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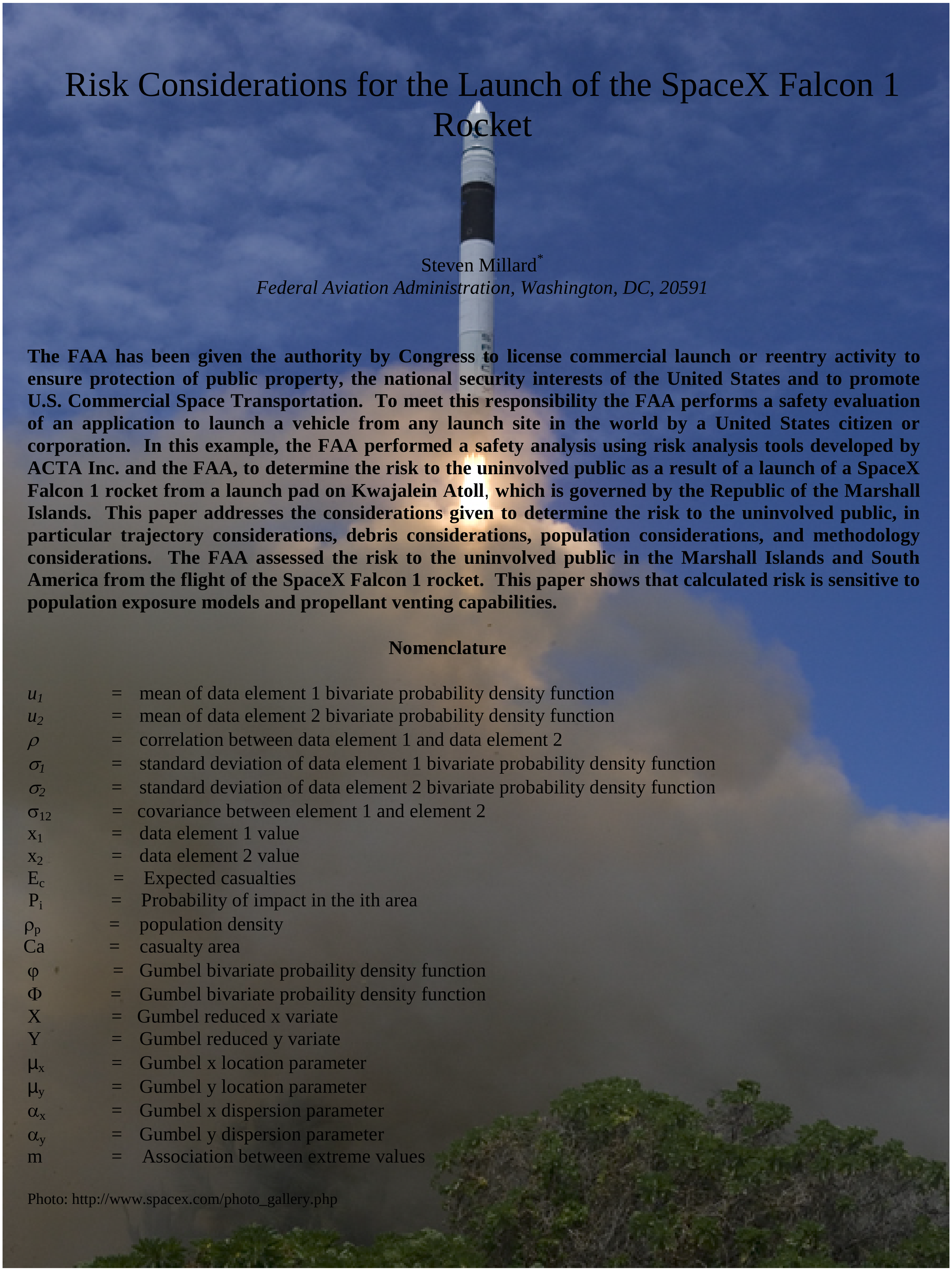

Risk Considerations for the Launch of the SpaceX Falcon 1 Rocket

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The FAA has been given the authority by Congress to license commercial launch or reentry activity to ensure protection of public property, the national security interests of the United States and to promote U.S. Commercial Space Transportation. To meet this responsibility the FAA performs a safety evaluation of an application to launch a vehicle from any launch site in the world by a United States citizen or corporation. In this example, the FAA performed a safety analysis using risk analysis tools developed by ACTA Inc. and the FAA, to determine the risk to the uninvolved public as a result of a launch of a SpaceX Falcon 1 rocket from a launch pad on Kwajalein Atoll, which is governed by the Republic of the Marshall Islands. This paper addresses the considerations given to determine the risk to the uninvolved public, in particular trajectory considerations, debris considerations, population considerations, and methodology considerations. The FAA assessed the risk to the uninvolved public in the Marshall Islands and South America from the flight of the SpaceX Falcon 1 rocket. This paper shows that calculated risk is sensitive to population exposure models and propellant venting capabilities.

