

A GEOMETRIC ANALYSIS TO PROTECT MANNED ASSETS FROM NEWLY LAUNCHED OBJECTS – COLA GAP ANALYSIS

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A safety risk was identified for the International Space Station (ISS) by The Aerospace Corporation, where the ISS would be unable to react to a conjunction with a newly launched object following the end of the launch Collision Avoidance (COLA) process. Once an object is launched, there is a finite period of time required to track, catalog, and evaluate that new object as part of standard on-orbit COLA screening processes. Additionally, should a conjunction be identified, there is an additional period of time required to plan and execute a collision avoidance maneuver. While the computed prelaunch probability of collision with any object is extremely low, NASA/JSC has requested that all US launches take additional steps to protect the ISS during this “COLA gap” period. This paper details a geometric-based COLA gap analysis method developed by the NASA Launch Services Program to determine if launch window cutouts are required to mitigate this risk. Additionally, this paper presents the results of several missions where this process has been used operationally.

INTRODUCTION

A safety risk for the International Space Station (ISS) was identified by The Aerospace Corporation as early as 2006, but awareness heightened following the launch of GPS IIR-20 (March 24, 2009), when the spent upper stage of the launch vehicle unexpectedly crossed inside the ISS notification box shortly after launch (Reference 1). This event highlighted a 56-hour vulnerability period following the end of the launch Collision Avoidance (COLA) process where the ISS would be unable to react to a conjunction with a newly launched object (typically the spent upper stage). Current launch COLA processes screen each launched object across the launch window to determine if an object’s nominal trajectory is predicted to pass within 200 km of the ISS (or any other manned/mannable object), resulting in a launch window closure. These launch COLA screens are performed from launch through separation plus 100 minutes. Once the objects are in orbit, they are cataloged and evaluated as part of routine on-orbit conjunction assessment processes. However, as the GPS IIR-20 scenario illustrated, a vulnerability period exists between the end of launch COLA coverage and the beginning of standard on-orbit COLA assessment activities. The gap between existing launch and on-orbit COLA processes is driven by the time required to track and catalog a launched object, identify a conjunction, and plan and execute a collision avoidance maneuver. For the ISS, the total time needed to accomplish all of these steps is 56

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hours. To protect human lives, NASA/JSC has requested that all US launches take additional steps to protect the ISS during this “COLA gap” period.

DERIVATION OF THE WORST-CASE COLLISION PROBABILITY

The uncertainty in the state of a spent upper stage can be quite large after all burns are complete and all remaining propellants are expelled to safe the stage. Simply extending the launch COLA process an additional 56 hours is not a viable option as the 3-sigma position uncertainty would far exceed the 200 km miss-distance criterion. Additionally, performing a probability of collision (P_c) analysis over this period is also impractical due to the limiting effects of these large orbit state uncertainties. The remainder of this section details the results of a worst-case P_c estimation for a typical spent upper stage nominally aligned for a direct broadside collision with the ISS.

From Reference 2, the probability of collision, assuming a nominal predicted miss distance of zero, can be estimated using the following relationship:

$$P_c = \left(\frac{A^*}{2\pi} \right) \left(\frac{1}{\sigma_T v_{eqv}} \right) \quad (1)$$

where:

- A^* = effective collision area
- σ_T = combined 1 sigma position error in x
- v_{eqv} = combined 1 sigma position error in y
- P_c = probability of collision

A complete definition of the variables and Relative Motion Coordinate System (RMCS) used in this equation, as well as its derivation, can be found in Reference 2.

The effective collision area, A^* , is calculated from the following formula (Reference 2):

$$A^* = A_1 + A_2 + \left(\frac{k_1 + k_2}{\sqrt{k_1 k_2}} \right) \sqrt{A_1 A_2} \quad (2)$$

where:

- A^* = effective collision area
- A_1 = area of body 1
- A_2 = area of body 2
- k_1 = ratio of length/width for body 1
- k_2 = ratio of length/width for body 2

Using dimensions of the ISS and launch vehicle upper stages, the estimated upper bound on A^* is 9301 m² for a conjunction between the Atlas V/Centaur upper stage and ISS, and 8672 m² for the Delta II second stage. These values assume that both the upper stage and ISS are projected into the collision plane as the largest possible rectangles (i.e., composed of each object’s two largest dimensions). This is the most conservative size characterization. The lower bound on A^* ,

which assumes an edge-on approach to ISS and a frontal cross section for the upper stage, is 1773 m² for Delta II and 1798 m² for Centaur.

The other information necessary for calculating Pc is the uncertainty in the launch vehicle position. For conservatism, this bounding assessment assumes zero uncertainty in ISS state knowledge. The size and shape of the launch vehicle position dispersion distribution is vehicle and mission-dependent, and will also vary as a function of time and location in the orbit. Analytically determined launch vehicle position uncertainties at the end of launch COLA screens generally range from tens of kilometers to 100 kilometers or more, and will only grow with time over the COLA gap period. These analytical results have been shown to correlate well with flight data (Reference 3).

Figure 1 illustrates the probability of collision, assuming the upper bound A* value of 9301 m² and a nominal predicted direct hit (zero miss distance) between the ISS and the upper stage, as a function of 1-sigma position uncertainties (in meters) in the conjunction plane as defined in Reference 2. Comparison of analytical results for flight missions to the trends observed in this plot indicates that upper stage dispersions during the COLA gap period generally exceed the values necessary to result in probabilities of collision greater than the 10⁻⁶ order of magnitude.

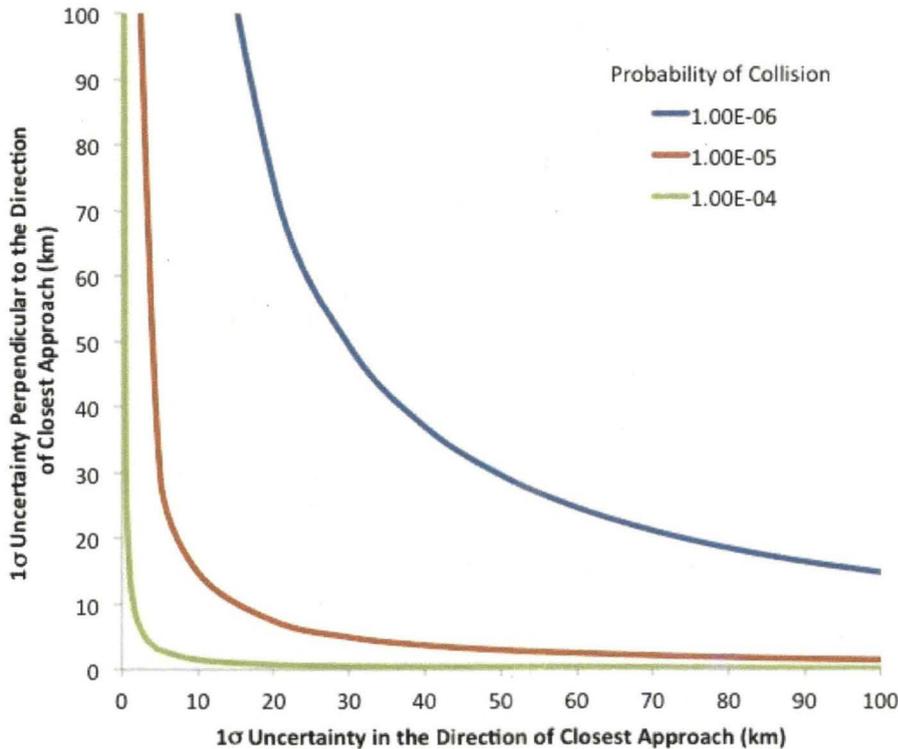


Figure 1. Probability of Collision as a Function of Launch Vehicle Position Uncertainties for Zero Miss Distance

Based on these bounding results, it is seen that even under very conservative assumptions (a pre-flight predicted zero miss distance between the ISS and a Centaur upper stage and worst case broadside approach for both objects), uncertainties associated with the upper stage state alone result in an estimated probability of collision on the order of 10⁻⁶ or less for all but the tightest possible uncertainties, which are themselves very unlikely to occur. When one factors in the like-

likelihood of the two conservative assumptions outlined above actually coming to pass, it is apparent that attempts to screen for conjunctions during the COLA gap period using standard techniques will yield probabilities that essentially never exceed the existing screening threshold for manned objects (10^{-6}). This issue, along with the desire to perform this analysis in-house at NASA KSC, led to the development of the geometric-based approach outlined in this paper.

GEOMETRIC-BASED ANALYSIS APPROACH

Given the limitations of the launch COLA evaluation techniques for the COLA gap problem, a geometry-based methodology may be used to determine if launch opportunities pose a threat to the ISS during the COLA gap period. The NASA Launch Services Program (LSP) at Kennedy Space Center has developed this COLA gap analysis method and has employed it for four NASA missions to identify potential ISS conjunctions and corresponding launch window closures during the 56-hour at-risk period. In each of these cases, the potential conjuncting object has been the spent upper stage of the launch vehicle.

In the analysis, for each launch opportunity, the nominal trajectory of the spent upper stage and the orbit state of the ISS are propagated simultaneously over the 56 hour period. Each time the upper stage crosses the ISS orbital plane, the only location where a collision could occur (cross-track = 0), the relative radial and argument of latitude separations are calculated (Figure 1). The argument of latitude is the sum of the argument of perigee and true anomaly and represents the angle in the plane of the orbit from the ascending node, measured in the direction of the object's motion.

