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Over-flight Risk Considerations for the Launch of an ELV Rocket to an ISS Inclination

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Congress granted the FAA the authority to license commercial launch and reentry operations to ensure protection of public, property, the national security and foreign policy interests of the United States and to encourage, facilitate, and promote U.S. Commercial Space Transportation. To meet this responsibility, the FAA performs safety evaluations of license applications to conduct commercial launches from the United States or outside the United States by a U.S. citizen or an entity organized under the laws of the United States. This paper discusses an example FAA analysis of the risk to the public resulting from the launch of a space vehicle to the International Space Station from a launch site at the Eastern Range, headquartered at Cape Canaveral, Florida, and the Mid-Atlantic Regional Spaceport, located in Wallops, Virginia. This work is presented to address some of the challenges launch operators competing for the Commercial Orbital Transportations Services (COTS) and the FAA face in their efforts to promote commercial space activities while ensuring the launch operator meets their regulatory obligations and responsibility for protecting the public.

Nomenclature

u_1	=	mean of data element 1 bivariate probability density function
u_2	=	mean of data element 2 bivariate probability density function
ρ	=	correlation between data element 1 and data element 2
σ_1	=	standard deviation of data element 1 bivariate probability density function
σ_2	=	standard deviation of data element 2 bivariate probability density function
σ_{12}	=	covariance between element 1 and element 2
x_1	=	data element 1 value
x_2	=	data element 2 value
E_c	=	Expected casualties
P_i	=	Probability of impact in the ith area
ρ_p	=	population density
Ca	=	sheltered casualty area

Photo: Delta II Wikipedia

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I. Introduction

NASA contracts to resupply the International Space Stations (ISS) require ascent trajectories to the ISS, which pose risk to the public on the ground in the event of a failure during ascent. Proposed COTS missions have chosen unique approaches to vehicle design and launch point. The choice of launch point and mission profile exposes a different area of the public to risk as the design of the nominal trajectory places the vehicle over different continents. To gauge the relative risk, the FAA compared example trajectories from WFF and CCAFS for generic missions of an expendable launch vehicle (ELV) to the ISS overflying Africa. This assessment assumes an identical launch vehicle flown from each launch pad to inclinations of 28.5, 34.5, and 51.6 degrees. From the Wallops launch pad, the FAA assumed a descending node ascent; while from the Cape Canaveral launch pad, an ascending node was assumed. For the Wallops launch, only a 51.6 inclination was assessed because a 28.6 and 34.5 degree inclination mission from this location is undesirable from a performance viewpoint. It should be noted that a significant factor for an operation choosing one launch site location over another is vehicle performance. This paper does not address the tradeoffs associated with vehicle performance and risk.

II. Objective

This paper identifies some of the key considerations for performing launch area and over-flight risk assessments of launch vehicles. It also identifies some of the risk trade-offs for launching space vehicles from different launch sites within the continental United States.

III. Authority

The FAA's authority to regulate commercial space launches is given by Title 49 as summarized.

TITLE 49--TRANSPORTATION

SUBTITLE IX--COMMERCIAL SPACE TRANSPORTATION

CHAPTER 701--COMMERCIAL SPACE LAUNCH ACTIVITIES

Sec. 70103. General authority

(a) General.--The Secretary of Transportation shall carry out this chapter.
(b) Facilitating Commercial Launches and Reentries.--In carrying out this chapter, the Secretary shall--
(1) encourage, facilitate, and promote commercial space launches and reentries by the private sector, including those involving space flight participants; and
(2) take actions to facilitate private sector involvement in commercial space transportation activity, and to promote public-private partnerships involving the United States Government, State governments, and the private sector to build, expand, modernize, or operate a space launch and reentry infrastructure.
(c) Safety.--In carrying out the responsibilities under subsection (b), the Secretary shall encourage, facilitate, and promote the continuous improvement of the safety of launch vehicles designed to carry humans, and the Secretary may, consistent with this chapter, promulgate regulations to carry out this subsection.

Title 14 of the Code of Federal Regulations (14 CFR)[1] section 413.3 addresses who must obtain a license or permit and states that a U.S. citizen or an entity organized under the laws of the United States or a State must obtain a license to operate a launch vehicle outside the United States. Section 415.35 addresses acceptable flight risk for a launch vehicle and states that the applicant for a launch license must demonstrate that the risk level associated with debris from an applicant's proposed launch meets the public risk criteria of section 417.101(b)(1). Section 417.101(b)(1) states that the acceptable risk is to be measured in terms of expected casualties and that the public risk should not exceed a value of 30 in a million. The assessment described in this paper only considers inert debris, however part 417 also addresses the risks to the public associated with explosive blast overpressure, distant focusing overpressure, and the release of toxics.

IV. Definitions

Citizen of the United States means--

(A) an individual who is a citizen of the United States;

(B) an entity organized or existing under the laws of the United States or a State; or

(C) an entity organized or existing under the laws of a foreign country if the controlling interest (as defined by the Secretary of Transportation) is held by an individual or entity described in subclause (A) or (B) of this clause.

Dwell time means the period during which a launch vehicle's instantaneous impact point is over a populated or other protected area.

Launch vehicle means--

(A) a vehicle built to operate in, or place a payload or human beings in, outer space; and

(B) a suborbital rocket.

Public safety means for a particular licensed launch, the safety of people and property that are not involved in supporting the launch and includes those people and property, that may be located within the boundary of a launch site, such as visitors, individuals providing goods or services not related to launch processing or flight, and any other launch operator and its personnel.

Protected area means an area of land not controlled by a launch operator that is a populated area, is environmentally sensitive, or contains a vital national asset.

Suborbital trajectory means the intentional flight path of a launch vehicle, reentry vehicle, or any portion thereof, whose vacuum instantaneous impact point does not leave the surface of the Earth.

Suborbital rocket means a vehicle, rocket-propelled in whole or in part, intended for flight on a suborbital trajectory, and the thrust of which is greater than its lift for the majority of the rocket-powered portion of its ascent.

United States means the States of the United States, the District of Columbia, and the territories and possessions of the United States.

V. Methodology and Approach to Risk Analysis

A. Risk Determination

The analysis begins with the generation of 6-degree-of-freedom (DOF) malfunction trajectories using the representative geometry, mass properties, propulsion, aerodynamics, winds, and a Monte Carlo algorithm to incorporate dispersed values of these parameters used in the analyses of similar vehicles. In the risk analysis, three failure modes originating from the nominal trajectory are of interest: on trajectory failures, malfunction tumble turns, and random attitude turns. These failure modes envelop the many possible debris generating trajectories that can result from failures of vehicle systems, such as the propulsion systems, structure, and guidance, navigation, and control (GN&C) system. On trajectory failures consider the structural loss of the vehicle at anytime during an otherwise normal flight. Malfunction tumble turn trajectories are generated by introducing a desired thrust vector gimbal offset and direction at a specified failure time in the launch area or over-flight portion of the flight before orbital insertion. This offset creates a moment about the vehicle's center of gravity that causes it to depart from its nominal trajectory and enter a turn that continues until the structural loads on the vehicle cause it to breakup or the flight is otherwise terminated. Random attitude trajectories are modeled by assuming the vehicle can reorient itself in a random direction and continue to fly in that direction until some thrust termination or vehicle destruct is activated, a structural limit is violated, or the vehicle exhausts all usable propellants. The trajectories associated with all three of these failure modes include the effects of guidance and performance dispersions about the nominal trajectory, or the normal operating area of the vehicle. For the purposes of this paper, the FAA modeled all trajectories using Sandia Laboratory's Trajectory Analysis and Optimization Software (TAOS) because of the flexibility available in the software.[2]

1. Trajectory Modeling
The preliminary process involves creating a representative nominal trajectory for the mission at hand. This requires knowledge of the vehicle's mass properties, including its center of gravity and inertia data, 6-DOF aerodynamics, propulsion parameters, and trajectory shaping requirements. The nominal trajectory is shaped to fly the first stage using an open loop guidance scheme, where steering commands are applied to achieve angle of attack and angle of attack constraints until first stage separation. The second stage flight is modeled using a closed loop guidance scheme, using optimization to achieve a set of guidance targets at main engine cutoff. The first stage staging conditions, altitude climb rate, or staging flight path angle are adjusted such that the overall optimal performance to the desired mission orbital targets is achieved.

2. Failure Trajectories
As mentioned in the introduction, the FAA used three sets of failure modes to characterize the possible failures that could result in the generation of falling debris that exposes the public to risk. We modeled each set of failure trajectories off of the normal or dispersed trajectory, which is generated using a Monte Carlo approach, to capture a reasonable corridor about the nominal trajectory representative of the vehicle's guidance and performance uncertainty. In practice, we also investigated the sensitivity of the resulting risk value to changes in the width of this corridor generated by the guidance and performance uncertainty, usually varying it by a factor of three greater and smaller to the normal corridor.