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 = casualty area
φ = Gumbel bivariate probaility density function
Φ = Gumbel bivariate probaility density function
X = Gumbel reduced x variate
Y = Gumbel reduced y variate
μ_x = Gumbel x location parameter
μ_y = Gumbel y location parameter
α_x = Gumbel x dispersion parameter
α_y = Gumbel y dispersion parameter
m = Association between extreme values

Photo: http://www.spacex.com/photo_gallery.php

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I. Introduction

The 3rd and 4th SpaceX Falcon 1 launch vehicles are scheduled to be launched from Kwajalein, Marshall Islands during the third quarter of the 2008 calendar year. Although these launches are overseas, SpaceX represents a United States corporation and therefore is subject to the regulations specified in 49 United States Code Chapter 701—Commercial Space Launch Activities and Code of Federal Regulations Chapter III—Commercial Space Transportation, Federal Aviation Administration (FAA), Department of Transportation[1]. To meet the FAA's responsibility to the public the FAA routinely performs an independent safety analysis of a launch operator's license for launch activity to determine if the launch operations create undue risk to the uninvolved public. The FAA uses contractor and in house tools to assess the risk of the launch of a launch vehicle. This paper addresses some of the considerations for risk assessment by using the ACTA Inc. Range Risk Assessment Tool (RRAT) and the FAA in house Risk Estimator for Suborbital Launch Vehicle (RESOLV) tool. The FAA tool RESOLV can assess risk for any flight in which a stage will reenter and impact the Earth's surface. Figures 1 and 2 depict the regions of interest where the Falcon 1 will launch and overfly.

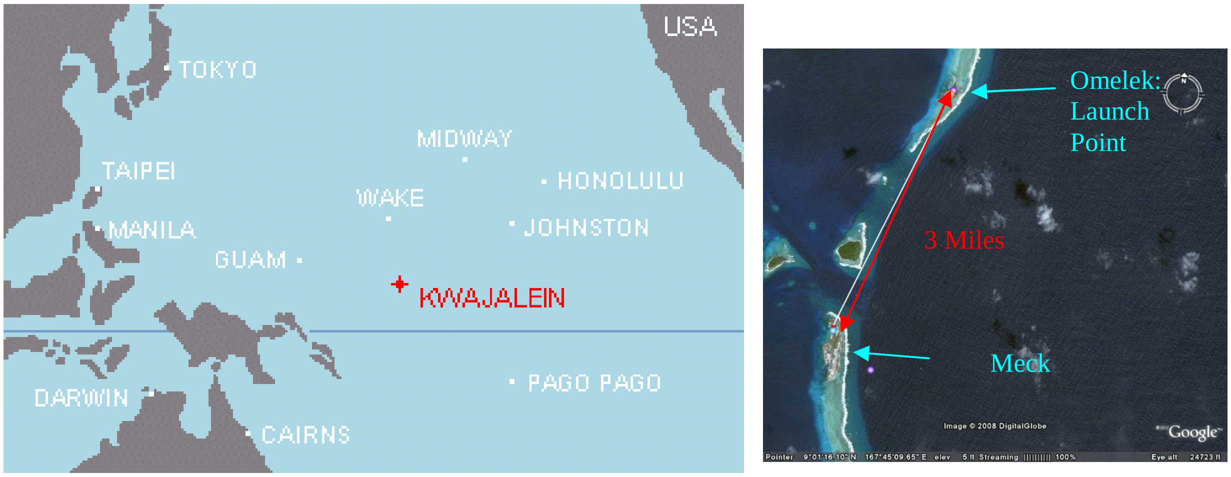

Figure 1. Region of Interest for Assessment of Falcon 1 Risk

Figure 2. Region of Interest for Assessment of Falcon 1 Risk

II. Objective

Identify some of the key considerations for performing launch area and over-flight risk assessment of launch vehicles and contrast and compare risk assessment tools ACTA RRAT and RESOLV using consistent trajectory inputs.

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) section 413.3 addresses who must obtain a license or permit and states that a person who is 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. SpaceX launches from Reagan Test Site fall into this category. 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. This assessment only considered inert debris, however part 417 also has considerations for explosive blast and 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.

“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. Method of Analysis

A. Risk Determination

The method for this analysis was to generate Monte Carlo 6-Degree-of-freedom (Dof) malfunction trajectories using the representative geometry, mass properties, propulsion, aerodynamics, winds, and dispersions provided by SpaceX in its license application. Malfunction turn trajectories were generated by introducing a desired thrust vector gimbal offset and direction at a specified failure time in the launch area or over-flight (557 seconds) portion of the flight prior to orbital insertion. A single over-flight time was examined for ease in comparison between methods and tools and this particular time was selected because it corresponds to the greatest contributor to E_c, in the over-flight region. The malfunction turn trajectory was flown for an additional 5 seconds in the first stage launch area and 15 seconds in the over-flight area beyond the simulated failure time, at which time a thrust termination was modeled. This practice is consistent with Reagan Test Site and SpaceX practice for modeling range safety delays. After the thrust had been terminated the vehicle was allowed to fly to impact conditions using a 3-Dof simulation that modeled drag aerodynamics. The trajectory simulation tool used for this analysis was TAOS[2], developed by Sandia Laboratories. Risk analysis tools using the TAOS state vector outputs were run to determine risk to the public. Risk was determined as the number of expected casualties resulting from malfunction failures at the prescribed failure time.

1. Rocket Trajectory Modeling

Representative geometry, mass properties, propulsion, aerodynamics, wind dispersion, and malfunction dispersions for the Falcon 1 were modeled to determine a baseline nominal trajectory and malfunction turn trajectories. The nominal trajectory created by the FAA was compared to a reference nominal trajectory supplied by SpaceX and deemed to be an acceptable match. The FAA generated its own nominal trajectory to provide an independent check of the Falcon 1 nominal trajectory as well as to serve as a baseline for this sensitivity analysis.

