

MITIGATION OF COLLISION HAZARD FOR THE INTERNATIONAL SPACE STATION (ISS) FROM GLOBALLY LAUNCHED OBJECTS

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ABSTRACT

For the International Space Station (ISS), it can take 6 to 24 hours to reliably catalog a newly disposed upper stage and up to 33 hours to plan and execute an avoidance maneuver. This creates a gap in the existing collision risk protection for newly launched vehicles, which covers the period when these launched objects are still under propulsive control; specifically, upper stage separation plus 100 minutes for most missions. This gap results in a vulnerability of the ISS from the end of current “Launch Collision Avoidance (COLA)” protection until approximately launch plus 56 hours.

In order to help mitigate this gap, conjunction analyses are being developed that identify launch times when the disposed upper stage could violate safe separation distances from the ISS. Launch window cut-out times can be determined from the analysis and implemented to protect the ISS.

The COLA Gap is considered to be a risk to ISS operations and vehicle safety. Methods can be used to mitigate the risk, but the criteria and process need to be established and developed in order to reduce operational disruptions and potential risk to ISS vehicle. New requirements and analytical methods can close the current COLA gap with minimal impact to typical launch windows for Geo-Transfer Orbit (GTO) and direct injection missions. Also, strategies can be established to produce common standards in the U.S. and the world to close the current Launch COLA gap.

1. WHAT IS THE HAZARD?

Launched objects, their disposed upper stage(s), and/or payloads may have orbits containing potential conjunctions (i.e. near misses) with the ISS. This condition is highly dependent on the trajectories (geometry) of the two vehicles and their respective uncertainties as shown in Fig. 1.

An example of this hazard can be seen in Fig. 2, an illustration of the geometry for both the ISS and the 2nd and 3rd upper stages of a launched vehicle during the 56-hour COLA gap interval.

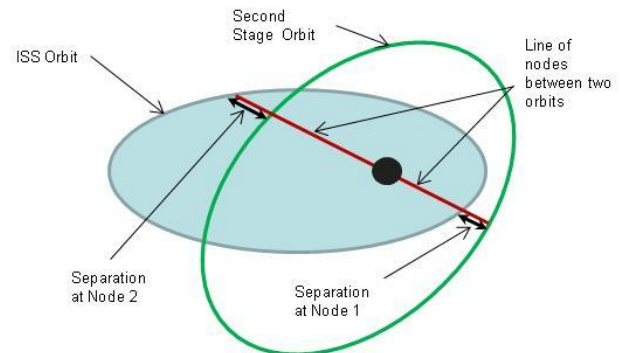


Figure 1: Orbital geometry between ISS and 2nd Stage of a launched object.

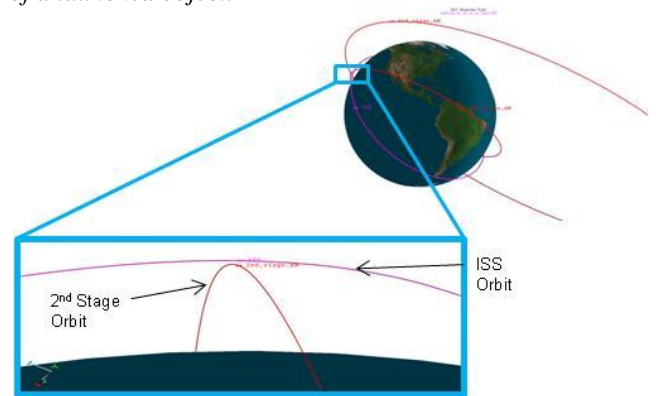


Figure 2: Illustration of geometry for both ISS and launched upper stage.