2.1 On Trajectory Failure
The on trajectory failure models a failure of the vehicle as it is flying along its normal course of flight. Here "normal" refers to the corridor of trajectories that result from a statistical sampling of guidance and performance dispersions usually considered at a three standard deviation variation. Typically, the FAA does not attempt to model an operator's particular GN&C system in order to determine these corridors but rather implements a variation approach that seeks to duplicate collecting dispersed trajectories obtained from the operator. However, the FAA does have tools to model the nominal and GN&C trajectories. The FAA has found that a suitable way of creating these dispersion corridors is to introduce wind variations in the first stage trajectory while flying the three degree of freedom steering requirements like angle of attack and angle of sideslip. Having the ability to generate our independent nominal and GN&C trajectories offers the FAA flexibility in assessing failure mode trajectories like malfunction tumble turns and random attitude trajectories. The failure times of interest are identified as the range of time from the point just before until just after the debris footprint passes over any continental land mass or island. This is considered the over-flight portion of flight.

2.2 Tumble Turn Failures
The tumble turn failures are those trajectories that result due to a loss of thrust vector gimbal actuator control. To model these trajectories, representative mass properties expressed in terms of center of gravity and moments of inertia are required. The FAA modeled the thrust vector gimbal loss of control in a Monte Carlo fashion by randomly sampling a range of pitch and roll angles at a specified failure time and flying the vehicle until a thrust termination condition was violated, a structural constraint was achieved, or the vehicle consumed all usable propellants. Over-flight of a land mass usually occurs during a stage of the vehicle's flight where the vehicle is well above the sensible atmosphere. The trajectory is terminated based upon one of the previous mentioned constraints. Note that this failure mode requires a six degree of freedom trajectory modeling that accounts for jet damping. Jet damping takes into account the momentum of the exiting mass from the propulsion system, which is a capability of the TAOS tool used by the FAA.

2.3 Random Attitude Failure
The random attitude trajectories characterize those failures where the vehicle can reorient itself in any direction. This reorientation is modeled as an instantaneously applied angle of deviation or vehicle attitude from the nominal trajectory. This approach simplifies the otherwise complex modeling of this failure mode and generally produces conservative results. Like the tumble turn trajectories, random attitude trajectories model vehicle flight from the

onset of the failure until some constraint is achieved. These trajectories require only a three degree of freedom trajectory model. Again, the FAA runs these trajectories at each failure time until a vehicle or range constraint is violated or ground impact occurs.

3. Casualty Area and Debris Modeling

3.1 Inert Debris

For inert debris, this analysis applied a modeling approach similar to the examples shown in Table 1 and Table 2. In its evaluation, the analysis considered the effects of the various levels of sheltering provided by structures on the ground to their inhabitants on the resulting casualty area. The license applicant typically provides the FAA with a debris catalogue by which to characterize debris for this model. Typical debris catalogues supplied by license applicants have shown casualty areas for the second stage vehicles which range from 2000 to 5000 square feet. The FAA groups the debris into classes by similar characteristics, such as ballistic coefficient characteristics and imparted energy. The resulting casualty area for each class is determined based upon a kinetic energy model that considers the kinetic energy of each class of debris and the integrity of the structure it is impacting. For this analysis no demise of the inert debris is considered, however, this effect could result in a 30 percent or greater reduction in the casualty area, but requires extensive heating analysis to confirm this effect. Note that if the kinetic energy of the impacting debris does not exceed the threshold value associated with the penetration of the structure, then it is subtracted from the overall casualty area. Likewise, if the kinetic energy of the debris does exceed the threshold, then an augmented casualty area is added to the basic casualty area. Table 1 shows an example of a simplified kinetic energy penetration model that includes the fraction of the public assumed to be in the three structure types, concrete buildings, residential homes, and unsheltered. Table 2 summarizes the resulting overall inert debris sheltering casualty area used for this assessment. To be consistent with the findings from other launch operator's second stage launch vehicles, this assessment baselined a sheltered casualty area of 3500 ft^2 as shown in Table 2.

Table 1: Example Sheltering Model

Shelter Type	Description	Kinetic energy (KE) based probability of casualty (P_{cs}) for the s^{th} shelter type	Fraction of people under specified s^{th} shelter (F_{ps})

1	Building with concrete or reinforced roof	If (KE > 74000 ft-lb); $P_{c1} = 1$
		If (6200 ft-lb ≤ KE ≤ 74000 ft-lb); P_{c1} ramps linearly from 0 to 1
		If (KE < 6200 ft-lb); Pc1 = 0
			$F_{p1} = 0.2$

2	Single story building such as houses or trailers	If (KE > 3200 ft-lb); $P_{c2} = 1$
		If (100 ft-lb ≤ KE ≤ 3200 ft-lb); P_{c2} ramps linearly from 0 to 1
		If (KE < 100 ft-lb); $P_{c2} = 0$
			$F_{p2} = 0.7$

3	Unsheltered	If (KE > 35 ft-lb); $P_{c3} = 1$ If (0 ≤ KE ≤ 35 ft-lb); P_{c3} ramps linearly from 0 to 1	$F_{p3} = 0.1$

Table 2: Inert Debris Casualty Area

Phase of Flight	Sheltered Casualty Area (ft^2) [C_a used in analysis]
Stage 2	3500.0

3.2 Explosive Debris

In some circumstances, it is possible for the vehicle to remain intact after a tumble turn or random attitude failure and impact with some residual propellant. In this situation, the casualty area would include explosive effects. The resulting casualty area is then many times greater than the inert debris casualty area. The FAA calculated this effective casualty area based upon the amount of propellant remaining at the time of impact, the estimated explosive yields due to propellant mixing at the expected impact speeds, and overpressure and fragment throw thresholds that result in a casualty. For this analysis, we assumed the breakup of the vehicle from the over-flight failure always to occur and therefore no explosive casualty area was considered. For most second stage vehicles using liquid propellants, this has been found to be true[3]. However, for a vehicle designed to survive reentry, we may have to consider an explosive or toxic casualty area. Also for vehicles using a solid propellant second stage, failure to sufficiently fragment the propellant could result in explosive casualty areas which could exceed the inert casualty area.

4. Population Modeling

Population models are critical to determining the risk to the public. Population models can be obtained from several sources as relevant to the area being analyzed as discussed in the following sections. In the past, the FAA has applied population databases from U.S. Census Bureau data, the Oak Ridge National Laboratory's LandScan population database, and Columbia University's Gridded Population of the World database[4]. For this particular assessment, the FAA selected the Gridded Population of the World due to its ease of use in the risk tool applied. Typically the FAA will examine the effect of the resolution of the population database and has found for over-flight that a one degree by one degree resolution provides stable risk results.

5. Statistical Modeling of Probability of Impact

The FAA models all the grouped debris in a debris catalogue. The trajectory of the intact vehicle and each class of debris is propagated from the point of the failure to the point at which it reaches ground impact. To determine the probability of impact, the FAA computed a bivariate distribution from the ground impact footprint as shown in equations 1 through 3. For the failure modes investigated, the FAA has shown that a bivariate distribution generally results in conservative risk results and is applicable in the majority of situations for the type of failure mode trajectories investigated[5].

i. Bivariate Normal

$$P(x_1, x_2) = \frac{1}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}} \exp\left[-\frac{z}{2(1-\rho^2)}\right], \qquad (1)$$

$$z \equiv \frac{(x_1-\mu_1)^2}{\sigma_1^2} - \frac{2\rho(x_1-\mu_1)(x_2-\mu_2)}{\sigma_1\sigma_2} + \frac{(x_2-\mu_2)^2}{\sigma_2^2}, \qquad (2)$$

$$\rho \equiv \mathrm{cor}(x_1, x_2) = \frac{\sigma_{12}}{\sigma_1\sigma_2} \qquad (3)$$

5. ***Vehicle Probability of Failure Modeling***

To determine the overall probability of impact of debris into a populated area, the trajectory probability of impact must be scaled by the vehicle probability of failure at the particular failure time of interest. The U.S. Air Force, NASA, and the FAA have developed a common standard for estimating the probability of failure for a new expendable launch vehicle as a function of the number of failures suffered by similar vehicles launched under similar circumstances[6]. For a new operator developing and launching a new launch vehicle, a suitable probability of failure may be as much as an order of magnitude higher than the probability of failure of a derived vehicle launched by an experienced operator. Figure 1 shows the range of probability of failure based upon historical data for various launches conducted by operators from around the world. The data is computed from the post 1970's probability of failure database provided to the FAA by ACTA Incorporated. This database examined all of the launches that have occurred from the 1970's to 2007 and analysis determined all of those launches that resulted in a failure such that the nominal mission was not achievable. In addition, the database attempts to identify the cause of the failure and the stage in which it occurred. Typically, the probability of failure for the first two flights is desired. The data presented in Figure 1 shows considerable variation in probability of failure, depending upon the country, varying from about .1 to .8 when considering the upper and lower 99% confidence intervals. Because the vehicle under consideration may be from an experienced or new developer having new or derived stages, a probability of failure of 0.5 was baselined for launches out of both sites being considered: the Cape Canaveral Air Force Station (CCAFS) and the Wallops Flight Facility (WFF).