2. Inert Debris Casualty Area Modeling

Casualty area was determined by investigating the size of the failed reentering Falcon 1 vehicle. The weight of the vehicle at the point in the second stage over-flight where a failure occurs was modeled as 2200 lbs. The size of the second stage Falcon resulted in an inert casualty area of 429 square feet. This casualty area accounts for variation in casualty area due to angle of incidence of impact, bounce, splatter, and skip. The explosive casualty area was determined using the RRAT explosive debris model and overpressure models that consider the amount of propellant at impact and the velocity of impact[3,4].

3. Population Modeling

The population in the first stage area of the Falcon 1 trajectory was obtained using the Landscan Oceania (2005) database at a resolution of 30 seconds of arc. The population for the over-flight area of South America, which included the Galapagos Islands, was modeled using the Gridded Population of the World (GPW) database[5]. The GPW data was obtained at resolutions of 60 minutes and 15 minutes to determine the sensitivity to gridded population resolution for the over-flight.

4. Statistical Modeling of Probability of Impact

For the first stage launch area RESOLV made use of a bivariate normal distribution. For second stage over-flight failure at 557 seconds, two statistical models were investigated. The first used a bivariate normal distribution defined by the equations below.

i. Bivariate Normal

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

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

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

Preliminary analysis of the impact data showed that a bivariate normal distribution may not be statistically reasonable as demonstrated in Figure 3. In this figure a normal distribution is represented by the dashed line. Deviations of the downrange (X) position at the low and high ends of the probability range indicate that a normal distribution is not a good fit of the trajectory data at this point. The use of a normal distribution overestimates the probability of impact at the low downrange region and underestimates the probability of impact at the high downrange region.

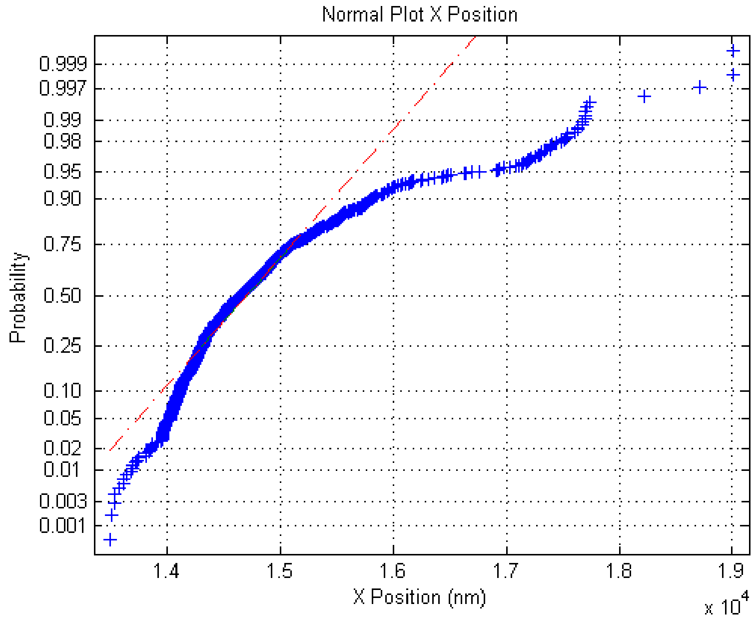

Figure 3. Probability plot downrange impact position for a normal distribution

The second statistical model investigated was an extreme value distribution, also known as a gumbel distribution. The equations identified below represent the gumbel distribution modeling.

ii. Bivariate Extreme Value (Gumbel)

$\varphi(X,Y,m) = \Phi(X,Y,m)[(\mathbf{e}^{-mX}+e^{-mY})^{1/m-2}\, \mathbf{e}^{-mX-mY}\{\, \mathbf{e}^{-mX}+e^{-mY})^{1/m} + m-1\}]$

$\Phi(X,Y,m) = \exp[-(\mathbf{e}^{-mX}+\mathbf{e}^{-mY})^{1/m}]$

$X=(x-\mu_x)/\alpha_x$

$Y=(y-\mu_y)/\alpha_y$

$\mu_x=xbar-\alpha x*xbar_n$

$\mu_y=ybar-\alpha y*ybar_n$

$\alpha_x=s_x/\sigma_n$

$\alpha_y=s_y/\sigma_n$

$m=[1-\rho]^{-1/2}$, where $m>1$

Figure 4 shows a probability distribution plot for an extreme value distribution for the same set of downrange impact points plotted in Figure 3. In Figure 4, the solid line represents the values associated with the fit of an extreme value distribution. Much better agreement between this distribution and the impact points is seen at the lower end of the range of probabilities. While there is some deviation at the upper end, the downrange (X) position values of the impact points exceed the values associated with the extreme value distribution, indicating that a higher probability would be associated with these points using this distribution. This indicates that the extreme value distribution appears to be a better model of the distribution of the downrange impact data and gives a more conservative distribution at the tails (high downrange position) of the data.