In Figure 2, the green disk is the orbital plane of the ISS and the actual propagated location is shown with the ISS graphic in the foreground. The red trajectory is the path of the upper stage and at this time, the simulation has been paused at an instance where the upper stage intersected the ISS orbital plane.

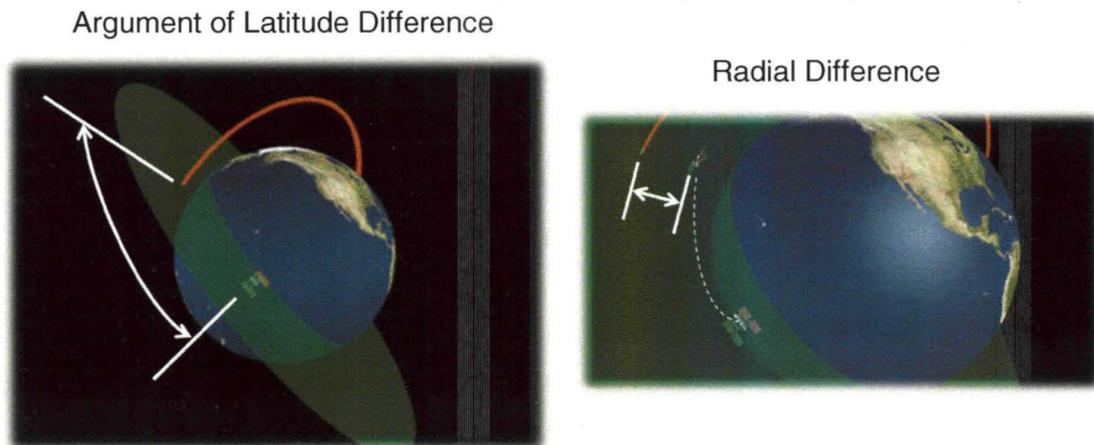


Figure 2. Argument of Latitude and Radial Difference Definitions.

The argument of latitude difference is computed by first calculating the argument of latitude of the upper stage in the ISS orbital plane. Then, the angular difference can be computed as a simple subtraction of the two argument of latitudes with a positive value indicating the ISS is ahead of the intersection location and a negative value indicating the ISS trails.

The radial difference could be calculated as a straightforward subtraction. However, the location of the ISS at the planar intersection time could be anywhere in the orbit. Consequently, its radial distance will vary due to both the osculating nature of the orbit coupled with an eccentricity slightly greater than zero. Since the goal of this analysis is to determine a radial difference in the instance of a potential conjunction, a simple subtraction based on the ISS location is not sufficient. A more relevant value would be based on the ISS radius measured at the location of the orbital intersection. Therefore in the simulation, at each orbital intersection location, the ISS is temporarily propagated to the argument of latitude of the intersection (either forward or backward, whichever is shorter) where the radial difference is then computed.

With the nominal differences computed at the orbital intersection locations, a potential collision could only occur if the upper stage variations in argument of latitude and radius were both greater than the nominal cases. Therefore, an evaluation of the variation in the upper stage trajectory must be performed to compute a mission-specific 'screening box'.

Based on Monte Carlo analyses performed by the launch service contractor, a set of dispersed final orbit states for the upper stage are produced. Each of these dispersed states is run through the simulation to compute the variation in argument of latitude difference at the final ascending and descending orbital intersections over the 56-hour period. While the radial variation remains essentially constant, the argument of latitude (along-track) errors grow with time. Therefore, capturing the final intersections bound the variations that will be seen. From this evaluation, a screening box for the nominal argument of latitude and radial difference can be constructed. This screening box consists of the maximum variations from the Monte Carlo evaluations plus an additional small contribution representing the ISS position error.

Utilizing a worst-case screening box is useful when evaluating the impacts to a mission a month or two before launch. Nominal test runs can be made for a range of launch dates to quickly quantify the frequency the COLA gap could impact any given launch date as well as an estimate of the portion of the launch window that could be impacted, as a violation would result in the closures of that time in the launch window. As the actual launch date draws nearer, a more detailed screening is performed to determine any window closures and if there is a significant impact, the screening box could be refined. For example, if the violation occurs early in the 56-hour COLA gap period, the argument of latitude error will not be as large and therefore could be reduced if needed.

All COLA gap analysis simulations are performed using the *FreeFlyer*® mission analysis software. Propagations are run using a Runge-Kutta 8(9) numerical integrator with full force modeling including: EGM96 Earth model, 21 x 21 geopotential; Jacchia-Roberts drag model using NOAA daily solar flux forecasts; Sun, Moon gravitational effects; and solar radiation pressure.

As is typical with any analysis, a key component of the quality of the output is the quality of the data input into the analysis. For the launch vehicle state vector information, the best predictions of the upper stage location following all propulsive events is provided by the launch vehicle contractor. For the ISS state vector to use in the propagations, LSP obtains the most recent orbit determination solutions from the JSC/ISS Mission Control Center (MCC). Additionally, the final

ISS COLA gap assessments are performed the day before launch so the final best predictions of the ISS state vectors are used to determine if window cutouts are required.

OPERATIONAL IMPLEMENTATION

The remainder of this paper discusses the key results of multiple missions LSP has performed the ISS COLA gap analysis for in support of launch operations. These missions span a variety of orbit cases including two low-Earth orbit (LEO) missions launched on a Delta II, the reentry of an Atlas V upper stage from a highly elliptical orbit, and the injection orbit for a secondary payload following an ISS rendezvous from a Falcon 9.

LEO Orbit Cases – Aquarius and NPP

Both the Aquarius and the Suomi National Polar-orbiting Partnership (NPP) missions were launched on a Delta II launch vehicle from Vandenberg Air Force Base, injecting the spacecraft into circular, Sun-synchronous orbits. Aquarius launched on June 10, 2011 and was inserted into a 660 km circular orbit. Following separation, the Delta II upper stage performed a depletion burn to lower perigee to 194 km. This low perigee resulted in a passive reentry of the upper stage within 2 months, thus complying with NASA's Orbital Debris policy (Reference 4). However as a result of this end-of-mission elliptical orbit (194 x 650 km), the upper stage intersected the ISS orbit twice per revolution thus prompting the COLA gap analysis.

The NPP mission (October 28, 2011) followed a similar mission profile to dispose of the upper stage. However, following separation of the primary spacecraft (825 km circular), perigee was initially lowered to 450 km so that six CubeSats (secondary payloads) could be jettisoned into their mission orbit. Then, another upper stage burn was performed to lower perigee to 185 km, its final end-of-mission orbit.

The selection of the CubeSats mission orbit demonstrates the most effective means to mitigate the ISS COLA gap issue - avoidance. Initially the CubeSats were to be inserted into an orbit with a perigee of 350 km. However, this orbit would have crossed the ISS orbit and significantly complicated the COLA gap problem. The six CubeSats were deployed in a staggered sequence and thus could not be treated as a single item. Additionally, the ISS orbital intersections with the upper stage would take place at different locations following the final perigee-lowering maneuver. Collectively, all seven objects could have created significant window closures. Consequently, the mission design was modified to raise the perigee of the CubeSats above the ISS altitude, thus limiting the COLA gap analysis to just the upper stage.

For both the Aquarius and NPP LEO missions, the upper stages crossed the ISS orbit 72 times (36 orbits, twice per orbit). For the actual launch date of October 28, 2011, the time-history of the radial and argument of latitude differences at the orbital intersections is shown in Figure 3. In this plot, the data shows the radial and argument of latitude difference between the ISS and the second stage at three possible launch times – the launch window open, middle, and close. For this launch date, the argument of latitude, or angular separation, crossed zero during the 56-hour period. However, at these intersections, the ISS was either at least 80 km above the second stage or 170 km below.