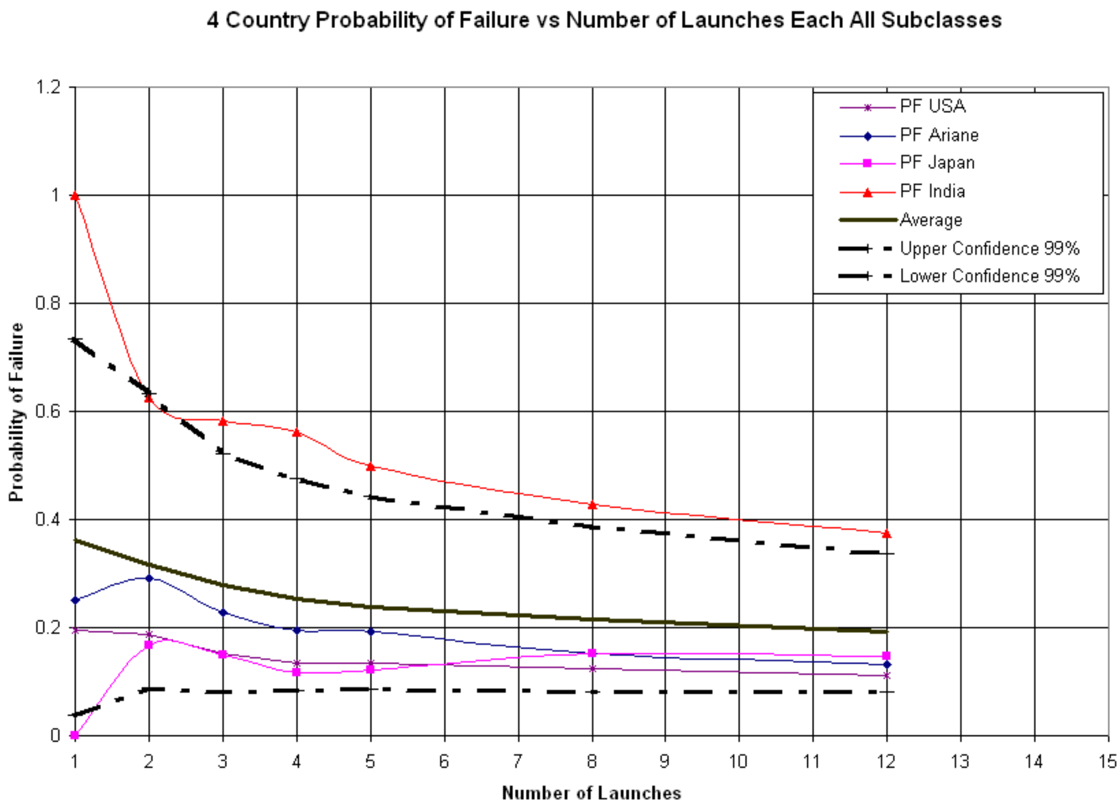

Figure 1: Probability of Failure as a Function of Flight Number Compared for Four Countries

The FAA determined the failure rate by dividing the total probability of vehicle failure by the duration of the total second stage over flight, scaling the total probability of vehicle failure at each instant of flight. Past work in probability of failure analysis performed by Research Triangle Institute (RTI) has shown that 2/3 of ELV failures have occurred during first stage flight while 1/3 of ELV failures have occurred during second stage flight[7] The resulting second stage failure probability also scales the total vehicle probability of failure to determine the overall probability of impact into a particular population center.

6. *Allocating Probability of Failure*

In addition to considering the probability of failure of the vehicle, knowledge of the probability of occurrence of each failure mode of interest is also required. One must answer what is the probability of the vehicle failure at an instant of time and what is the probability of the failure mode, whether the failure mode be an on trajectory, tumble turn, or random attitude. RTI recommended an allocation of 0.73 for on trajectory failures, 0.22 for malfunction turn failures, and 0.05 for random attitude failures. Thus, given the probability of failure and allocation for the failure mode and the probability of impact due to the trajectory data, the FAA can compute a probability of impact into any population center for each failure mode.

7. E_c Modeling

Expected casualties (Ec) for all population centers or Gridded Population of the World (GPW) grid locations are computed using equation 4 as illustrated below.

$$E_c = \Sigma P_i \times \rho_p \times Ca \qquad (4)$$

Note that P_i is the final computed probability of impact and the summation is applied over all population grid locations (represented by the population density term ρ) and over all failure times. The casualty area represents the sheltered casualty area from each debris class.

VI. Analysis Results

B. RESOLV Assessment

The Risk Estimator for Suborbital and Orbital Launch Vehicles (RESOLV) is an independent risk analysis tool the FAA developed to independently verify risk results produced by ACTA's Range Risk Assessment Tool (RRAT) and to perform sensitivity studies that inform its licensing and permitting evaluations. The tool takes user supplied failure trajectories defined at an impact point and user defined sheltered casualty area and population database to determine the risk to exposed populations by applying either a bivariate normal distribution or extreme value distribution to the impact data. As part of the its internal procedures, the FAA performs an independent risk analysis to insure consistency and confidence in the risk assessment for a particular operator.

1. Over-flight of Africa from a CCAFS Due East Launch

Over-flight of Europe on a trajectory to the ISS represents a new endeavor for a truly commercial operator. The FAA compared the risk assessments to a baseline value corresponding to an over-fight of Africa, because most commercial ELV launches from the Eastern Range have trajectories that overfly Africa. The FAA examined to Africa missions, one for a due east or 28.5 degree inclination and one for a 34.5 degree inclination. The due east mission was used as the normalization reference mission.

Figure 2 shows the instantaneous impact point (IIP) of the vehicle as it overflies Africa for a due east launch. Figure 3 and Figure 4 show typical outputs from the RESOLV tool for a on trajectory failure. Figure 3 shows the impact trajectories for all failure times and shows the population as a function of the longitude and latitude. As seen by this data, the over-flight portion of the trajectory passes mostly through some populated areas. Figure 4 shows the maximum expected casualty for any failure point at each grid point. As seen by examination of this data, the maximum expected casualty occurs on the western one third of Africa.