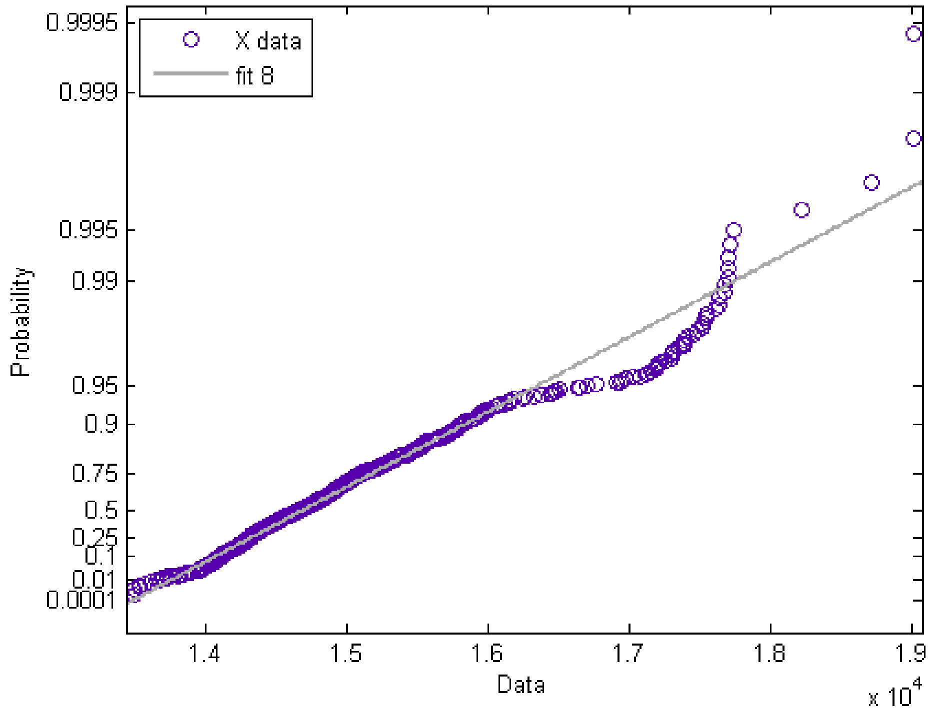

Figure 4. Probability plot downrange impact position for an extreme value distribution

5. E_c Modeling

Expected casualties were computed using equation 8 as illustrated below.

$$E_c = \Sigma P_i \times \rho_p \times Ca \tag{8}$$

The summation represents an integral over the region of impact. The FAA in-house tool RESOLV employed an integral approach using a fourth order two variable Runga Kutta and Trapezoidal integrator for the purpose of the analysis. The probability of impact was calculated as a function of impact position using the bivariate normal or bivariate extreme value distribution; the population data represented a matrix of cells of population density over the Pacific Oceania region and South America; and the casualty area represented a constant area of 429 ft^2 for inert debris and an equivalent RRAT explosive model for explosive debris based upon propellant yield and overpressure constants[4]. The combinations of probability of impact, population density, and casualty area were integrated over each population cell. Note that for this analysis only one time of flight, a failure at 557 seconds, which represented the greatest contributor to E_c, in the over-flight region, was investigated. In general practice, failure times every one second from the initiation of launch to orbital insertion would be investigated. The ACTA tool method used a summation of the individual contributions over each population cell to calculate E_c as shown in equation 8. RRAT has the option to use a feature that adds a user-defined covariance matrix or kernel density estimation (using the metric body axis data (MBOD) file) to the impact points and results in a distribution about all the known impact points. RRAT was investigated with and without this uncertainty method using the TAOS trajectories at impact.

6. *Probability of Failure*

The probability of failure was baselined at .72 for the Falcon 1's third flight, which is consistent with the reference value recommended in the FAA's guide to probability failure for new ELVs given the history of the first two SpaceX launches (both classified as failures). This information and knowledge of the staging time of 158 seconds and orbital insertion time of 569 seconds was used to determine a failure rate for the first stage and second stage (over-flight) portion of the trajectory. Consistent with RTI findings[6] a probability of failure 2/3 was also introduced for the first stage while a probability of failure of 1/3 was used for the second stage. The failure time per second was calculated as $3.038\text{x}10^{-3}$ per second for first stage and $5.83942\text{x}10^{-4}$ per second for second stage. The malfunction turn was assumed to be the only defining failure.

VI. Results

A. RRAT Assessment

1. *SpaceX Preliminary Flight Data Package Considerations*

The FAA performed a formal risk analysis of the entire flight regime of the Falcon-1 SpaceX mission using the application data supplied by SpaceX, which included the launch area and over-flight regions. This assessment showed the Falcon-1 to meet the expected casualty requirements imposed by 14 CFR parts 415 and 417 for debris. No attempt was made to duplicate these results in this ancillary independent analysis, however this independent analysis did provide additional insight in the FAA's formal SpaceX assessment. This independent analysis focused on risk in the launch area and a specific point in time, 557 seconds, and was used to gain insight into various risk considerations and assessment tools that AST uses. This independent risk analysis uses the FAA generated malfunction turn trajectories in the launch area and over-flight and the ACTA RRAT and AST RESOLV risk tools.

2. *FAA Trajectory Considerations for Over-flight at Failure Time of 557 seconds*