There are two scenarios that cause concern for the ISS. The first, and less likely, is the object actually colliding with the ISS. The more imperative concern is that of the object passing within the same vicinity of the ISS, thereby disrupting Ground Control operations and/or ISS Crew operations. The U.S. Joint Space Operations Center (JSpOC) has stated approximately six (6) to twenty-four (24) hours are required after launch to acquire an orbital track and calculate possible conjunctions with the ISS. Once a conjunction warning is received, NASA ISS operations typically requires a minimum of thirty to thirty-two hours to plan and execute an ISS evasive maneuver depending on vehicle configuration, flight planning, and on-board operational activities.

Launch Collision Avoidance (Launch COLA) analysis is performed for all United States (U.S.) launches: military, civilian, and commercial. The current Launch COLA safety requirements for all three types of launches are designed to protect against collision/conjunction with orbiting assets that are occupied or can be occupied by human beings. The time period covered by launch COLA extends from launch to approximately end of spacecraft/upper stage separation plus 100 minutes. This duration is by convention, but there are some practical limits associated with large uncertainty in predicting the position of a typical liquid fueled upper stage and payload after burn out. Conjunctions are often determined between launched objects (upper stages and their payloads) and all objects in the U.S. catalog of resident objects for mission assurance purposes. Miss distance and probability are computed and compared to thresholds for each opportunity during the launch window.

As a result, a “COLA Gap” occurs between current Launch COLA protection and prior to routine ISS on-orbit conjunction assessment capability following the new object cataloging. The ISS is vulnerable during this COLA Gap from the end of the current Launch COLA until ~L+36 to ~L+56 hours. Even though there is a small likelihood of an actual collision, the consequences would be catastrophic for both the launcher and ISS.

2. CURRENT LAUNCH COLA METHODS

Two independent yet similar geometric assessment techniques have been developed for analyzing spacecraft launches during the identified gap. The Aerospace Corporation and the Launch Services Program (LSP) respectively analyze Nodal Separation (Radial) and Argument of Latitude (In-track) distances between upper stage/payload and the ISS orbits in support of The U.S. Air Force and NASA. The analyses first determine the minimum nodal separation (Radial) distance between orbit traces over a 56 hour interval, for each launch window over a range of launch dates as shown in Fig. 2.

Nodal Separation analysis is performed primarily to reveal which launch dates might have an ISS/upper stage COLA Gap issue. This initial look determines the minimum nodal distance between orbit traces over the analyzed interval. If Nodal Separation is outside the mission specific uncertainty region, then the ISS will not pass through the upper stage’s dispersion cloud, and collision would not be possible. If Nodal Separation is within a specified uncertainty region, there could be a COLA Gap issue.

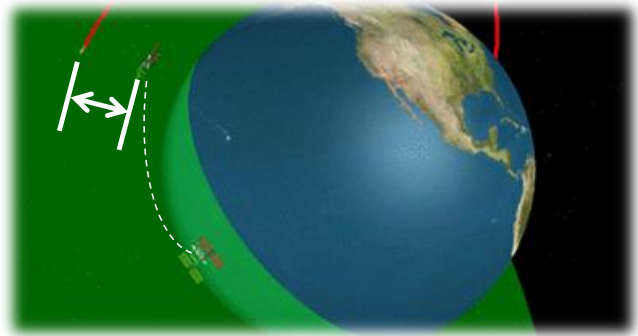


Figure 2: Illustration of Nodal (Radial) separation obtained from Kennedy Space Center (KSC) Launch Services Program (LSP).

Even if the Nodal Separation check fails--meaning there is a good chance of a conjunction--there is still the possibility that the objects will remain far apart (i.e., phased over different regions of the Earth, even though the full orbit traces come within close range of each other). An additional analysis using the Argument of Latitude (In-track) position of both objects (Depicted in Fig. 3) is used to confirm close proximity location of both the ISS and second stage.