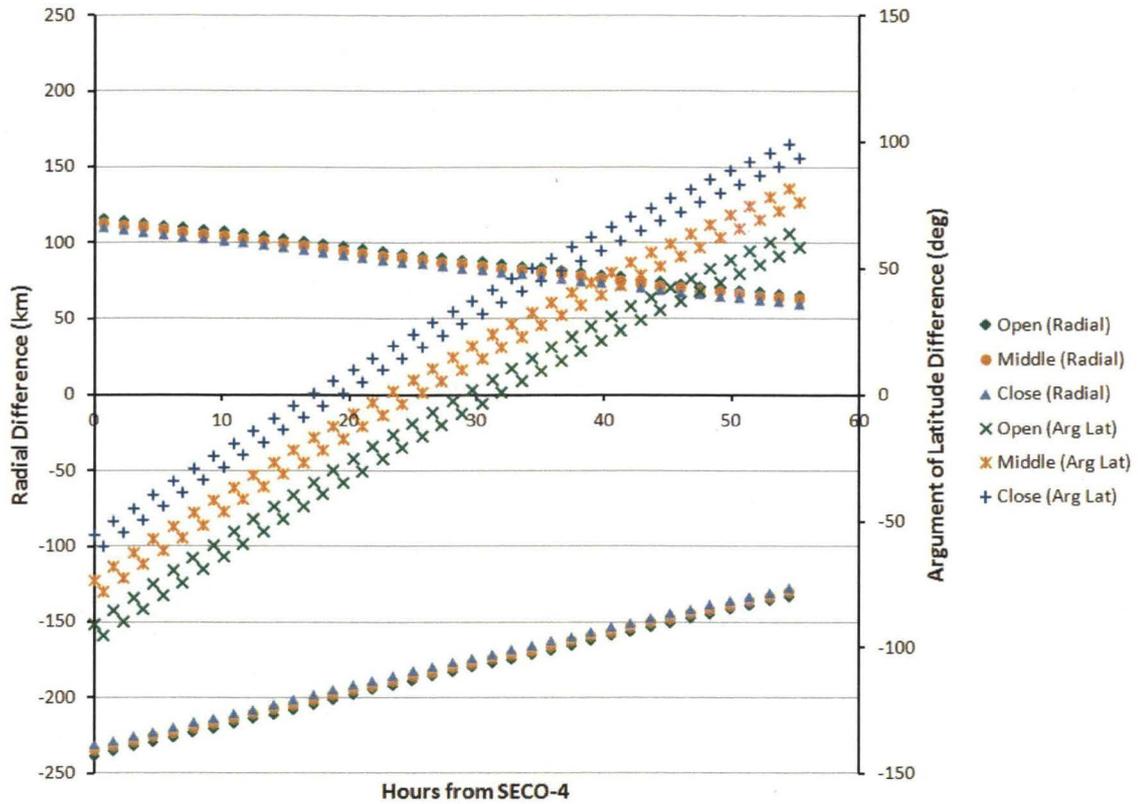


Figure 3. NPP Argument of Latitude and Radial Differences versus Time.

A different way to visualize this same data in a more physically representative manner is to plot argument of latitude versus radial differences. In this way, the origin is located at the second stage when an orbital intersection occurs. Then each data point plots the location of the ISS relative to the second stage at that time (above, below, in front, behind). Figure 4 shows the NPP October 28 data in this manner.

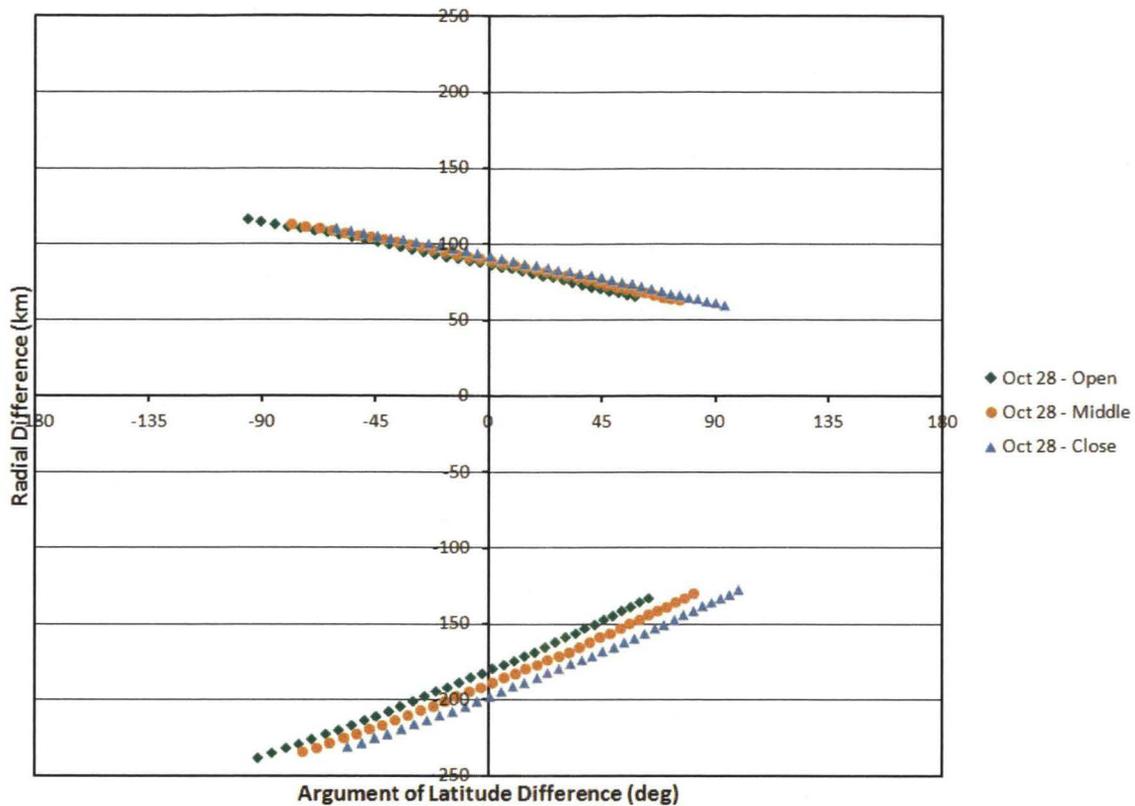


Figure 4. NPP Argument of Latitude and Radial Differences.

The relative distances at the orbital intersection points seen in Figure 4 are nominal predictions. To determine if the distances at the intersection points could theoretically result in a collision, a screening box must be developed to capture the maximum variations in radial and argument of latitude differences that could occur during the mission, as described earlier. For NPP, a set of 1000 dispersed final orbit states were propagated to determine the variations at the final two intersections as shown in Figures 5 and 6 (Reference 5). As seen, the variations are non-symmetrical, with a bias towards the lower right quadrant.

A screening box was then constructed based on the maximum variations from the final two intersections plus added uncertainty for the ISS (± 0.5 km radial, ± 1 degree argument of latitude). Based on these results, the screening box dimensions were -19 to $+4$ km in radial uncertainty, -6 to $+28$ degrees in argument of latitude uncertainty. When overlaying the screening box on the argument of latitude versus radial plot, the location is inverted from the lower right bias to the upper left quadrant. Therefore, if any of the nominal intersections occurred inside this box, then it is theoretically possible to have a collision with the ISS. Conversely, any nominal intersections outside this box has a P_c of zero.

Figure 7 repeats the data in Figure 3, but with the addition of the screening box. This clearly illustrates that there was no ISS COLA gap concern for the actual launch day of October 28. Additionally, Figure 8 shows the results for the backup launch date of October 29, which again showed no COLA gap concerns. While the majority of the launch dates analyzed did not impact the launch window, a long-range estimate of the impact frequency was performed for NPP in the event of a launch delay. These results are shown in Figure 9.

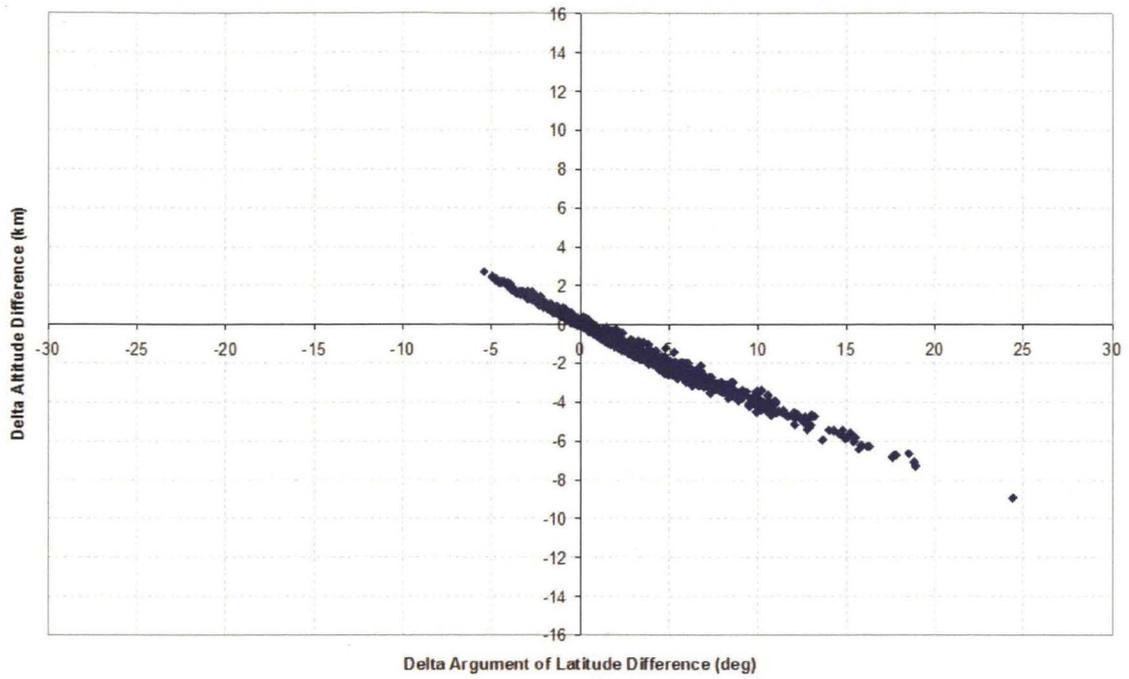


Figure 5. NPP Argument of Latitude and Radial Variation (Intersection 71).