To obtain analysis results using representative Falcon trajectory data in its application, the FAA generated malfunction turns using the TAOS 6-DOF/3-DOF simulation capabilities to independently obtain analysis results using representative Falcon trajectory data. Ten thousand malfunction turn trajectories were generated, where the malfunction thrust angle was varied from 0 to 10 degrees (normal distribution) and the orientation of the thrust vector (uniform distribution) was varied using a Monte Carlo approach. In addition, 3 sigma winter winds were assessed also using a Monte Carlo approach to apply winds to the entering vehicle. The vehicle impact points assumed the vehicle would remain intact during entry and may contain propellant. It is realized that the vehicle would most likely not survive reentry, but an explosive impact was considered to be conservative. The ten thousand trajectories were input into RRAT as breakup state vectors at ground impact with and without the kernel density estimation method. Figure 5 shows the results in terms of expected casualties versus the number of Monte Carlo trajectories assessed, starting with one thousand trajectories and incrementing to ten thousand trajectories. In RRAT E_c is computed for each impact location and all associated population centers and summed for all impacts and all population centers. Figure 5 shows the RRAT results with and without using the kernel density estimation (KDE) approach. The data presented in Figure 5 shows that when using the KDE approach, the expected casualty converges quickly on a result of approximately 8x10^{-9} casualties at ten thousand trajectories for the baseline population resolution of 1 population cell for every 15 minutes of longitude and latitude. The dynamic trend in the data may be an artifact of using breakup state vectors at ground impact and the KDE method. Discussion with ACTA revealed that the KDE approach while feasible is considered a subpar approach relative to the capabilities of RRAT. ACTA suggested that the FAA implement breakup state vectors at the prescribed failure time using a guidance and performance state vector (GPSV) data file method which the FAA agrees is a more rigorous method to apply; however, due to the limitations of the FAA RESOLV tool, the FAA chose to use the KDE approach. The approach investigated by the FAA does suggest that reasonable and conservative results can be obtained by using breakup state vectors at impact and the KDE approach.

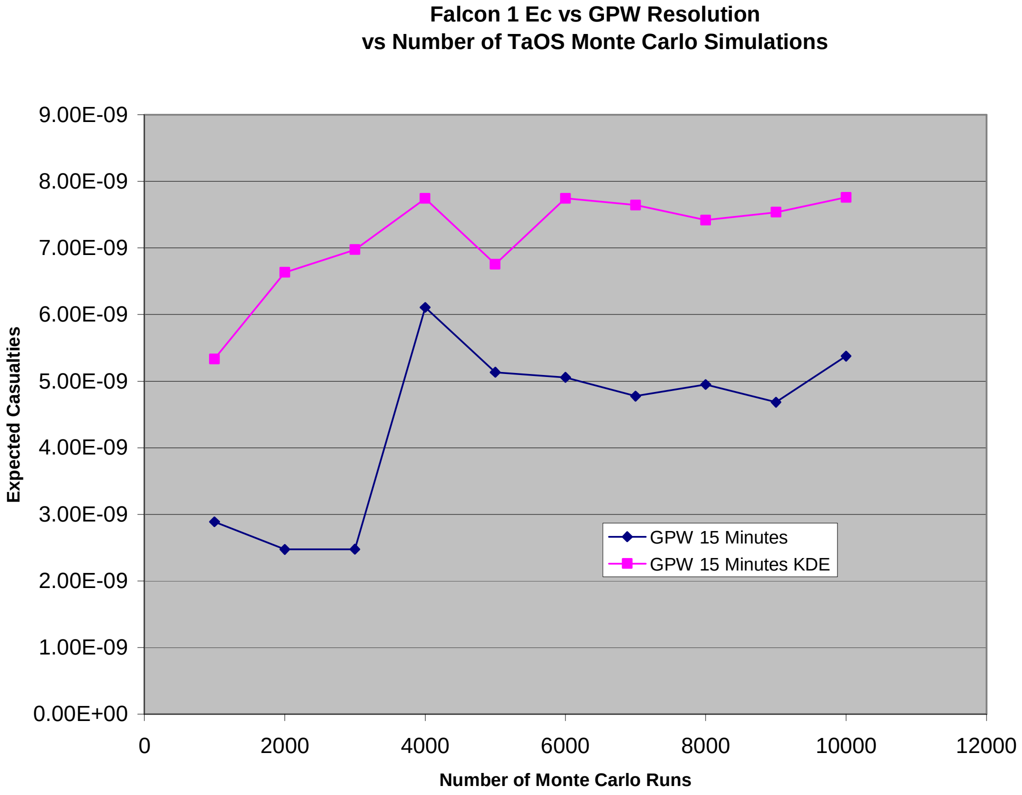

Figure 5. Expected casualty results versus number of Monte Carlo simulations at Failure time of 557 seconds (KDE approach).

Figure 6 shows the sensitivity of the results to the resolution of the population database. The analysis investigated a Gridded Population of the World database with a resolution of 15 minutes and 60 minutes over South America. The data shows that a lower resolution population grid results in a more conservative expected casualty. The assessment also shows that when using a KDE approach in combination with impact breakup state vectors one can obtain stable and reasonable results as the number of TAOS Monte Carlo simulations is increased.