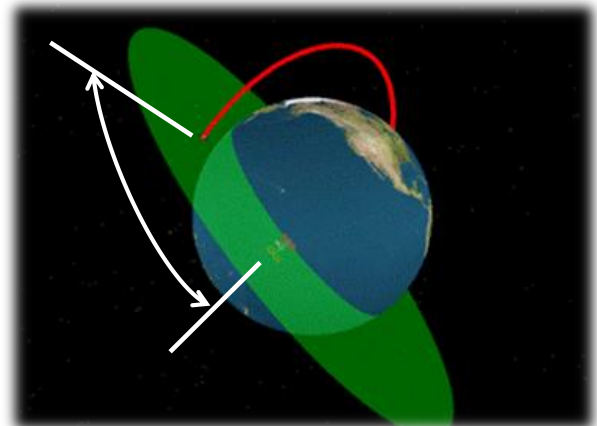


Figure 3: Illustration of Argument of Latitude (In-track) separation courtesy of LSP.

At each intersection point, both Radial and In-track miss distances are computed. These miss distances are compared to initial screening criteria based on position uncertainties to determine if a conjunction is likely.

The analysis uses nominal trajectory and a miss distance threshold encompassing 3-sigma dispersions. This analysis is performed for a range of launch days at launch window points to determine if there is effectively a zero or extremely remote chance of a conjunction.

3. ISS ACCEPTABILITY

These analyses define the distribution of Radial and In-track positions between the launcher and the ISS, which can be used to determine if there is essentially a zero or extremely low chance of an actual collision. However, these analyses do not consider the operational impacts of an occupied orbiting asset. There is no real identification of the risk that the upper stage will pass close enough to the ISS to be within established thresholds that trigger a potential debris avoidance maneuver, thus disrupting on-board and ground operations.

Ground operators, JSpOC Orbital Safety Analyst (OSA) and NASA's Johnson Space Center (JSC) Trajectory Operations Officers (TOPO) must cooperatively manage any close approach passing through the ISS notification volume.

In such gap situations, where there is not sufficient notification time, the ISS does not have time to plan and execute a standard evasive maneuver. In these situations, the crew is required have to stop all on-board operations and shelter-in-place.

4. PROPOSED PROBABILISTIC PROCESS

Specialists at JSC are working with Aerospace Corporation and Kennedy Space Center's (KSC's) Launch Services Program (LSP) to develop a more formal risk evaluation process that is consistent with existing ISS Program on-orbit collision avoidance techniques. The goal is to establish a set volume that balances protecting ISS collision and limiting the disruptions to ground and Crew operations with an acceptable confidence level from the launcher.

In order to provide adequate protection for the ISS and based on current operational threshold criteria, NASA has proposed using a 1×10^{-8} probability of actually hitting the ISS to warrant closing out a launch opportunity during a window.

In order to meet the proposed probability of collision, launchers would have to ensure their spacecraft and/or second stage will remain outside a 20 km x 100 km "COLA Box" centered about the ISS. Launchers would have to verify that the probability of either object entering this volume is 1 in 1000 or less. Then, the probability of entering the current ISS Notification Box (4 km x 50 km) will be 1 in 10,000. Ideally, up to 100,000 Monte Carlo cases would be necessary to verify no penetration of the smaller ISS Notification Box. The larger COLA Box requires less computational resources, yet still maintains the desired level of protection. Given a 1 in 1000 chance of

entering the COLA Box and the ratio between COLA Box area and ISS area, this further reduces to a 1×10^{-8} chance of hitting the station. The complete reduction is shown in Fig. 4.