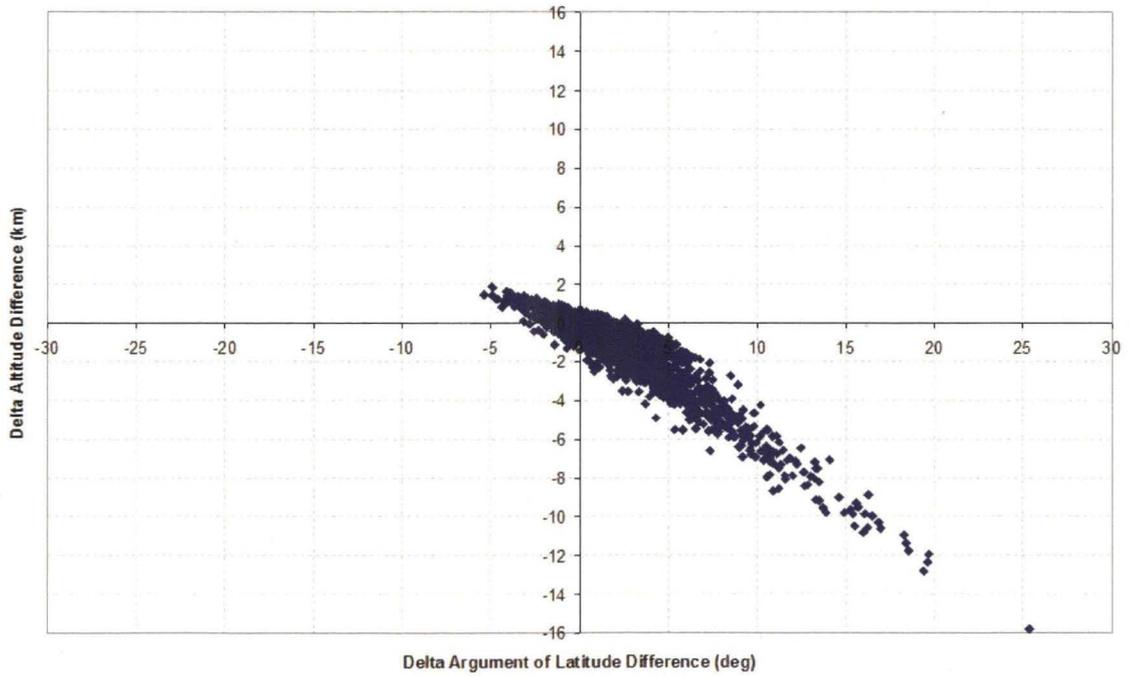


Figure 6. NPP Argument of Latitude and Radial Variation (Intersection 72).

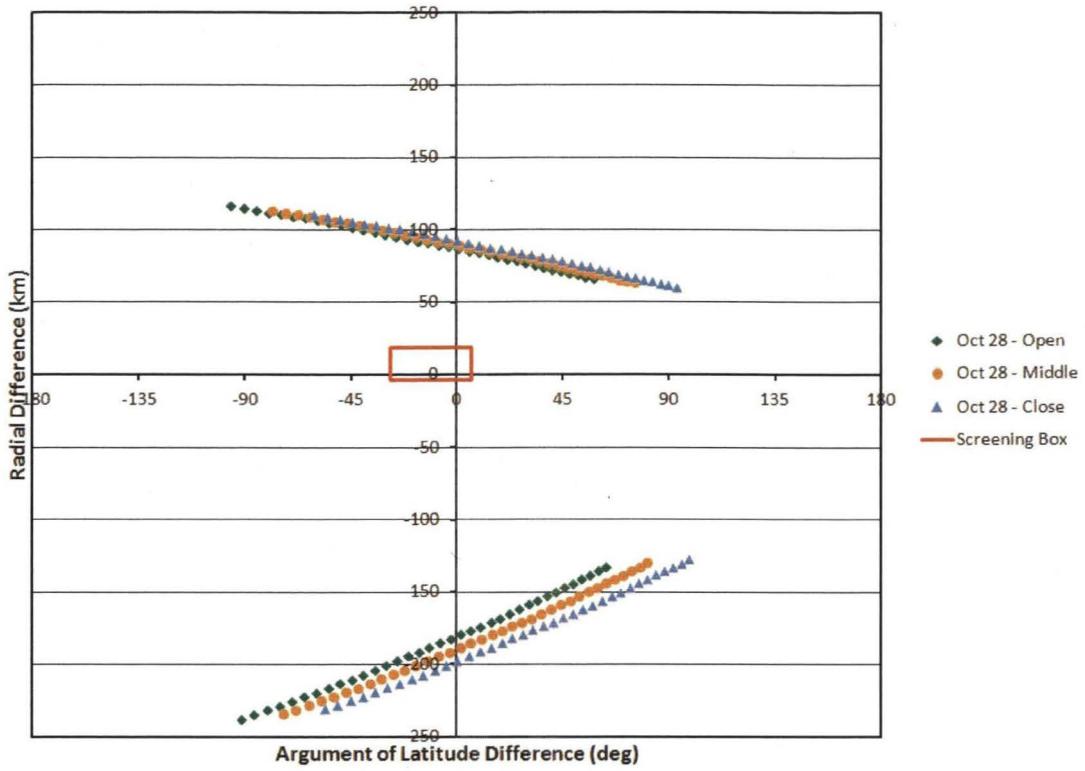


Figure 7. NPP Argument of Latitude and Radial Differences (October 28 launch date).

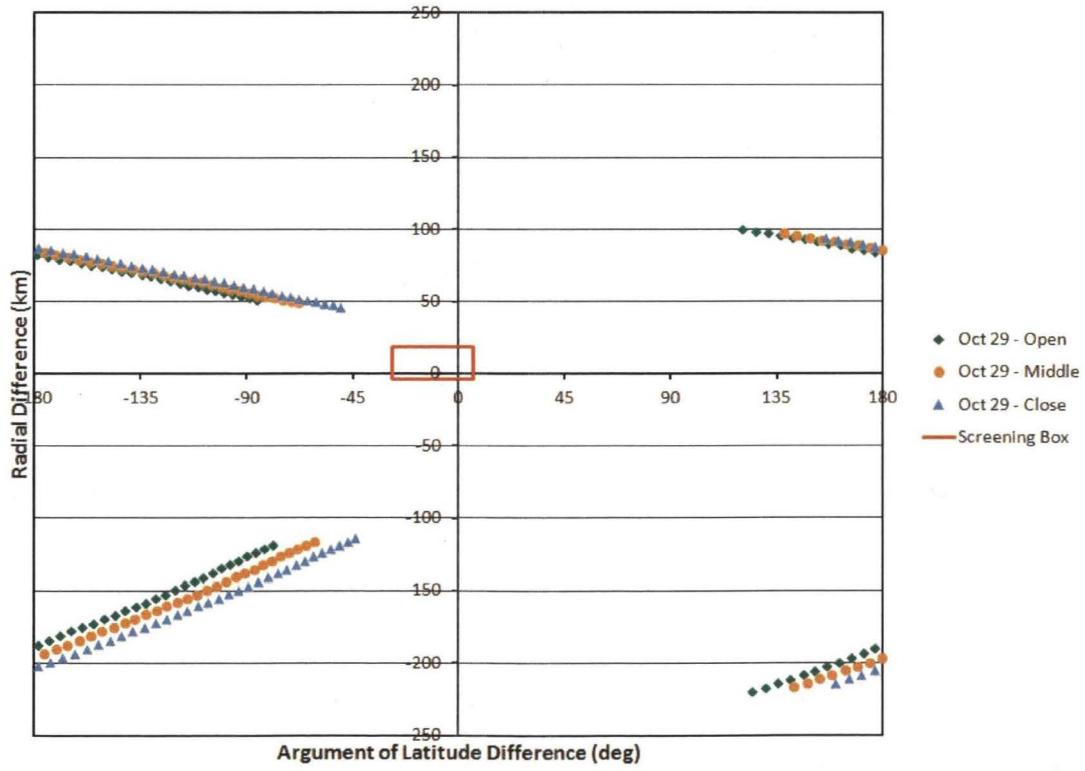


Figure 8. NPP Argument of Latitude and Radial Differences (October 29 launch date).

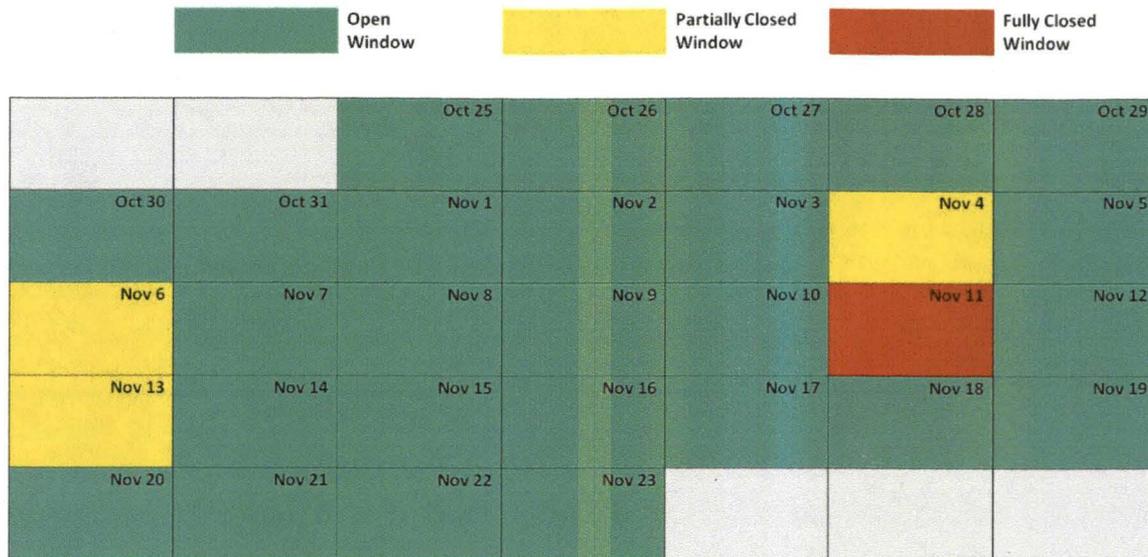


Figure 9. NPP 30-day Window Impact Estimate.

