however, that while a more advanced calculation method would change the simulation values, the methodology itself is independent of the orbital mechanics used. The simple mechanics here can be substituted for more accurate dynamics with no loss of generality.

To illustrate the methodology the simulation was run using 1,500 debris cluster objects randomly placed in low earth orbit. The variation used is listed in Table 1, below. The values for the eccentricity were taken from a study of debris in geosynchronous orbit [21].

**Table 1 Minimum and maximum orbital parameters**

| Orbit Parameter | Minimum | Maximum |
|---|---|---|
| a (km) | 6820 | 7970 |
| e | 0 | 0.3 |
| i (deg) | 0 | 90 |
| Ω (deg) | -180 | 180 |
| ω (deg) | -180 | 180 |
| Eo (deg) | -180 | 180 |

The positions of the objects are shown in Fig. 5, below. This debris field, while randomly generated, is used for both the launch analysis and the on orbit maneuver analysis.

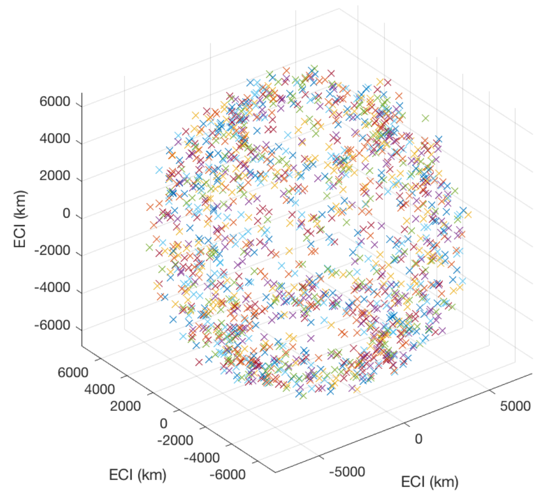


**Fig. 5 Initial debris distribution for orbital and launch analysis**

## A. Launch analysis

For our launch scenario, we assume that we are using an Atlas V launching from Kennedy Space Center. The trajectory determination is set to achieve a delivery to the ISS. The mechanics used to determine the launch trajectory were determined using a simplified mechanic system as described in [22]. Once again, it is important to note that while the particular results shown here would change with different dynamics and simulators, the methodology itself is independent of the dynamics used.

We are determining the lowest risk launch. As was discussed in section III, we have only two goals, the first is to not collide with anything, and the second is to hit our launch window. For this, we assume a 45 min launch window (chosen arbitrarily) with a launch window risk shown in Fig. 6, below.

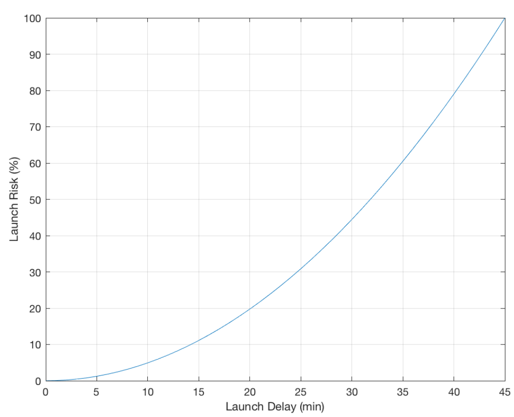


**Fig. 6 Launch window risk curve**

The collision risk was then run using the methodology presented above. Each launch time was looked at in 5 min intervals for a total of 45 min. The results of the launch trajectories' risk values are shown in Fig. 7, below. This plot shows that delaying the launch will drop the risk of collision. Also it should be noted that this plot shows the instantaneous risk during the launch of colliding with in orbit debris.