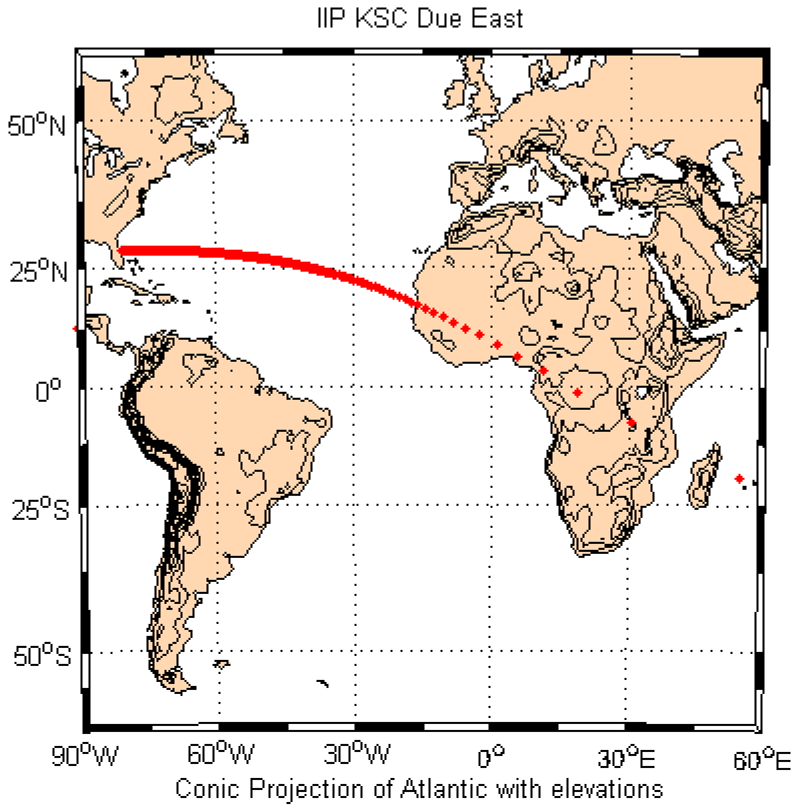

Figure 2: Instantaneous Impact over Africa Due East

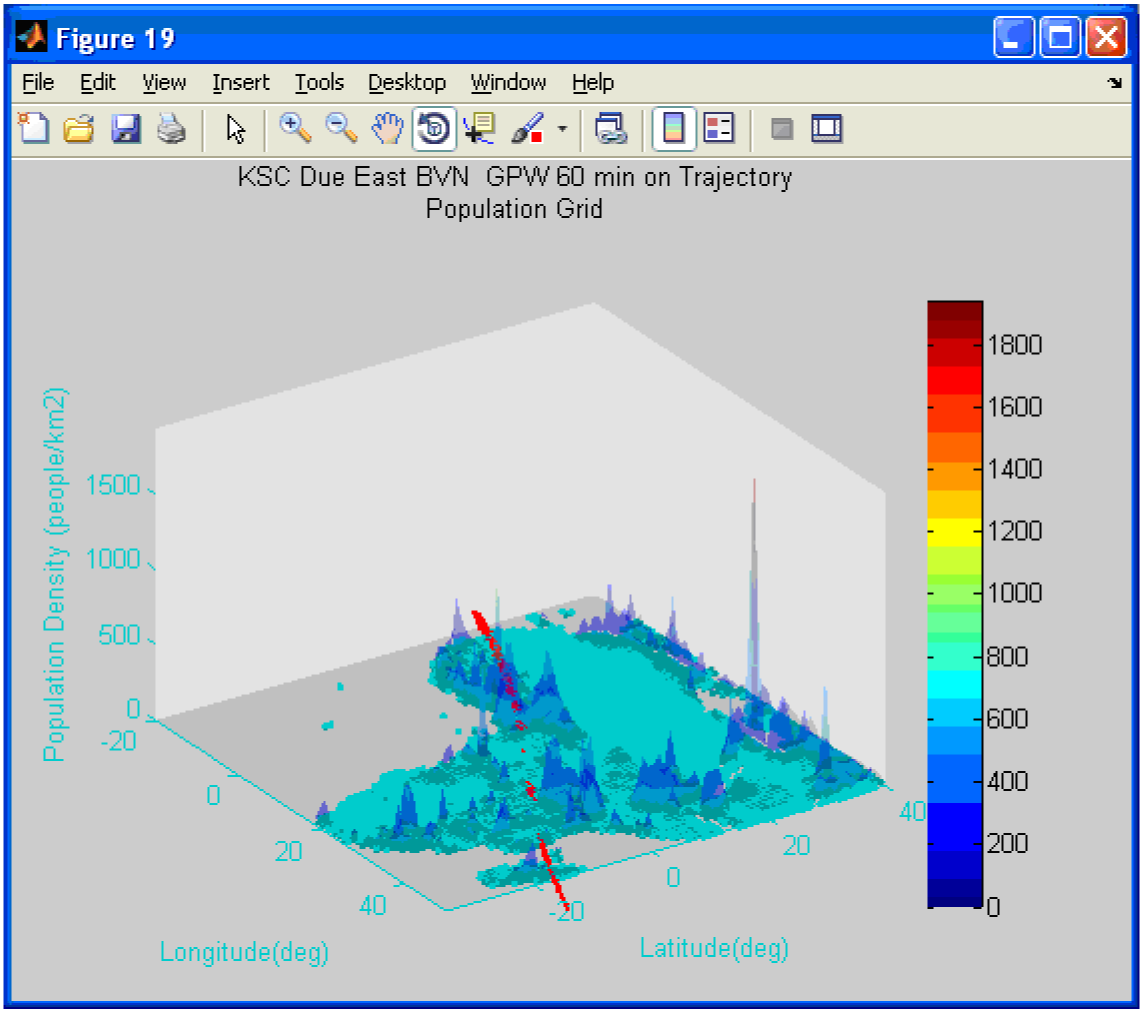

Figure 3: Population Trajectory Corridor for On Trajectory Failure versus Location over Africa Due East

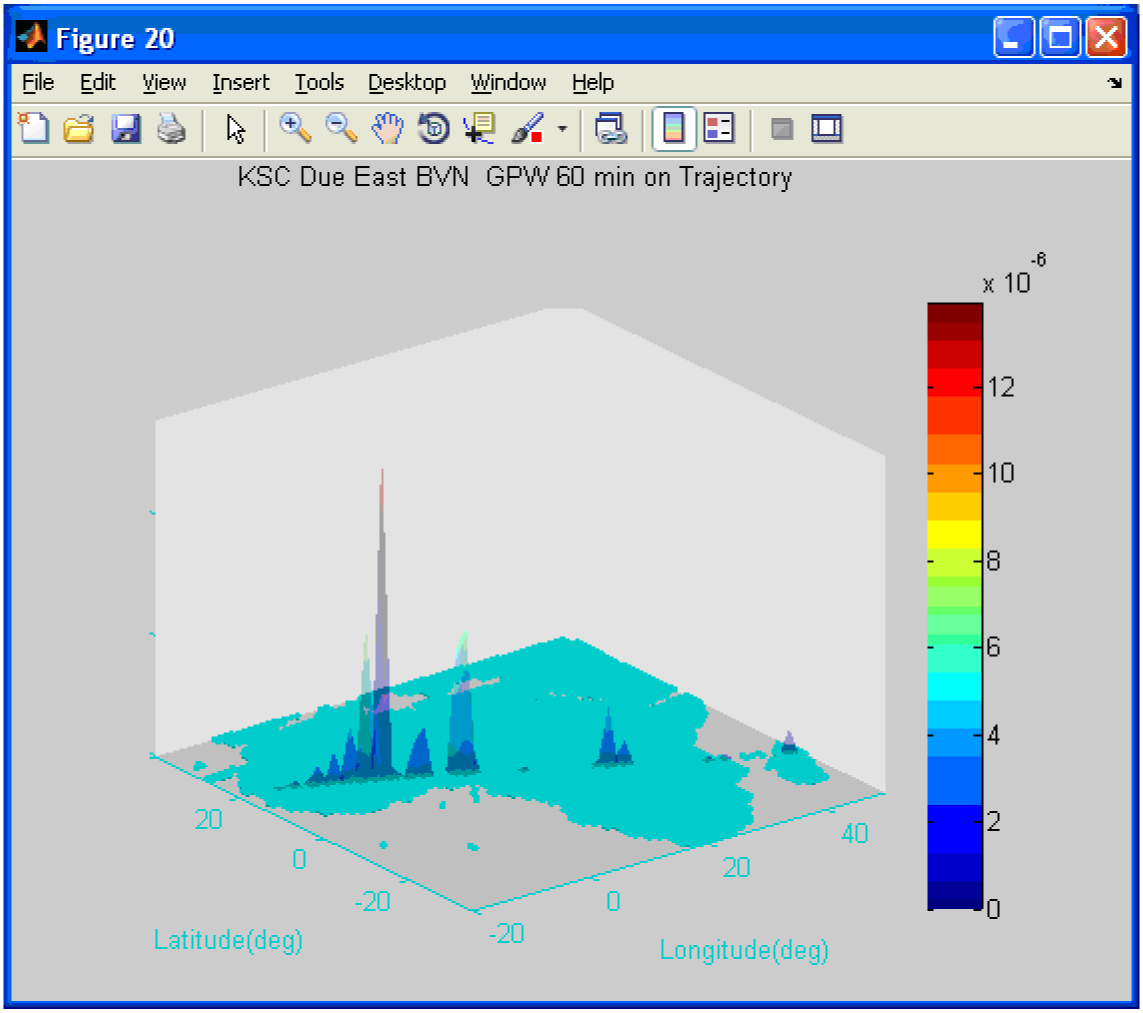

Figure 4: Relative Risk On Trajectory Failure versus Location over Africa Due East

Table 3 summarizes the over-flight risk considering the allocation of the probability of failure to both vehicle stages and to the three failure modes, as described previously. Note that the allocation for each failure mode directly scales the risk calculated for that failure mode. For over-flight of Africa, the baseline risk to the public is normalized as a ratio of one. It can be seen from this table that the major contributor to risk is the on trajectory failure mode which accounts for about 70% of the risk followed by the malfunction tumble turn failure mode which accounts for about 26% of the risk. The random attitude failure mode was found to account for less than 1% of the total risk. Note that this does not include the risk due to tumble turn and random attitude trajectories, which can result in trajectories that have debris reentering after one or more orbits. These trajectories are considered random reentry trajectories because they have the potential for impacting anywhere on the Earth within the inclination band of the mission. For a previous assessment, the FAA and ACTA determined that the risk from random reentry trajectories was in excess of 50% of the risk for the over-flight risk from the on trajectory, tumble turn, and random attitude failure modes.

Table 3: Summary of Over-flight Results 28.6 degrees inclination

Failure Mode	Allocation	Total (ratio after allocation)
On Trajectory	.73	0.70
MFT	.22	0.26

RA	.05	0.04
Total	1.0	1.0

2. Over-flight of Africa from a CCAFS Launch 34.5 degrees inclination

Figure 5 shows the instantaneous impact point (IIP) of the vehicle as it overflies Africa. Figure 6 and Figure 7 show typical outputs from the RESOLV tool for a tumble turn failure. Figure 6 shows the impact trajectories for all failure times and shows the population as a function of the longitude and latitude. As seen by this data, the over-flight portion of the trajectory passes mostly through less populated areas. Figure 7 shows the maximum expected casualty for any failure point at each grid point. As seen by examination of this data, the maximum expected casualty occurs on the west and east coasts of Africa.