The NPP daily launch window was 9 minutes and 10 seconds in duration. For a 30-day period, the window open/middle/close cases were simulated and the argument of latitude and radial differences at the nominal intersections were compared to the screening box. The results indicated four dates were impacted due to the ISS COLA gap. Three dates would have partial window closures while one date would be completely closed.

As stated earlier, a key component in these analyses is the quality of the data inputs. During the NPP and Aquarius analyses, the most recent ISS orbit determination solutions were used as provided by the JSC MCC. Additionally, JSC provided other key information, including any Soyuz launch and on-orbit maneuver plans. For early Aquarius launch dates, the manned Soyuz capsule was evaluated as a separate orbital object in the same manner as the ISS, from orbit insertion through ISS docking. The same procedure was used, though the 56-hour period was subdivided into segments corresponding to the periods between on-orbit maneuvers. If any conjunctions had been identified with the manned Soyuz capsule, these window cutouts would have also been enforced.

In addition to any Soyuz launch plans, JSC provided ISS stationkeeping maneuver plans. This information was also included in the COLA gap evaluations, and as shown in Figure 10, is critical to include. For the Aquarius mission, the backup launch date was June 11. On this date, the 56-hour COLA gap period encompassed two ISS reboost maneuvers planned for June 12. As Figure 10 shows, the reboost maneuvers resulted in a step function that shifts the argument of latitude/radial difference trace after each maneuver. For this date, the screening box was clipped (solid markers) in the upper right hand corner if the ISS burns occurred nominally. Per the process, LSP performed a more detailed look at this nominal case and with a refined screening box, showed the full launch window would be valid. However, if the ISS maneuvers were off-nominal or one or both burns were aborted (dashed lines), launch on June 11 would violate even the refined box. Fortunately, Aquarius did successfully launch on June 10 and no COLA gap issue arose.

June 11 Launch - ISS Location Relative to Stage 2 at Plane Crossings

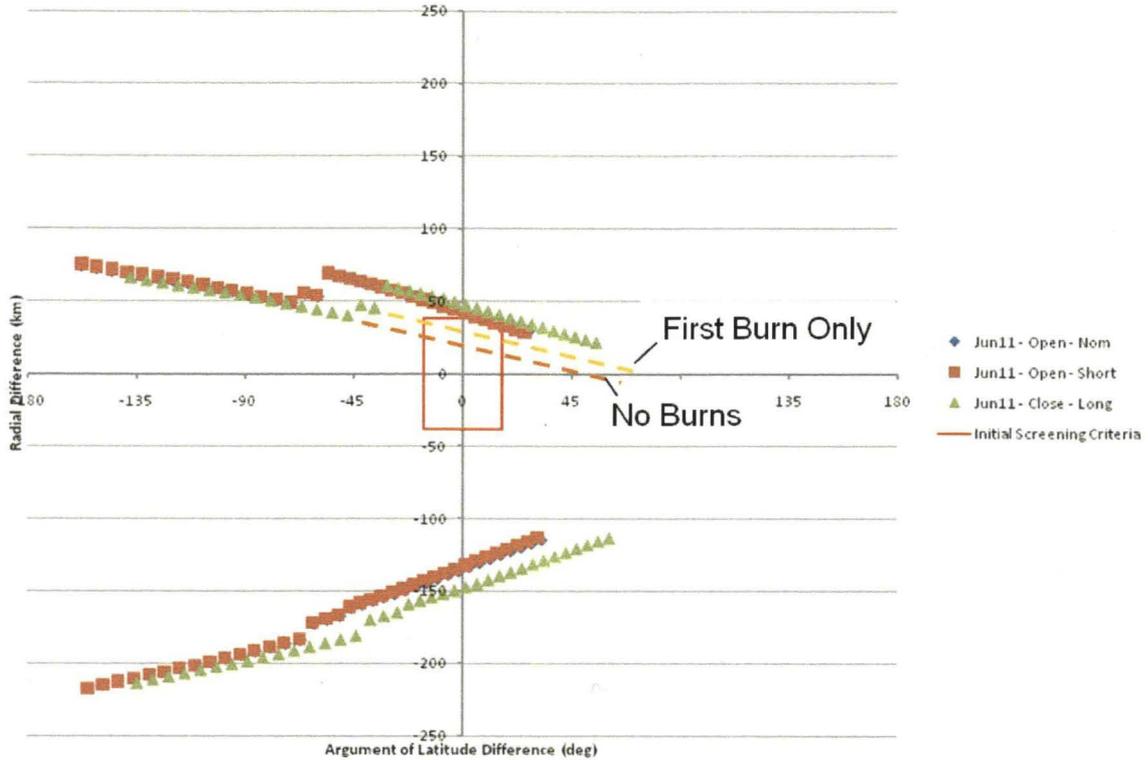


Figure 10. Impact of ISS Reboost Maneuvers.

Upper Stage Reentry Case Study – RBSP

The Radiation Belt Storm Probes (RBSP) mission was launched on an Atlas V launch vehicle from the Eastern Range on August 30, 2012. The RBSP mission consisted of a pair of probes inserted into a highly eccentric orbit (597 x 30,647 km) at a 10 degree inclination. Following the separation sequence of the dual payload and contamination and collision avoidance maneuvers (CCAM), the upper stage performed a propellant depletion burn to achieve perigee ≤ 50 km for a controlled reentry within 12 hours after launch. Preliminary LCOLA feasibility analyses confirmed that standard LCOLA processes could not be meaningfully extended to cover the reentry event. Therefore, NASA Range Safety, the Goddard RBSP Project Office, and 45th Space Wing Range Safety concurred that the LSP ISS COLA gap analysis would provide appropriate COLA protection for the Centaur reentry phase of the mission.

The primary difference in the RBSP assessment is that over the 56-hour period, RBSP had only a single potential orbital intersection while the LEO cases had continuing evolving orbital intersections. For the Centaur to have a conjunction with the ISS, the relative orbit geometry must align fairly precisely to intersect the ISS orbital plane as it passes near 400 km shortly before impact. This is demonstrated in Figures 11 through 13, which show three distinct relative geometry conditions that can be grouped into three launch blocks over the 30-day initial assessment.

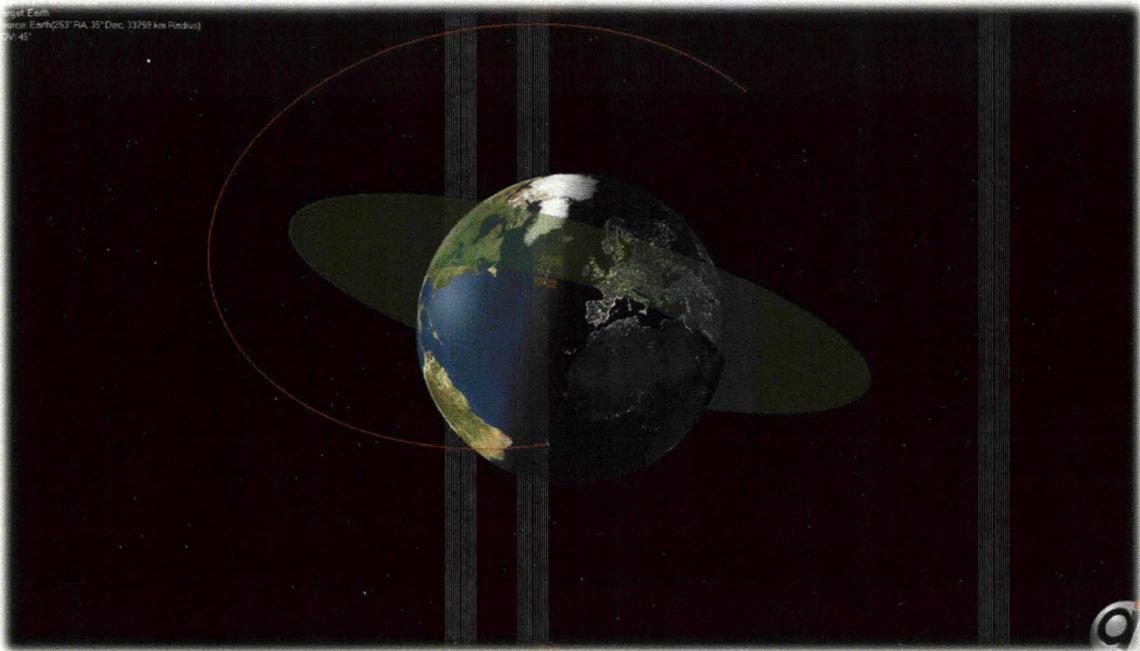


Figure 11. Centaur Reentry Path – Block 1 (August 23 – September 5) .