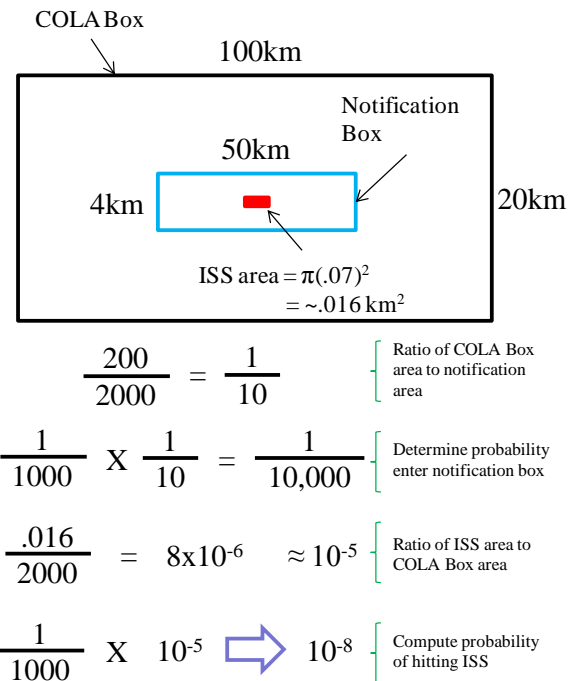


Figure 4: Reduction of proposed COLA Box to the probability of hitting the ISS

A recent study was conducted to determine if there would be an appreciable impact to launch windows by using the NASA proposed probability threshold for ISS protection. Two previous missions that had the potential to be affected by the COLA Gap were chosen for the study. The results generally indicated that there was no significant impact to the launch window by using a probabilistic method.

The methods described earlier are aimed at protecting the ISS from U.S. launched objects. However, this problem is not constrained to just the U.S. nor only to the ISS. Launched objects around the world could impact any other global space assets including existing international Low Earth Orbit (LEO) satellites. It is imperative that launch safety organizations around the world collectively use resources to understand and develop the best method to mitigate the risk of on-orbit collisions because such collisions can dramatically increase the threat from orbital debris impacts on all other on-orbit assets.

U.S. launchers do not have a formal documented requirement to conduct COLA Gap analysis for protecting ISS operations. Currently, the U.S. is using a letter from the NASA Associate Administrator of Human Exploration and Operations as the justification

for funding the routine analyses in Aerospace Corp and the LSP.

5. U.S. REQUIREMENTS AND PROCESS DEVELOPMENT

Major new formal requirements to govern the safety of space operations in the U.S. are often built on a foundation of common standards and guidelines developed in the Range Commanders Council (RCC). For example, the recent evolution of the launch and reentry risk criteria began with the development of consensus based voluntary standards and implementation guidelines adopted in RCC 321-07 [1]. These standards were later adopted as formal requirements by the organizations that govern U.S. space operations: by NASA in NPR 8715.5 [2] and by the USAF in AFI 91-217 [3]. The same update to the formal public risk criteria is under deliberation by the FAA [4]. Similarly, the RCC Risk Committee is now working to develop improved consensus-based standards and implementation guidelines that will protect the ISS against launches from the time of lift-off through the point when the ISS can react.

As explained more thoroughly in the RCC policy and organization document, [5] the mission of the RCC is to serve the technical and operational needs of U.S. test, training, and operational ranges. The RCC membership includes all Department of Defense (DoD) ranges, as well the NASA and the FAA. The RCC provides a framework wherein:

- a. Common needs are identified, and common solutions are sought,
- b. Technical standards are established and disseminated,
- c. Joint procurement opportunities are explored,
- d. Technical and equipment exchanges are facilitated,
- e. Advanced concepts and technical innovations are assessed, and potential applications are identified.

The RCC shares its insights and products with the armed services, DoD, and other U.S. government oversight boards and committees and stands as an expert consultant to those organizations. From its inception to the present, the RCC has remained outside formally established DoD structures and independent of all other formal authorities. This has been one of the organization's strengths as it has allowed frank and open dialogue among the RCC members and the freedom to address a broad range of issues. The independence of the RCC and its positive impact on range operations is well recognized throughout DoD, other U.S. government agencies, industry, and institutions of higher learning. The advantages of informal assistance and guidance on common problems have been salient factors in the RCC's development of

widely-accepted technical standards for the ranges. The RCC remains an effective consulting body to more formally-established military and civilian organizations.