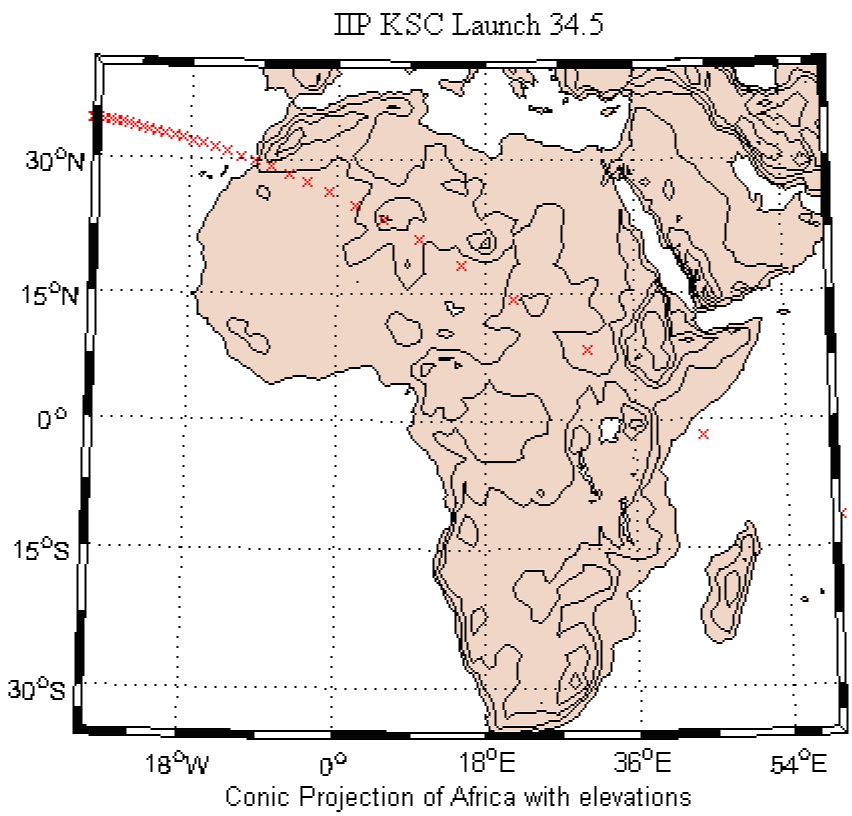

Figure 5: Instantaneous Impact over Africa CCAFS (KSC) Launch

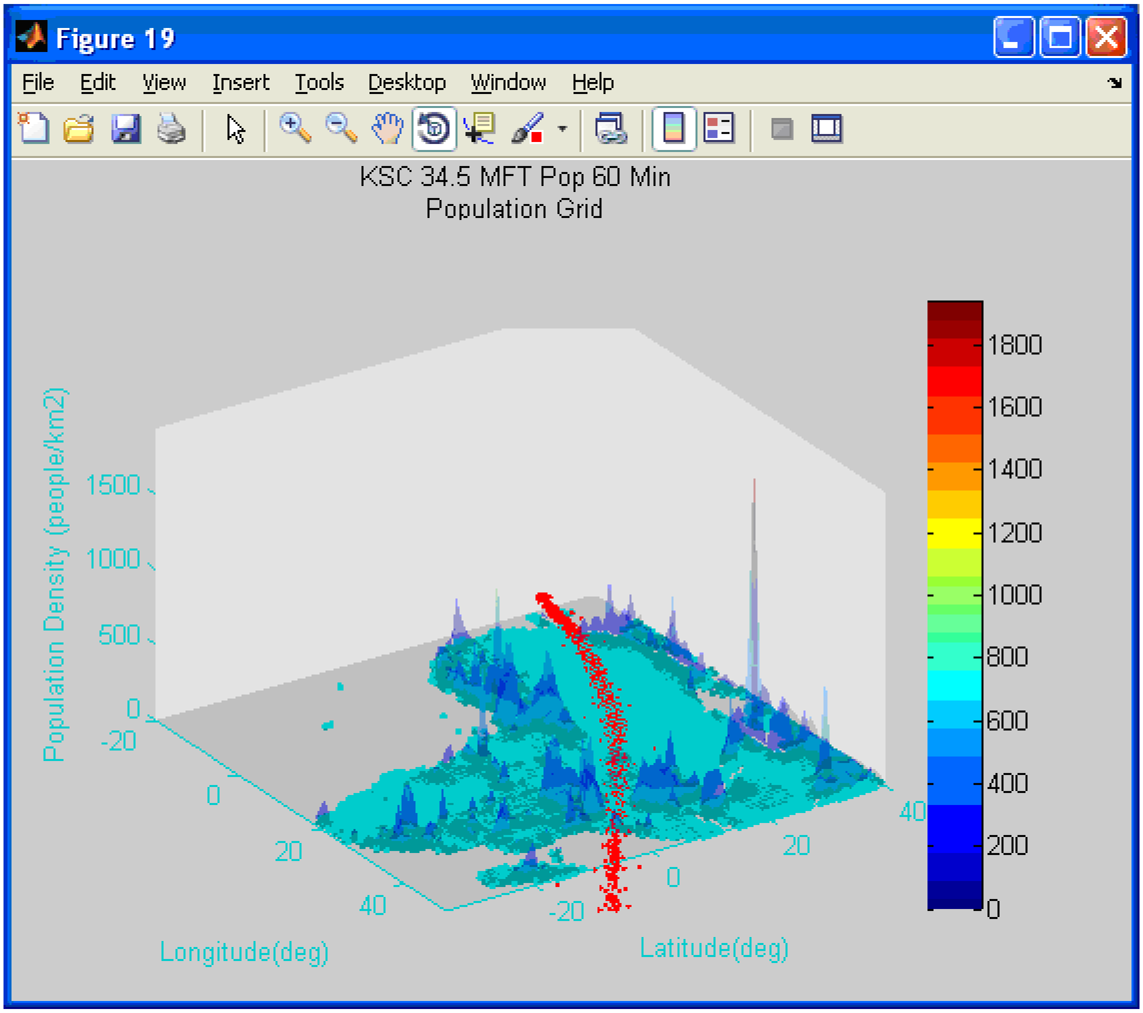

Figure 6: Population Trajectory Corridor for Malfunction Turn versus Location over Africa

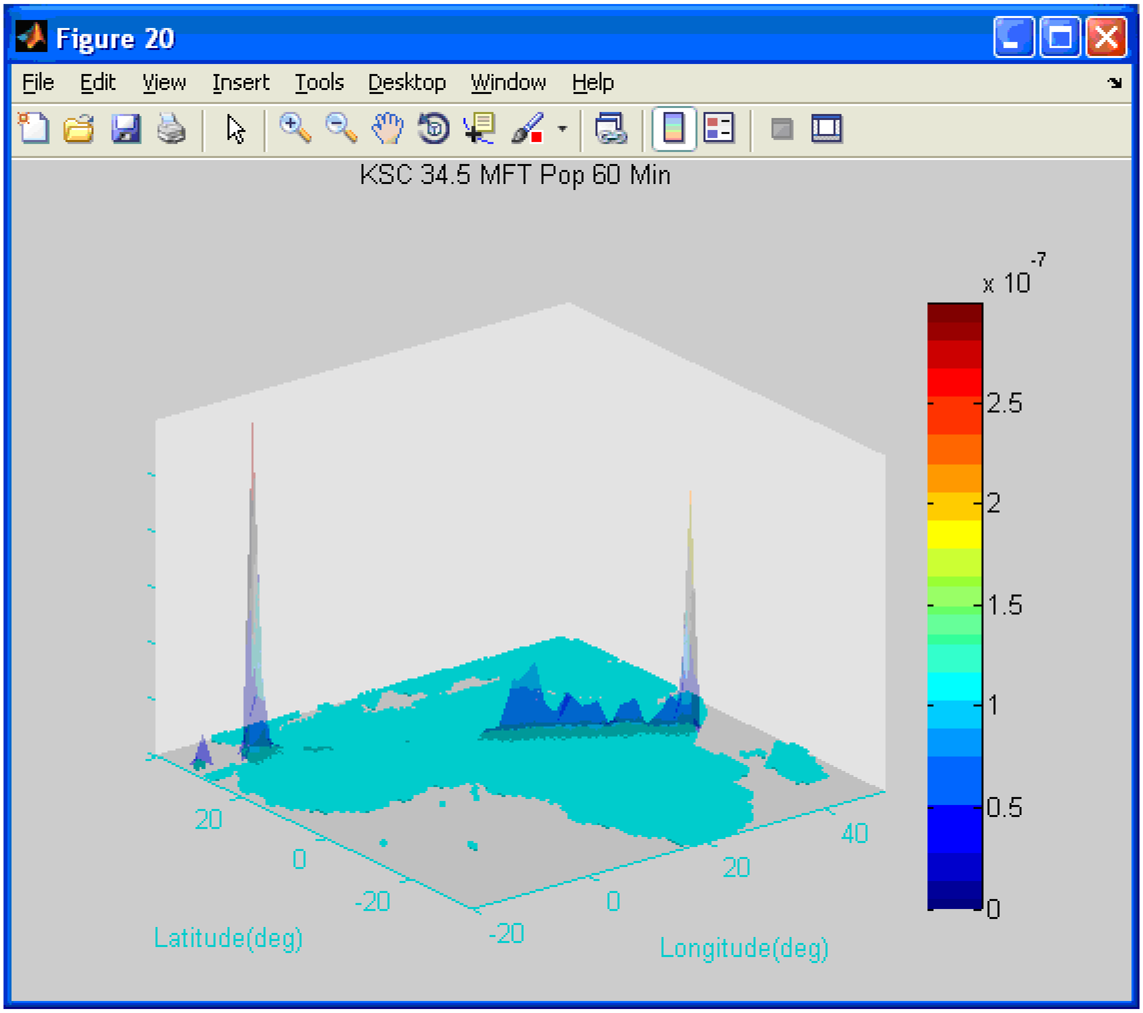

Figure 7: Relative Risk Malfunction Turn versus Location over Africa

Table 4 summarizes the over-flight risk considering the allocation of the probability of failure to both vehicle stages and to the three failure modes, as described previously. Note that the allocation for each failure mode directly scales the risk calculated for that failure mode. For over-flight of Africa to a 34.5 degree inclination, the baseline risk to the public is a factor of 4 less than the baseline mission.