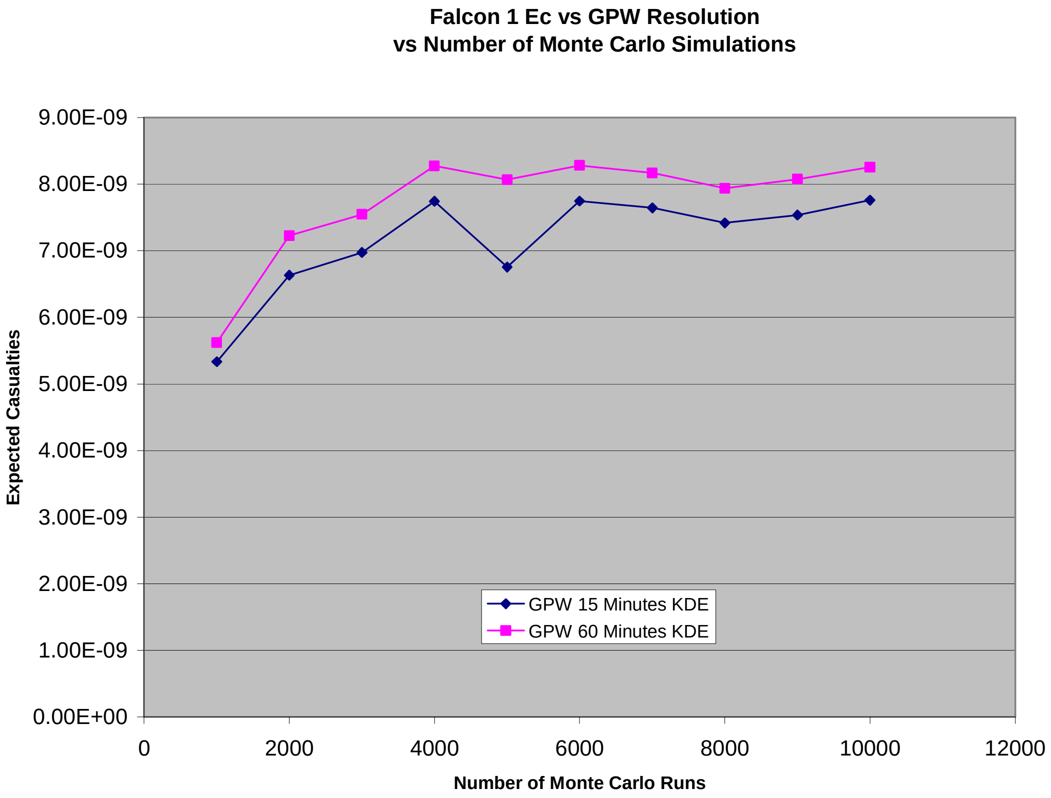

Figure 6. Expected casualty results versus number of Monte Carlo simulations and population resolution at failure time of 557 seconds (KDE approach).

B. RESOLV Assessment

1. Number of Monte Carlo Simulations Considerations

The second evaluation tool assessed was the RESOLV developed in house by the FAA. This tool uses a statistical method to calculate risk: the statistical parameters are determined from the impact trajectories, the population is input as a grid, and the casualty area is input as a constant or a value representing the impact propellant and explosive yield factor and an overpressure constant[4]. Note that all the trajectories are calculated from an external simulation tool such as TAOS. Also note that the same ten thousand trajectories used in the RRAT analysis were used in this assessment as well as the same population grid and inert casualty area (the casualty area modeling for explosive debris was considered to be equivalent). This was done in attempt to perform analysis where inputs are nearly identical allowing for investigation of the different methodologies associated with these two tools. Figure 7 shows the expected casualties versus number of Monte Carlo trajectories with the previous KDE (MBOD input) approach results as reference. The data shows that the KDE approach produces more conservative results than RESOLV as the number of TAOS Monte Carlo runs is increased.

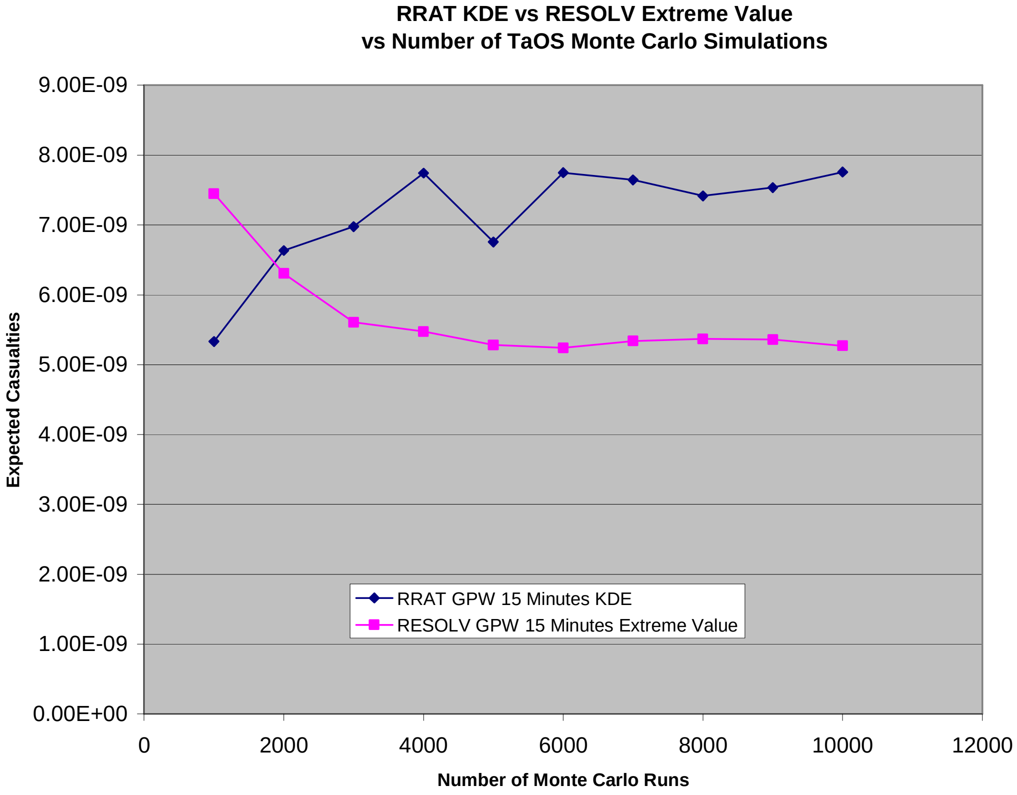

Figure 7. Comparison of RESOLV and KDE E_c results vs number of Monte Carlo runs

2. Population Grid Considerations

The effect of population density was investigated for the RESOLV assessment. Two population data sets were investigated, one at a resolution of 60 minutes and the other at a resolution of 15 minutes. Figure 8 shows the results in terms of expected casualties for one thousand to ten thousand Monte Carlo trajectories. The results show that a lower resolution database produces a more conservative expected casualty. Even though the population density is lower, a specific integration occurs over a larger area and results in a higher E_c since neighboring grids for a lower resolution population data tend to have greater population than neighboring grids for a higher resolution population data. This is similar to the trends observed with the RRAT tool using the breakup state vectors at impact and the KDE (MBOD input) approach.