The RCC has numerous groups that focus on different technical areas of concern to the ranges. The Risk Committee is a relatively small but influential group that reports to the Range Safety Group (RSG) within the RCC. The RSG charter is quite broad and includes support, standardization, development, and continuous improvement of the safe conduct of hazardous operations on the test, training, and operational ranges and related facilities. Hazardous operations include, but are not limited to, ordnance and expendable releases, directed energy and laser operations, missile flight, space launch and reentry, unmanned vehicle operation, gunfire, explosive use, and hazardous emissions.

The Risk Committee reports to the RSG, and is primarily focused on the continuous improvement of the RCC 321 Standard and Supplement documents that provide guidance on risk acceptability and flight safety analyses. The latest published version of RCC 321-07 describes the scope as follows: "The policies and criteria in this document are intended for use by DOD national ranges and Major Range and Test Facility Bases (MRTFB). These policies and criteria apply to launch and reentry hazards generated by endo-atmospheric and exo-atmospheric range activities including both guided and unguided missiles and missile intercepts, space launches and reentry vehicles. This does not include aviation operations or UAV operations. RCC 323-99 provides criteria for unmanned air vehicles." The primary focus of RCC 321 is on risk acceptability policy and guidelines for evaluation of debris risks, although some information is provided about evaluation of "other hazards" such as toxic releases, distant focusing overpressure, and radiation.

6. IMPACT ON LAUNCH WINDOWS

An assessment of the foreseeable operational impacts is often performed during the development of consensus-based standards and guidelines for the safety of U.S. space operations. In the case of the proposed standards to close the COLA gap, an assessment of the potential impact on launch windows was recently performed by the Aerospace Corporation and reported to the RCC Risk Committee.

The Aerospace Corporation study assessed the potential impact on launch windows for typical GEO and direct injection missions from the proposed requirement for a maximum 1 in 10,000 chance of violating the current ISS notification box (4x50 km) which, when reduced to the size of the ISS, results in a

probability of hitting the ISS of $1E-8$ (one in a hundred million). Specifically, this study examined the predicted trajectories of the upper stages used for two recent Atlas V missions: AEHF-2 (representative of a typical mission to GEO), and L-38 (representative of a direct re-entry). In order to have a good statistical representation, the study considered seven 1-day launch windows with hypothetical opportunities at each minute (1440 total opportunities per day).

The method used to compute the potential launch window closures consisted of several steps:

- 1) Generate of 10,000 Monte Carlo trajectories based on launch vehicle component uncertainties (performed by Guidance Analysis Department at Aerospace with uncertainty data provided by the launch vehicle operator: the United Launch Alliance or ULA),
- 2) Convert the trajectories into EFG coordinates,
- 3) Compare of each of the 10,000 feasible trajectories at each launch opportunity to the ISS position (as represented by a two-line element set),
- 4) Compute the closest approach and nodal separation distance as the upper stage passes through perigee or directly re-enters,
- 5) Determine if the closest approach vector violates any of the following criteria:
 - a) Identify closeouts due to nodal separation violation only (highly conservative). This is a good approximation to the lower bound on conjunction miss distances for non-coplanar orbits but is conservative as it does not account for in-track position of the objects. For this study, a launch opportunity is closed when any one of the 10,000 trajectories have a nodal separation distance < 1 km. When the actual launch operations were performed for the L-38 and AEHF-2 COLA gap assessments, the nodal separation analysis was augmented by in-track analysis, but that additional in-track analysis was not considered for this study.
 - b) Identify closeouts due to 200 km sphere about ISS being violated (conservative). This is the criteria that is often used to protect the ISS by launch COLA.
 - c) Identify closeouts due to 4x50 km box about ISS being violated (least conservative): if any of the 10,000 trajectories violated the 4x50 km box about ISS, and then that launch opportunity was considered closed. Note that the number of trajectories that violate the criterion can be roughly considered as a measure of the risk relative to other launch opportunities in that window. However, asymmetry in the large uncertainties does not allow for a one-to-one correlation between the number of violations and probability of collision. A method to more accurately compute impact probability values is in development.