Table 4: Summary of Over-flight Results 34.5 degrees inclination

Failure Mode	Total (after allocation)
Ratio Relative to Due-East Baseline	**.23**

3. Over-flight of Europe for a Launch to the ISS from a CCAFS Launch Site

An operator may choose to launch a vehicle to the ISS from the CCAFS launch site. Figure 8 shows the instantaneous impact point for a launch out of CCAFS to the Space Station inclination of 51.6 degrees. Note that the IIP passes just south of Great Britain, over France, and through Saudi Arabia.

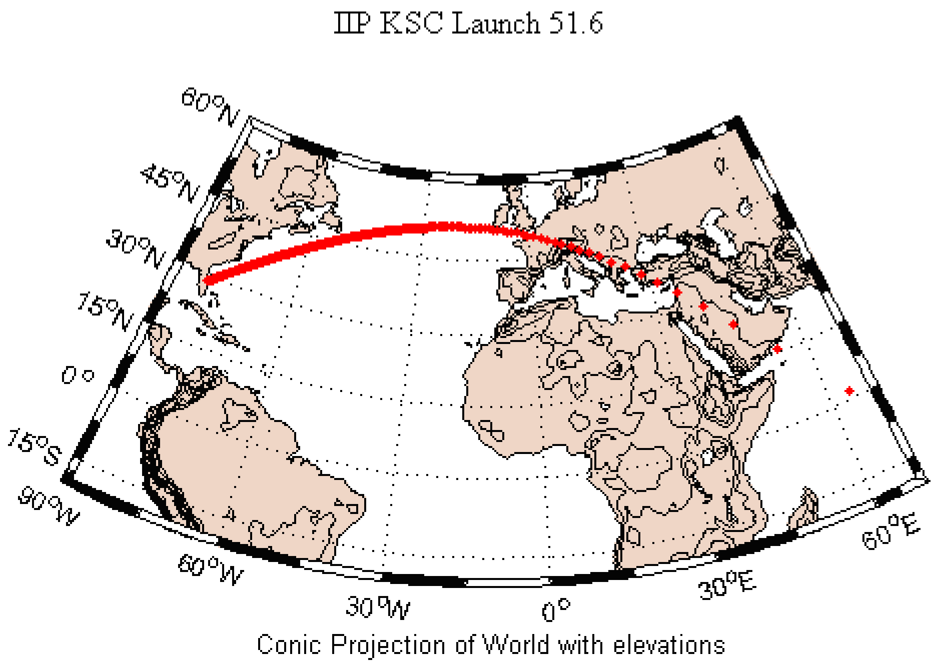

Figure 8: IIP for 51.6 degrees inclination from CCAFS (KSC)

Figure 9 summarizes the populations, trajectory footprint, and risk for the tumble turn failures associated with this trajectory, and shows the population density and the impact corridor. Figure10 shows the maximum contribution to Ec over the continent for the failure times investigated.

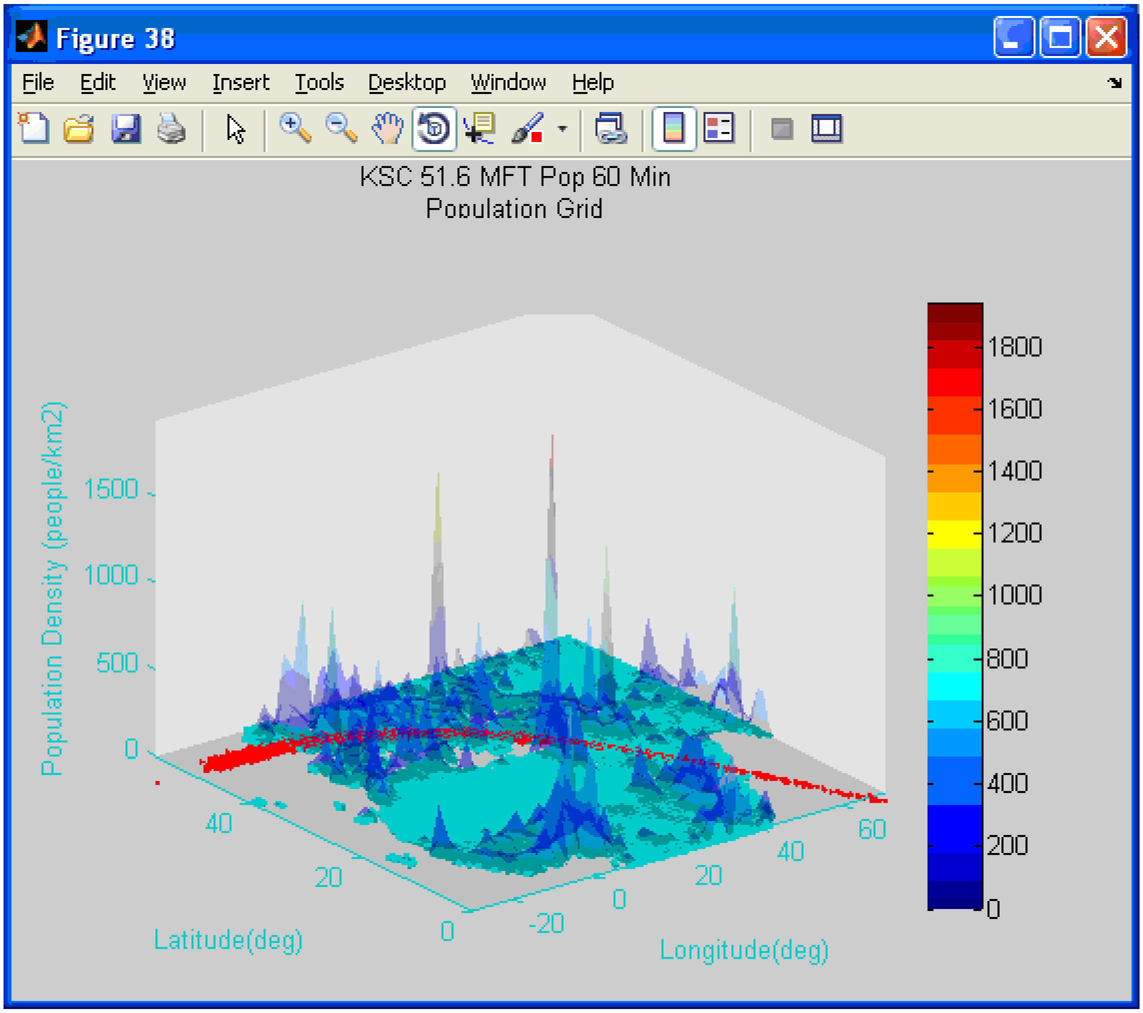

Figure 9: Population and Impact Trajectories for Tumble Turn Failures over Europe-Middle East-Africa

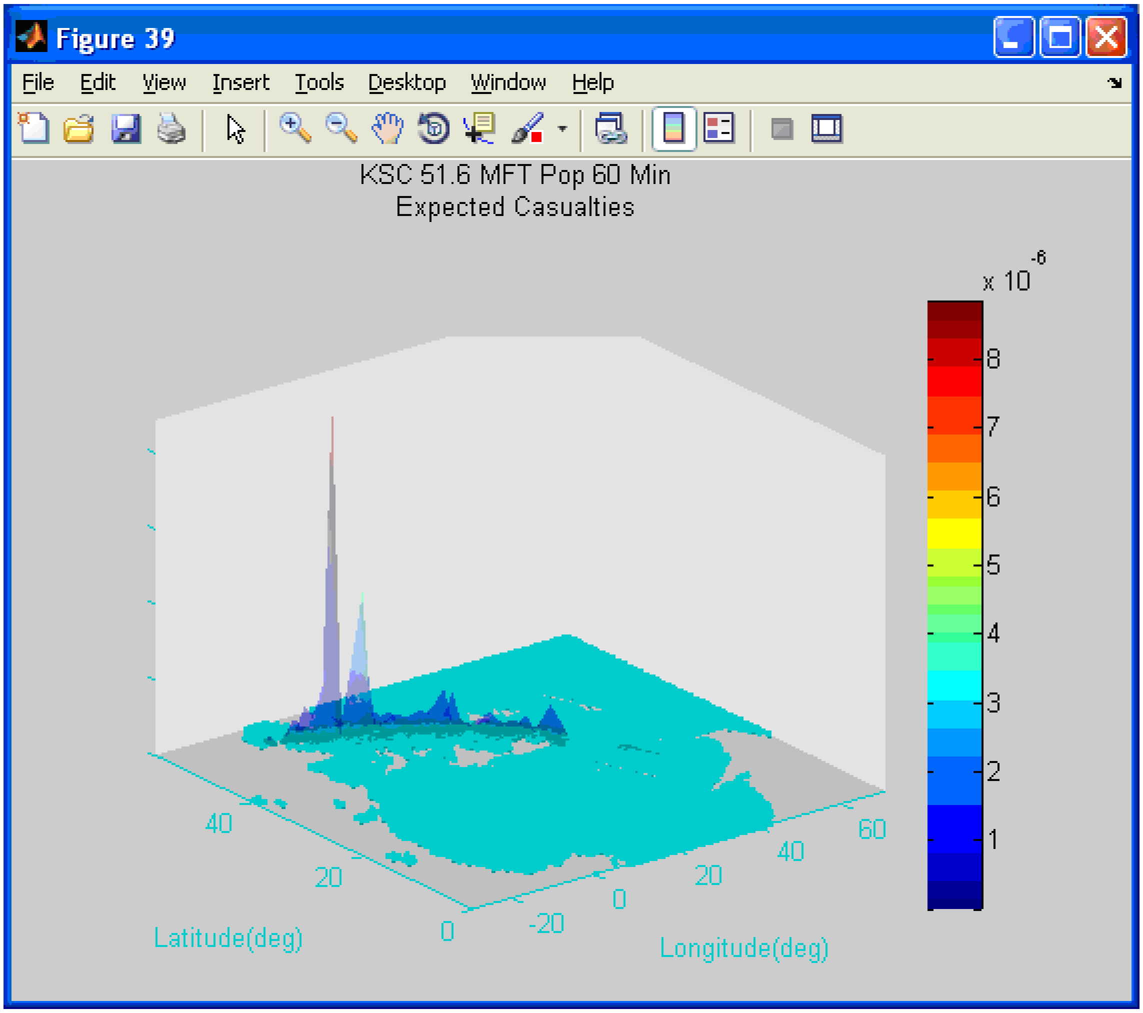

Figure 10: Relative Risk Tumble Turn versus Location over Europe-Middle East-Africa