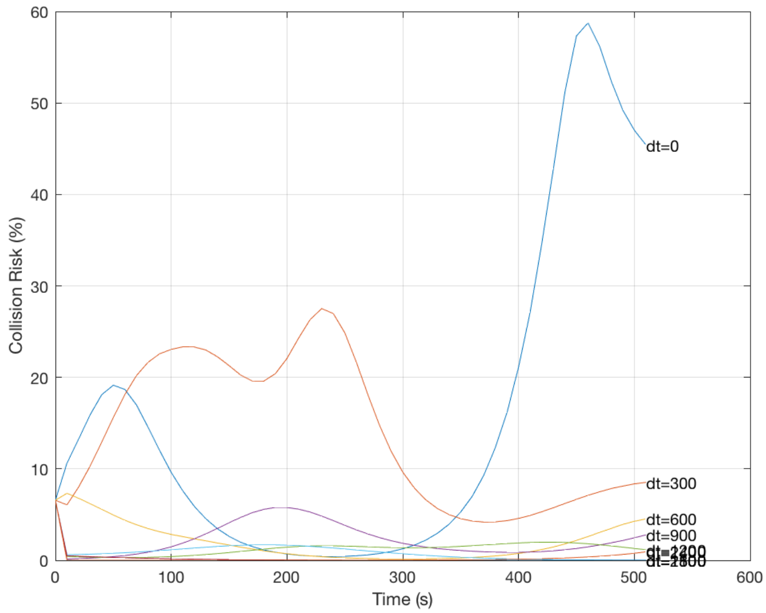


**Fig. 7 Launch trajectory instantaneous collision risk**

To determine the risk of the entire trajectory we use the method shown in Section IV-D. With this we get the results in Table 2.

**Table 2 Total launch trajectory risk with delay risk**

| Launch Delay (min) | Trajectory Collision Risk | Launch Window Risk | Total Trajectory Risk |
|---|---|---|---|
| 0 | 10.57% | 0.00% | 10.57% |
| 5 | 15.55% | 1.23% | 16.59% |
| 10 | 3.91% | 4.94% | 8.65% |
| 15 | 2.12% | 11.11% | 12.99% |
| 20 | 1.17% | 19.75% | 20.69% |
| 25 | 1.46% | 30.86% | 31.88% |
| 30 | 0.78% | 44.44% | 44.88% |
| 35 | 0.57% | 60.49% | 60.72% |
| 40 | 0.58% | 79.01% | 79.13% |

On this set of risks and goals alone it would be recommended to delay the launch by 10 min for a more favorable debris field pattern.

## B. In orbit collision risk

This method can also be used for determining the risk of a given orbit given the debris field in orbit. To do this we first look at what the risk of our current orbit is. With no loss of generality, we use the same random debris field described above. We then place "us" in a nearly circular orbit (e=0.001) in the middle of the LEO orbit band (a=7400 km) at an inclination of 63.4°. The result of this over a 2 day orbital period gives us the risk plot shown in Fig. 8. The associated integrated collision risk is 8.96%.

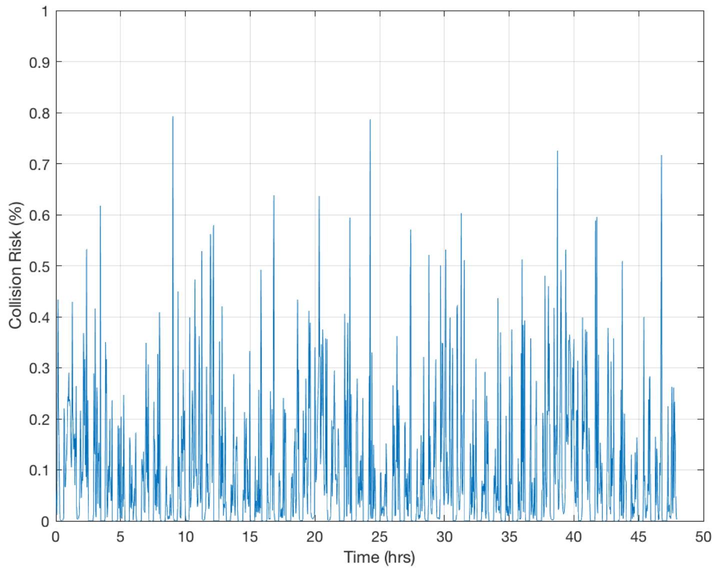


**Fig. 8 Unmodified instantaneous collision risk over time**

We assume that currently the integrated risk and the maximum absolute risk is currently too high. So we will now look at the effect of changing our orbit to minimize the overall risk. While we could investigate the effect of performing a 3-d velocity maneuver, we restrict the maneuver to be a change of inclination. This is done for visualization purposes only, but, like before, the methodology is easily generalizable to any type of proposed maneuver. When we do this we come up with the results shown in Table 3, below.