The results indicate that:

1. About 7-10% of the window gets closed when nodal separation only is applied,

2. About 1-9% of the window gets closed when the 200 km sphere is applied, and
3. Less than ~1% of the window gets closed when the 4x50 km box is applied.
4. Adding a second manned object in space to protect, Tiangong-1 (TG-1), roughly doubled the launch window closures.

The specific results for the AEHF-2 mission are shown in Table 1, which lists the number of one-minute launch opportunities closed due to the various criteria over a seven day period (10,080 one minute launch opportunities total).

May Day	3	4	5	6	7	8	9
Nodal Sep	103	98	103	109	100	105	103
200km Sphere	122	117	133	128	109	133	139
4x50km Box	0	15	12	2	15	8	4

Table 1: Results of AEHF-2 Mission

The specific results for the L-38 mission are shown in Table 2, which also lists the number of one-minute launch opportunities closed due to the various criteria over a seven day period. However, for the L-38 mission, protection was provided for both the ISS and the TG-1, since the TG-1 was a possible issue for the actual L-38 launch.

June/July Day	27	28	29	30	1	2	3
Nodal Sep	279	277	303	299	285	258	248
200km Sphere	27	29	20	27	29	15	31
4x50km Box	8	10	3	15	2	4	9

Table 2: Results of the L-38 Mission

These results demonstrate that the 4x50km box provides the fewest launch window cutouts of the three protection criteria considered. These results indicate that the COLA gap can be closed with a minimal impact on the launch window for at least some GTO and direct injection missions.

7. CONCLUSION

Launching any object into space can create a potential catastrophic hazard for the ISS. Although actual collision is highly unlikely, orbital geometry and launcher trajectory uncertainties induce potential instances where ground resources would be activated and/or ISS Crew on-orbit operations interrupted. Analytical processes, based on orbital geometry, have been developed to identify times where there could be

a collision between a second stage of a launched satellite or the payload itself with the ISS. However, these techniques do not provide complete insight into the level of risk or impacts to ground control and on-orbit operations. Discussions with the U.S. Air Force and NASA are underway to determine if the current geometric methods can be applied with a NASA-proposed probabilistic technique to ensure sufficient ISS risk protection while allowing some launcher flexibility.

In order to institute a standard method for protecting the ISS during the COLA Gap, requirements need to be established to which launchers throughout the U.S. and the world can adhere. Two options initiated from the Johnson Space Center are: Option 1 – With 95% confidence, there shall be a no greater than 1 in 1000 chance that a launcher's spacecraft, upper stage, or payload violates a 20x100 km COLA Box. Launcher can perform lower resource, lower fidelity analysis against a larger box that will confirm there is an acceptable chance for disruptions to ISS operations. Option 2 – With 95% confidence, there shall be a no greater than 1 in 10,000 chance that a launcher's spacecraft, upper stage, or payload violates the 4x50 km ISS Notification Box. Launcher would have to increase the analysis resources and run higher fidelity models against a smaller box to confirm the same acceptable ISS conditions.

In parallel to establishing a technique for mitigating the COLA Gap threat, formal requirements are needed for U.S. and world-wide launch ventures to adequately protect the ISS and any other human habitable assets against launches from the time of lift-off through the point when these orbiting assets can react.

Efforts are currently underway in the U.S. to update the high level Memorandum of Agreement (MOA) and USAF Instructions. Concurrently, the process has started to revise Range Commanders Council (RCC) Standards documentation, as well as all applicable supplemental documentation.

REFERENCES

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3. Air Force Instruction 91-217, *Space Safety and Mishap Prevention Program*, 18 February, 2010
4. Wilde P., *Public Risk Criteria and Rationale for Commercial Launch and Reentry*, 5th IAASS Safety Conference, Versailles, FR, 17-19 October 2011
5. Range Commanders Council, *Organization and Policy Document*, RCC 321-07, White Sands Missile Range, New Mexico, 2003 (email rcc@wsmr.army.mil to request a copy)