Table 5 is similar to Table 3. It summarizes the risk for all failure modes investigated and shows that the risk for this mission is about a factor of four greater than the baseline.

Table 5: Summary of Over-flight Results 51.6 degrees inclination

Failure Mode	Total (after allocation)
Ratio Relative to Due-East Baseline	**4.03**

4. Over-flight of South America for a Launch to the ISS from WFF

Another commercially available launch site is the Wallops Flight Facility located in Wallops, Virginia. Figure 11 shows the instantaneous impact trace for a launch out of Wallops to the Space Station Inclination of 51.6 degrees using a descending node trajectory. Note that these trajectories are without any yaw steering. As a result, the IIP passes over the eastern tip of Brazil. Flight to the ISS would most likely require some form of steering to perform rendezvous with the ISS as a function of the time of launch from an in-plane or optimal performance rendezvous time and thus may not result in land overflight, note that for a launch from CCAFS for an ascending node, overflight of land is inevitable.

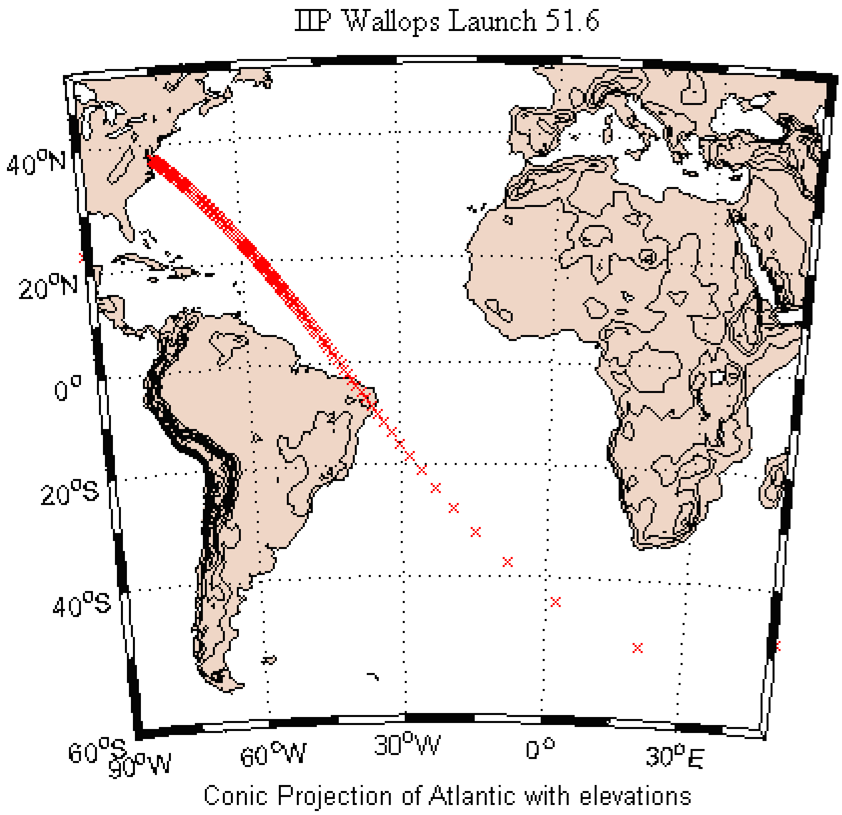

Figure 11: ISS IIP for 51.6 degrees inclination from Wallops

The random attitude trajectories result in the widest trajectory corridor because the vehicle maintains a constant attitude until burnout of the second stage. Figure 12 shows the corridor for the random attitude trajectories.

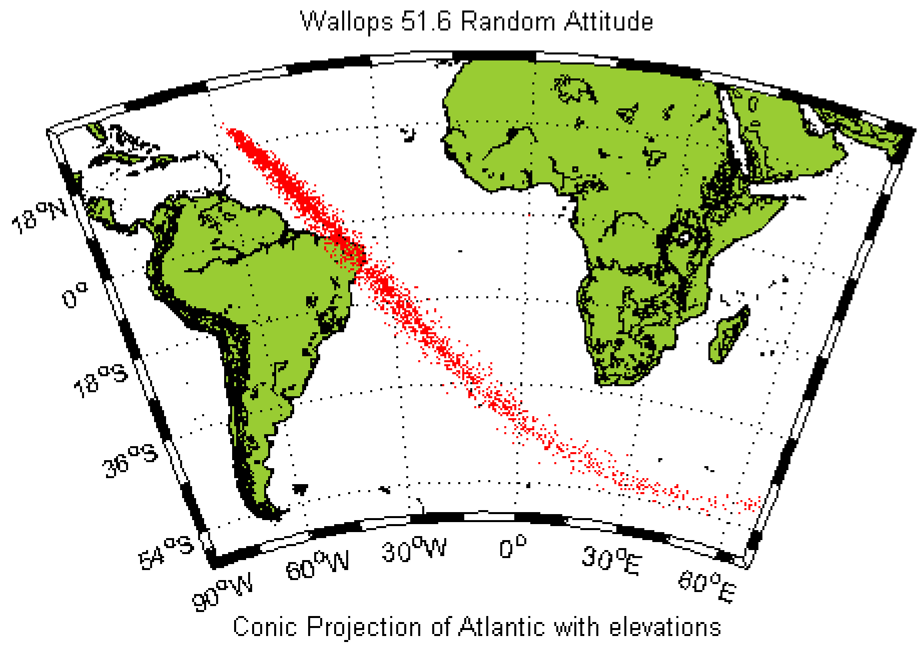

Figure 12: Over-flight Random Attitude Impacts for Launch from Wallops

Figures 13 and 14 show an example of the results obtained for the on trajectory failure mode. Figure 13 illustrates the trajectory impacts as a function of longitude and latitude and shows the population density for each grid point in the population database. As seen by examination of Figure 13, the corridor for the random attitude trajectories failure that the FAA modeled passes near some fair-sized or around 100,000 people, population centers. Figure 13 also summarize the unallocated risk for this failure mode. Figure 11 illustrates the maximum expected casualties that occurred at any population grid location as a function of longitude and latitude. Figure 11 shows the greatest maximum risk is at the point where the corridor first passes over Brazil and then exits Brazil.