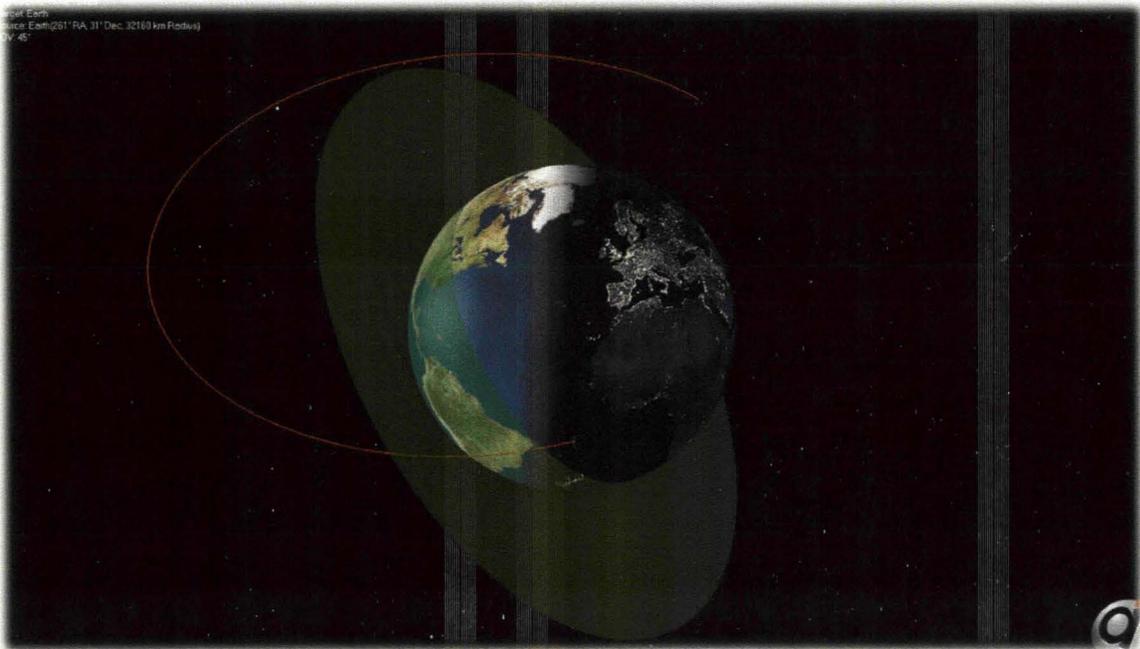


Figure 12. Centaur Reentry Path – Block 2 (September 6 – 10).

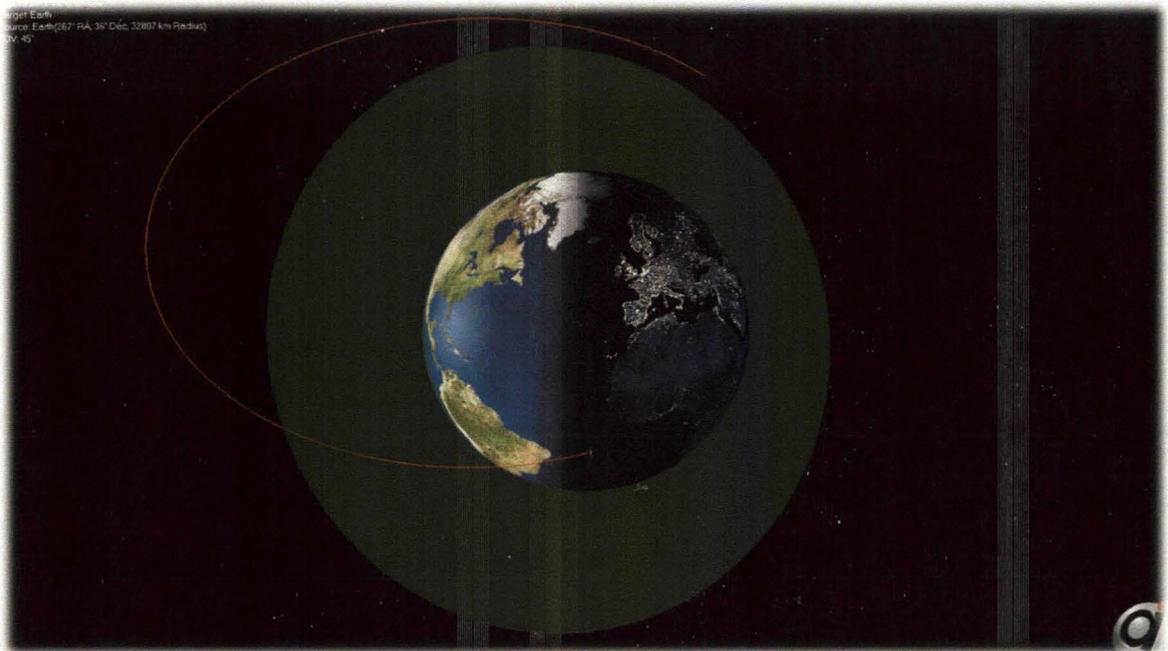


Figure 13. Centaur Reentry Path – Block 3 (September 11 – 24).

The orbit trajectory shown in each figure is the Centaur path from the end of the depletion burn through impact in the Atlantic Ocean. In Block 1 (Aug 23 – Sept 5), the Centaur crossed the ISS orbit near apogee but did not intersect the ISS orbit on the final reentry approach, but rather passed well underneath the ISS orbital plane. In Block 2 (Sept 6 – Sept 10), the ISS orbital plane rotated such that the Centaur reentry path crosses the ISS orbital plane in low-Earth orbit (LEO). This is the only phase where a conjunction cutout could occur. Then in Block 3 (Sept 11 – Sept 24), the ISS plane has continued to rotate so that the intersection of the Centaur reentry path with the ISS orbital plane again occurs outside of LEO, and the reentry path is well above the ISS orbital plane.

Even in Block 2, when the planar intersections are in LEO, the continually changing Right Ascension of the Ascending Node (RAAN) of the ISS coupled with the Centaur's steep reentry path resulted in a rapidly changing radial difference at the intersections (Figure 14). This plot shows the radial difference for the Block 2 launch dates at the open/middle/close of the 20-minute launch window.

After a more detailed review of the Monte Carlo states to size the screening box, it was determined that only September 8 would be impacted with a partial window closure confirming the expectation that a reentry scenario would be less impacted than the LEO cases previously examined.

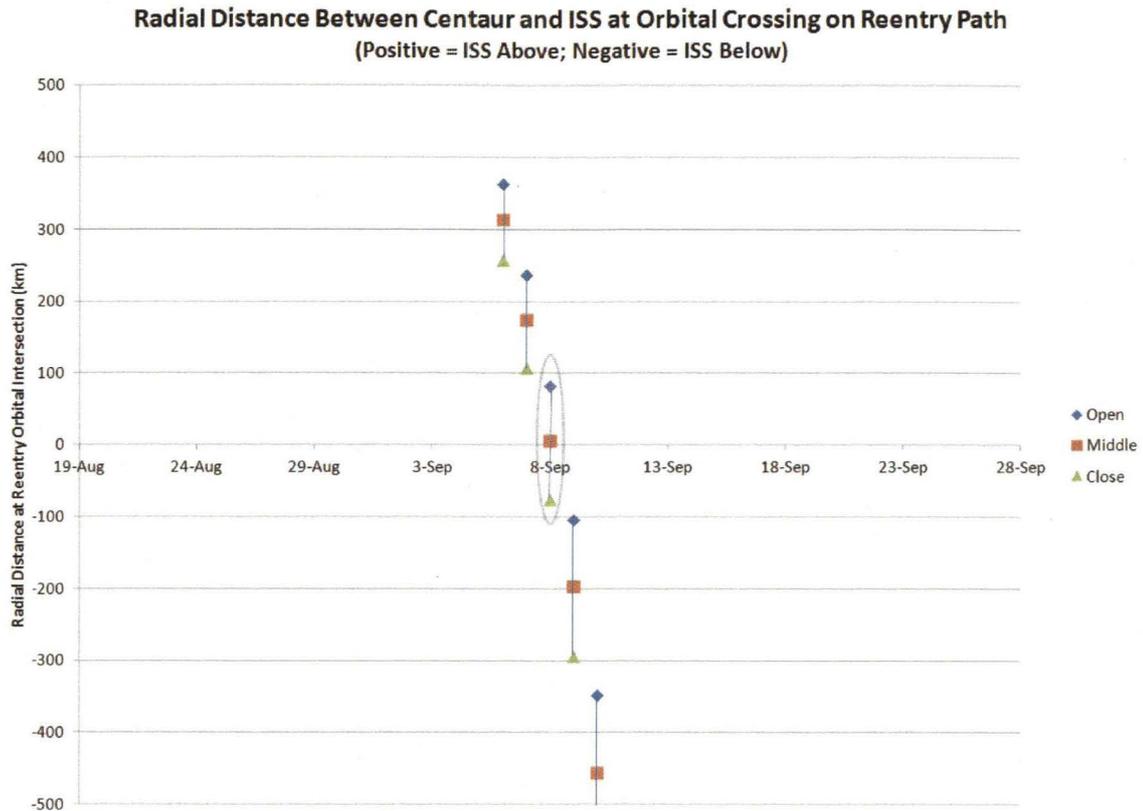


Figure 14. Centaur Radial Difference in Phase 2.