**Table 3 Trajectory change risk results**

| Δ-inc (deg) | Δv (km/s) | Trajectory Collision Risk | Maximum Collision Risk | Maneuver Risk | Total Trajectory Risk | Total Maximum Risk |
|---|---|---|---|---|---|---|
| -10.0 | 0.330 | 8.54% | 75.97% | 53.73% | 57.68% | 88.88% |
| -7.5 | 0.248 | 8.60% | 86.15% | 30.26% | 36.26% | 90.34% |
| -5.0 | 0.165 | 8.74% | 89.55% | 13.46% | 21.02% | 90.96% |
| -2.5 | 0.083 | 8.40% | 76.97% | 3.37% | 11.48% | 77.74% |
| 0.0 | 0.000 | 8.11% | 78.28% | 0.00% | 8.11% | 78.28% |
| 2.5 | 0.083 | 8.19% | 79.49% | 3.37% | 11.28% | 80.18% |
| 5.0 | 0.165 | 8.64% | 78.35% | 13.46% | 20.93% | 81.26% |
| 7.5 | 0.248 | 8.05% | 78.65% | 30.26% | 35.87% | 85.11% |
| 10.0 | 0.330 | 8.00% | 88.69% | 53.73% | 57.43% | 94.76% |

In Table 3 the 0°, inclination change is the results that were shown initially. As we look at changing the inclination, the risk changes and we can lower the maximum collision risk for the next 48 hours by decreasing the inclination by 2.5°. However, the lowest integrated collision risk would occur when we increase the inclination by 10°. When we look at the risk to us changing our orbit (we have assumed that we chose that orbit for mission success) the lowest risk would occur when we do not perform any maneuver. However, if we wanted to lower the maximum risk and included the cost of the maneuver we would choose to decrease the inclination by the 2.5°, as discussed above. The risk trajectory for this decrease is shown in Fig. 9.

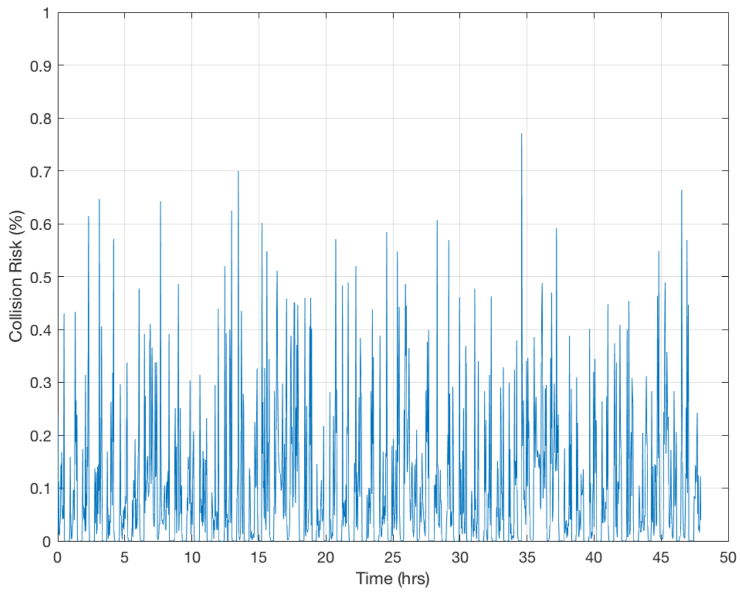


**Fig. 9 Minimized maximum instantaneous risk orbit**

## VI. Conclusion

The iSC methodology is able to look at all different types of problems where decisions are made in dynamic systems with uncertainty. This paper shows the methodology is appropriate for multiple scenarios. However, the key is that we go in with no prior assumption of how the system will behave. We only look at the data and only use the known physics to act as a constraint to infer what the data are saying.

Future work in the area will occur in two areas. The first is in adding more uncertainty to the data and using that uncertainty in both the dynamic model itself, and also in the navigation errors. These errors can be incorporated to the final decision by acting as a weighting on both our state and the state of the other objects' in the situation.

Second, by developing data driven decision-making we can utilize pattern recognition systems and machine learning to characterize the risk much more efficiently. Also using these methods will allow us to access more and broader databases to determine the best course of action.

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