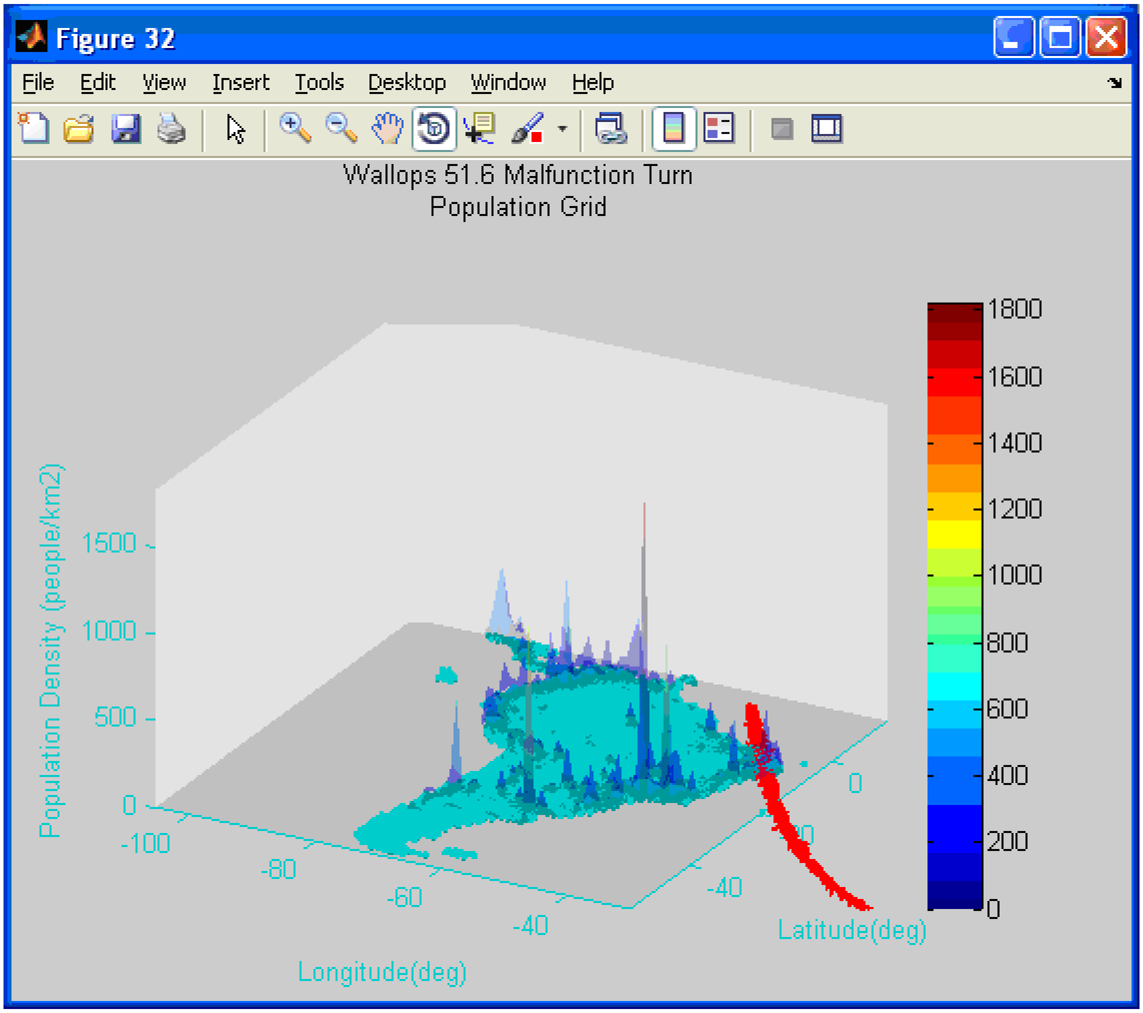

Figure 13: Population and Impact Trajectories for On Trajectory Failures over South America

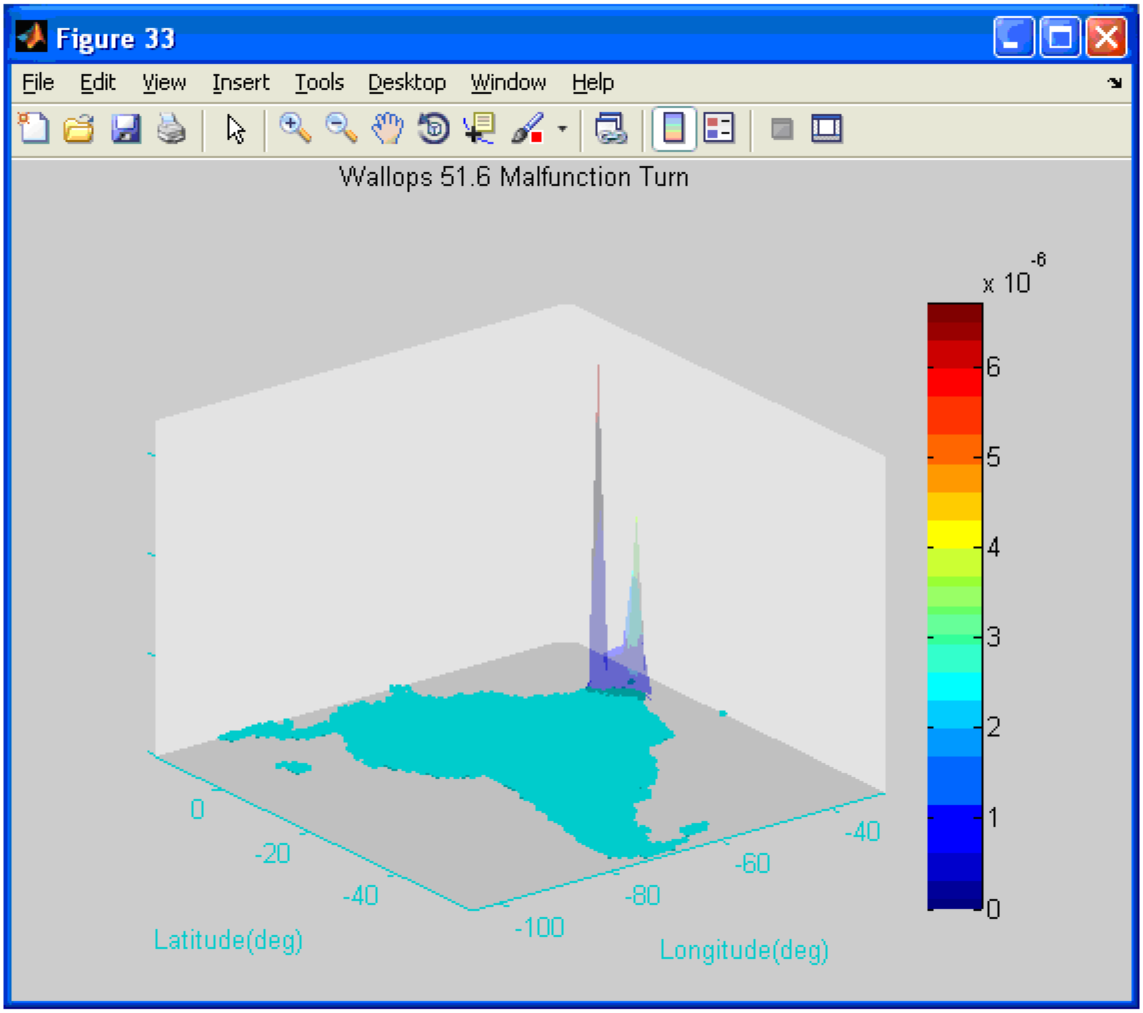

Figure 14: Relative Risk On Trajectory versus Location over South America

Similar to Tables 3 and 4, Table 6 summarizes the overall risk for each of the failure modes investigated. Table 5 states the risk to the public for the mission assessed is a factor of 1.6 increase over the baseline.

Table 6: Summary of Over-flight Results 51.6 degrees inclination Wallops Launch

Failure Mode	Total (after allocation)
Ratio Relative to Due-East Baseline	**1.61**

For a launch from WFF, it is possible to mitigate the risk to South America by yaw steering in the first stage. It is possible to yaw steer east of Brazil while still being west of Bermuda. The FAA found the performance penalty for this mitigation measure to be about 200 to 300 lbs payload weight. It is interesting to note that there is no performance advantage for flying to an ISS inclination out of CCAFS as opposed to WFF because the Earth rotational inertial velocity contribution at main engine cutoff (MECO) is almost the same for both trajectories at the point of orbital insertion.

5. Individual Risk Considerations

The individual risk represents the probability of casualty for one individual. Assuming an individual occupies an area of three square feet, the individual risk can be computed from the probability of impact contours knowing the casualty area of the inert or explosive debris. The most conservative individual risk comes from the analysis of the launch area for the case where explosive debris is considered. Typical assessments have shown this to be on the order of 3×10^{-8}. Because of the vast footprint of the over-flight portion of the trajectory, individual risk for over-flight is an order of magnitude less than the individual risk for the launch area and thus not a factor in this risk assessment.

VII. Conclusion

It is important to note that the risk evaluation presented does not represent the risk assessment for any particular launch operator that has pursued an application for an FAA license. It is illustrative of the relative risk. Table 7 summarizes the total results for baseline mission, over-flight of Africa, and compares it with the over-flight risk for launch from a CCAFS launch site and launch from a WFF. As can be seen from Table 7, if the probability of failure for each vehicle from each launch site and the casualty area is considered the same, then there is a noticeable difference from flying to the ISS from WFF because the risk is 40% of the risk for a launch from CCAFS. Compared to the African baseline, the over-flight risk for a mission to the ISS is 1.6 to 4 times greater dependent upon the launch site location. A launch to a 34.5 inclination as opposed to 28.6 degrees inclination reduces the risk by a factor of 4. The overflight risk for an ISS launch from CCAFS is attributed to the greater population densities associated with overflight of Europe. Absolute risk values are sensitive to vehicle probability of failures and debris casualty areas which are unique to each operator depending upon their level of experience and the type of vehicle they plan to put into service.

Table 7: Summary of Over-flight Results 51.6 degrees inclination Compared to Africa Baseline

Launch Location	Ratio
CCAFS Africa Baseline 28.6	1.0
CCAFS Africa 34.5	0.23
CCAFS 51.6	4.0
Wallops 51.6	1.6

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VIII. Acronyms

CFR – Code of Federal Regulation
COTS – Commercial Orbital Transportation Services
IIP – Instantaneous Impact Point
ISS – International Space Station
TAOS – Trajectory Analysis and Optimization Software
FAA – Federal Aviation Administration
AST – Office of Commercial Space Transportation
RRAT – Range Risk Assessment Tool (RRAT)
DOF – Degree of Freedom
RESOLV – Risk estimator for suborbital and orbital launch vehicles
GPW – Gridded population of the world
ELV – Expendable launch vehicle

IX. References

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