Post-ISS Rendezvous Mission – Orbcomm

The Orbcomm mission was launched on October 7, 2012 on a Falcon 9 (F9) launch vehicle from the Eastern Range as a secondary payload. The primary mission was to launch the Dragon capsule into a rendezvous orbit with the ISS. Following deployment of Dragon, the upper stage of the F9 would raise the orbit to 325 x 750 km, the injection orbit of the Orbcomm spacecraft. From this insertion orbit, the upper stage will cross the orbital plane of the ISS twice per orbit thus prompting a COLA gap analysis. NASA JSC requested that LSP perform a COLA gap analysis using LSP techniques to independently confirm an analysis performed by SpaceX, which employed a different method.

In the previous LEO examples, the launch windows for the Sun-synchronous missions were based on injecting into a required mean local time, resulting in daily variations in the relative orbital planes of the launched objects and the ISS. In this example of an ISS rendezvous mission, the launch time is based on injecting into a coplanar orbit with the ISS. Therefore, the relation between the orbit planes will always be relatively constant. What does change with launch date is the initial in-plane angular difference, or phase angle, between the upper stage and ISS. Consequently, in the analysis the full range of initial phase angles were analyzed to determine if there were any cases that would result in a COLA gap conjunction.

A series of COLA gap screening runs were performed at each ISS phase angle case against the nominal upper stage state. For each case, the argument of latitude and radial differences were calculated at the 70 intersections to see if any of the phase angles resulted in a violation of the initial screening box. Using a set of dispersed Monte Carlo states for the upper stage, the maximum variations at the final orbital intersections were used to develop the initial screening box along with added uncertainty for the ISS position as previously described.

In Figure 15, these results are plotted for five initial phase angles. The plot shows that while there is variation in the relative argument of latitude difference (right/left shifts) due to the difference in phase angle, there is very little difference in the radial separation. Additionally, the near-zero slope of the radial difference points indicates that the orbital intersections occur at nearly the same orbital location and remain well above or below the ISS altitude. Figure 16 shows the results for all phase angles, which confirms there is zero chance of collision between the upper stage and the ISS.

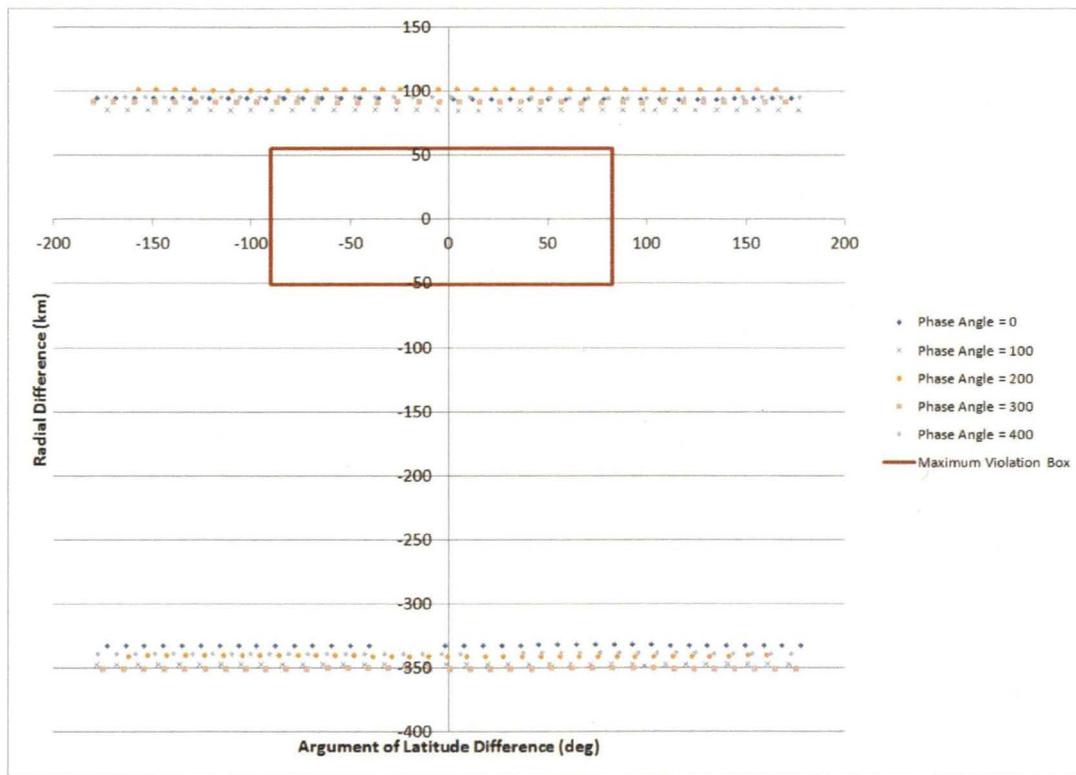


Figure 15. COLA Gap Screening for Sample Phase Angles.

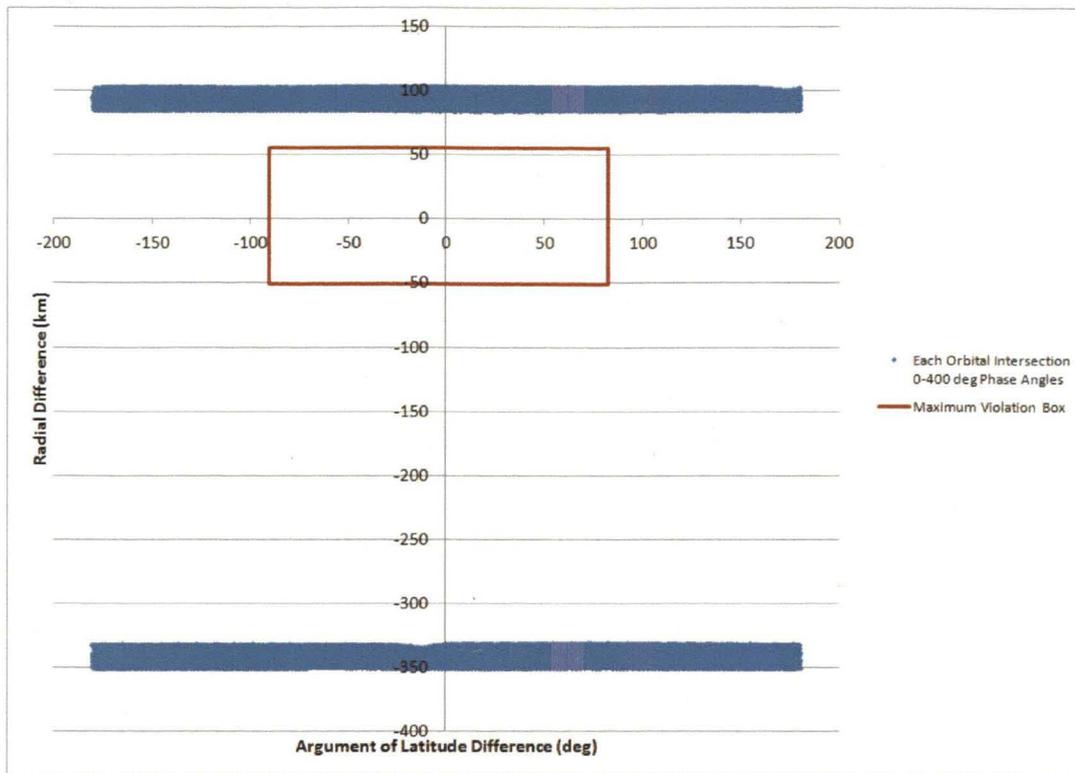


Figure 16. COLA Gap Screening Results for All Phase Angles.

This conclusion can be further validated by examining the relative orbital geometry of the orbits. Figure 17 shows an expanded view of the orbital planes of the ISS and the upper stage (ISS – red plane, F9 – green plane) from a near-polar, edge-on orbit view. As this shows, for two nearly coplanar orbits that are separated by primarily a RAAN difference, the orbital plane intersections will occur near the poles, or near an argument of latitude of 90 and 270 degrees.