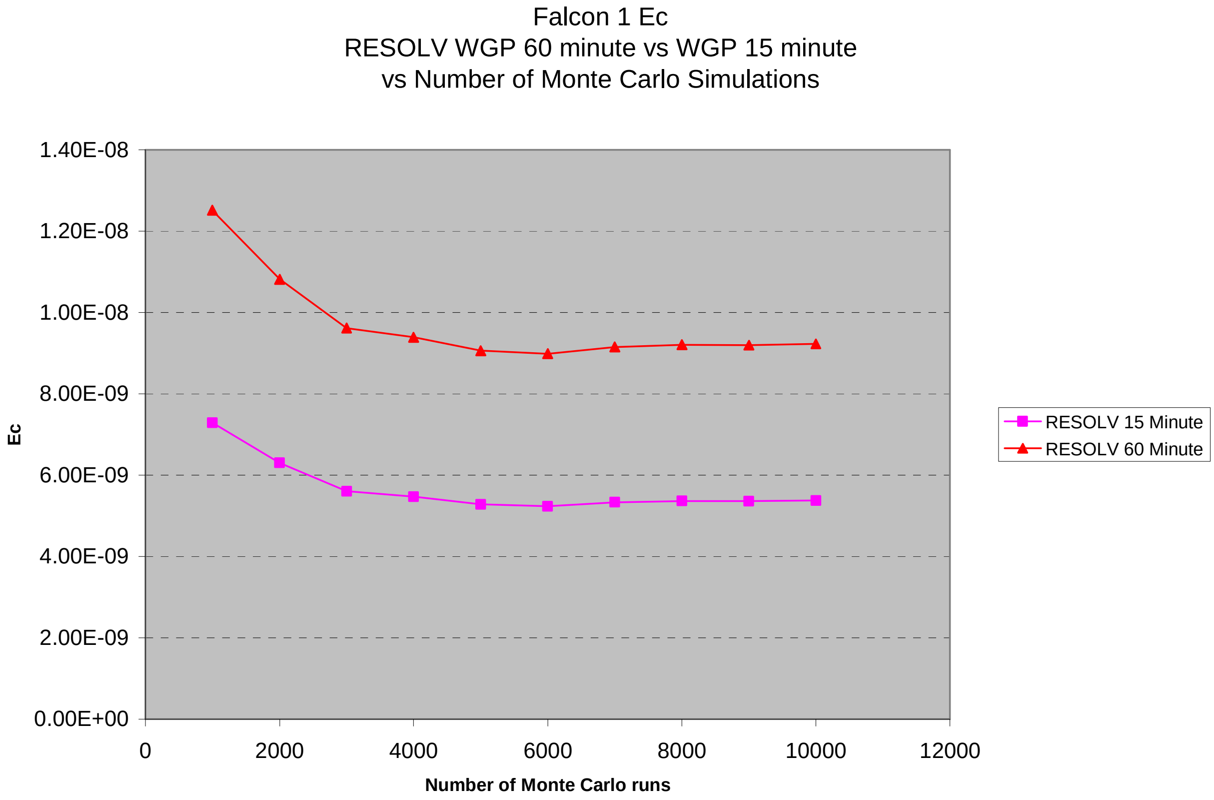

Figure 8. RESOLV GPW 60 minute versus GPW 15 minute, extreme value distribution

3. *Normal versus Extreme Value Distribution Considerations vs KDE method*

The results obtained with a bivariate normal and extreme value are contrasted. Figure 9 depicts the results using a bivariate normal and a bivariate extreme value distribution. It should be noted that the bivariate normal is not a good fit of the Falcon 1 over-flight impact data, as addressed in Figure 3, and when used as a statistical method for determining probability of impact, produced fewer expected casualties than the extreme value statistical distribution. Assessment of the probability density function contours per square foot for the two statistical methods presented in Figure 10 and Figure 11. The data shows that the bivariate normal results in a lower probability density function over the critical region of interest: populated areas, when compared to the extreme value distribution as seen by the extreme probability contours shown in Figure 10 and 11 at 10^{-19}. The extreme value distribution appears to be more representative of the actual distribution of the impact points. As a result of this analysis, the FAA concludes that for this example the extreme value presents more conservative results. The FAA suggests that risk analysts should carefully evaluate their data to ensure proper distributions are modeled when using statistical methods to determine probability of impact.