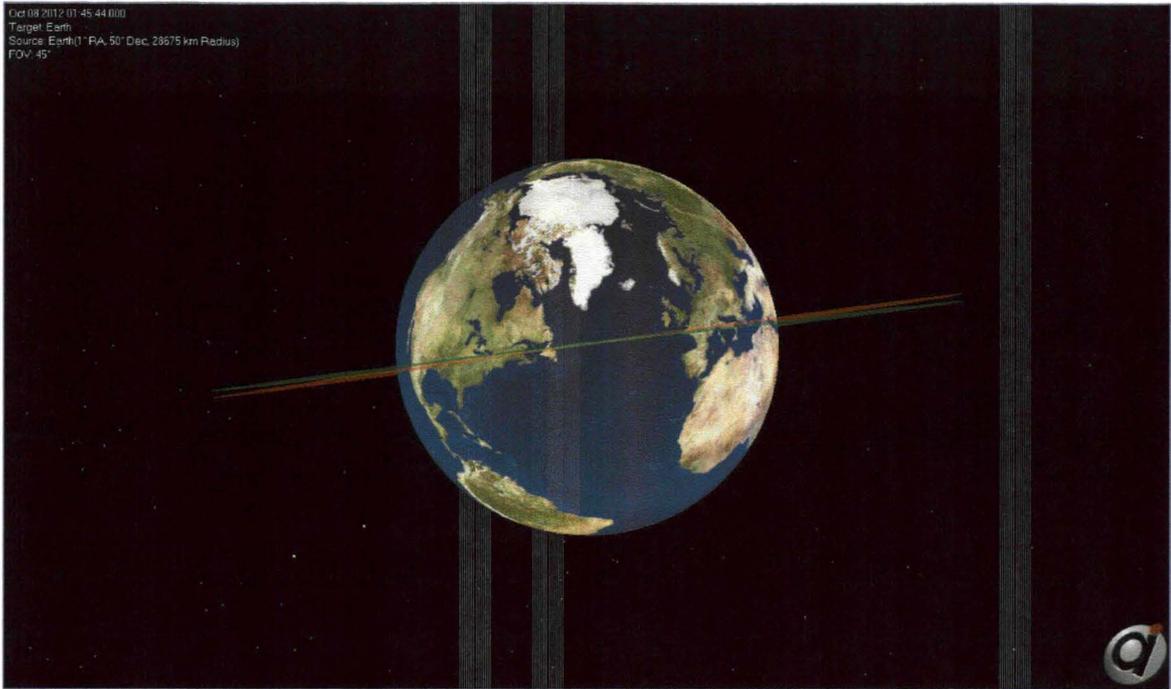


Figure 17. Polar View of the Orbital Planes.

Either by coincidence or by design, the orientation of the elliptical orbit of the upper stage ensures a zero collision risk. Figure 18 plots the height of the upper stage and ISS as a function of argument of latitude. Also shown is the nominal argument of perigee for all phase angles (solid blue bar) and variation in the argument of perigee from the Monte Carlo cases (light blue bar). Then in Figure 19, these data are again plotted with the addition of the nominal argument of latitude range for all phase angles (yellow bars) and the full variation in the argument of latitude at all intersections from the Monte Carlo runs (light yellow bars). The data shows that the nominal and dispersed argument of perigee remains near 270 degrees, while all orbital plane intersections occur near the line of apsides. That is, the orbital plane intersections always occur near apogee and perigee. This confirms there is zero chance of a collision between the upper stage and the ISS as there will always be a significant radial difference.

This case study demonstrates another possible mitigation technique, which is orbit design strategy. As there is typically little rotation in the line of apsides over 56 hours, careful selection of the location of apogee and perigee of an elliptical disposal orbit can avoid any collision potential.

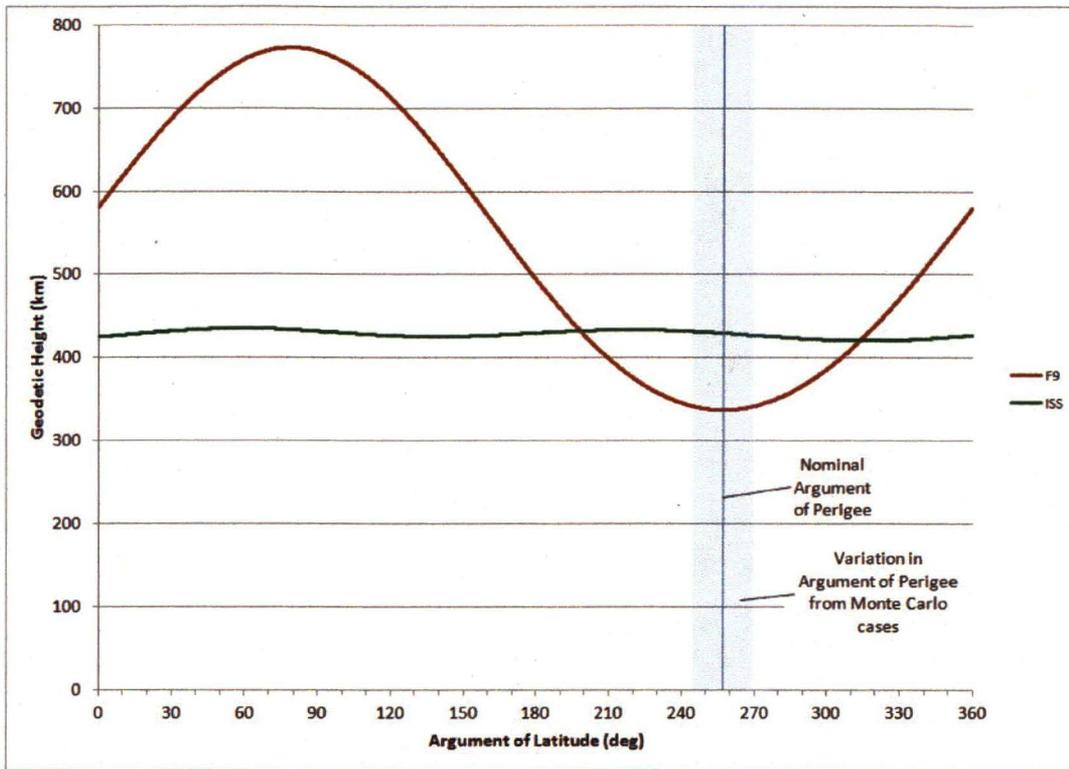


Figure 18. Range of Argument of Perigee Locations.

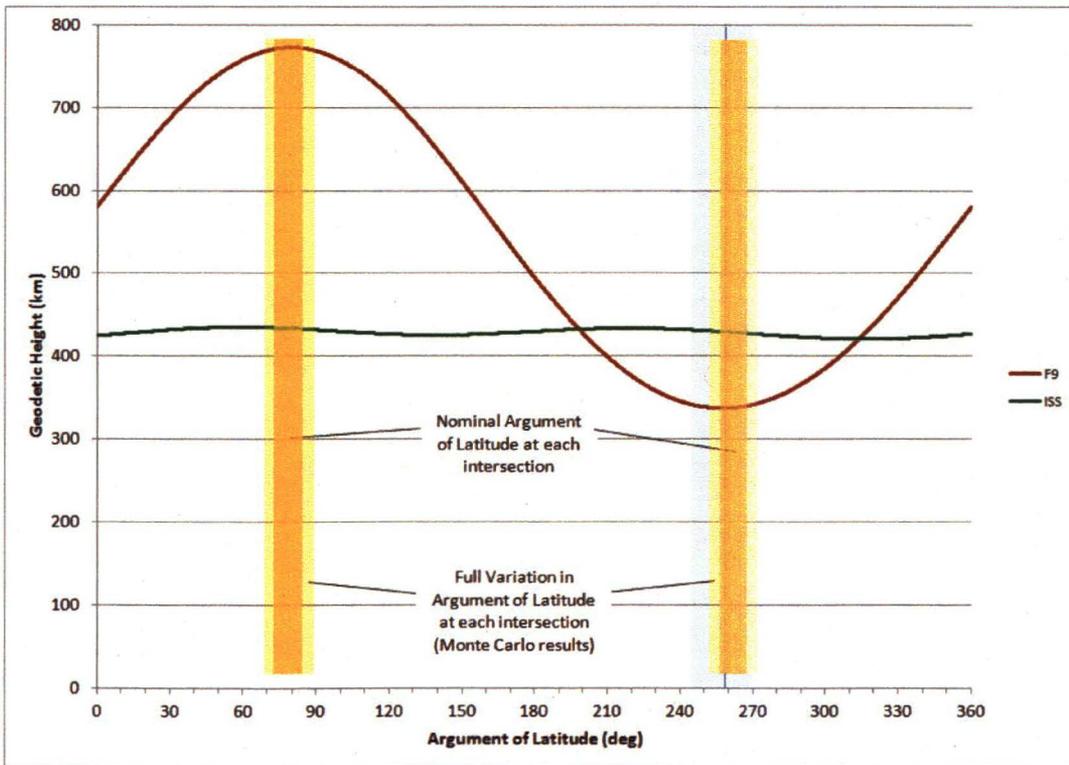


Figure 19. Range of Argument of Latitude Location at Orbital Intersections.

CONCLUSION

The Aerospace Corporation correctly identified a vulnerability period for the ISS between the end of the launch COLA phase and the beginning of the on-orbit COLA phase. In this time period, or COLA gap, there are no actionable means to avoid a collision. Therefore, for the safety of the astronauts and protection of the ISS, other prelaunch methods must be used to mitigate the risk.

Avoidance is the first means to eliminate the risk, as was done for the CubeSats on the NPP mission. If possible, the mission orbit should be selected to avoid crossing the orbit of the ISS in the first 56 hours. If intersections are not avoidable, then orbit selection/orientation should be examined to determine if the radial distances can remain sufficiently large to ensure no collision potential, as in the Orbcomm case study. If neither of these options is possible, then this paper has presented the LSP analysis methodology used on multiple missions to determine if any launch window cutouts are required to ensure a zero threat of collision.

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