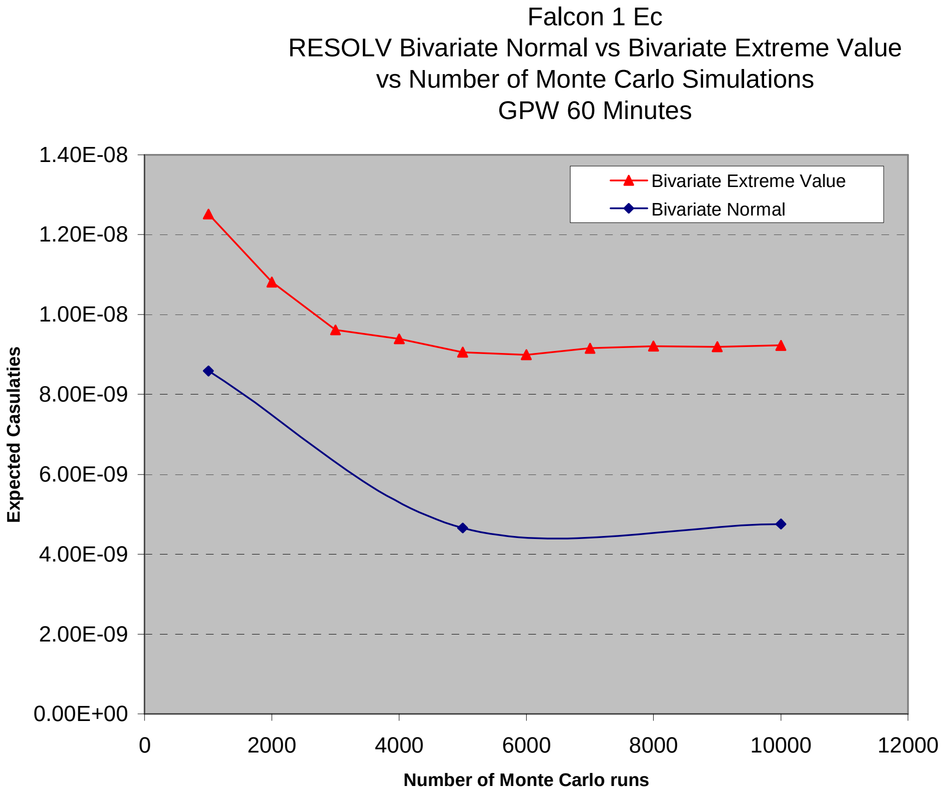

Figure 9. RESOLV comparison of E_c using bivariate normal and bivariate extreme value

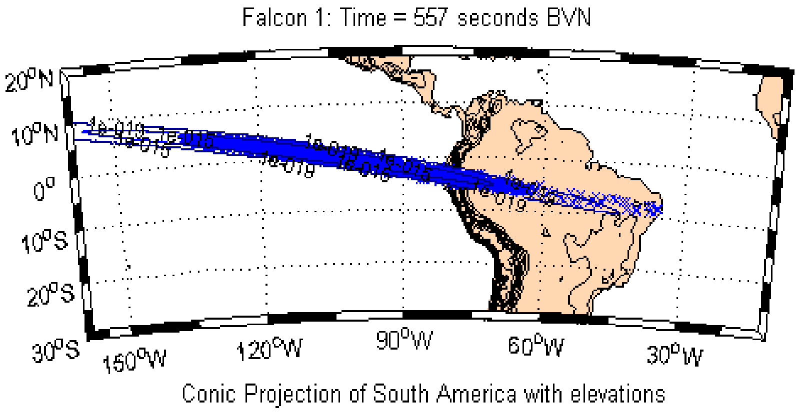

Figure 10. Probability Density Contour for Bivariate Normal

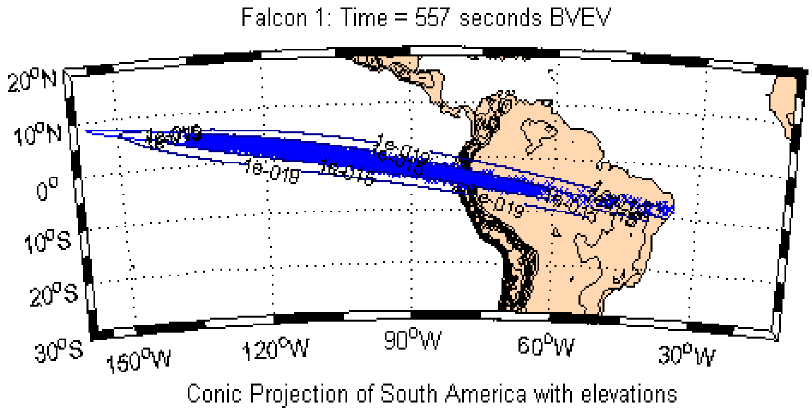

Figure 11. Probability contours for extreme value distribution

Figure 12 shows the impact points resulting from the ten thousand trajectory simulations as plotted by the RRAT processor. The probability of impact for each trajectory is the same using the RRAT breakup state vector method. However, using a subjective method that disperses each trajectory point applying a covariance matrix or KDE to the impact points, a composite probability density contour per square-foot based upon these dispersed trajectories can be created as shown in Figure 12. This probability density function shows the probability of impact for any one trajectory as a function of impact position and is comparable to the probability density functions calculated with the RESOLV tool using the bivariate normal and the bivariate extreme value distribution. Note the similar agreement between the RRAT probability density function using the KDE method and the bivariate extreme value using a statistical method. Using the KDE method the FAA calculated an E_c of $7.8x10^{-9}$ casualties compared to the RESOLV calculation of $5.9x10^{-9}$. The difference between the KDE and RESOLV risk values seem to be due to the greater probability density function that results when using the KDE method. The FAA investigated several values for the kernel density estimator and felt that the data presented in figure 12 was a valid use of the kernel density estimator; no attempt was made to optimize the KDE method to improve the agreement between the KDE results and the RESOLV results. This is still good agreement between the two risk tools given the population, casualty area, and trajectories were all controlled inputs common to both tools.

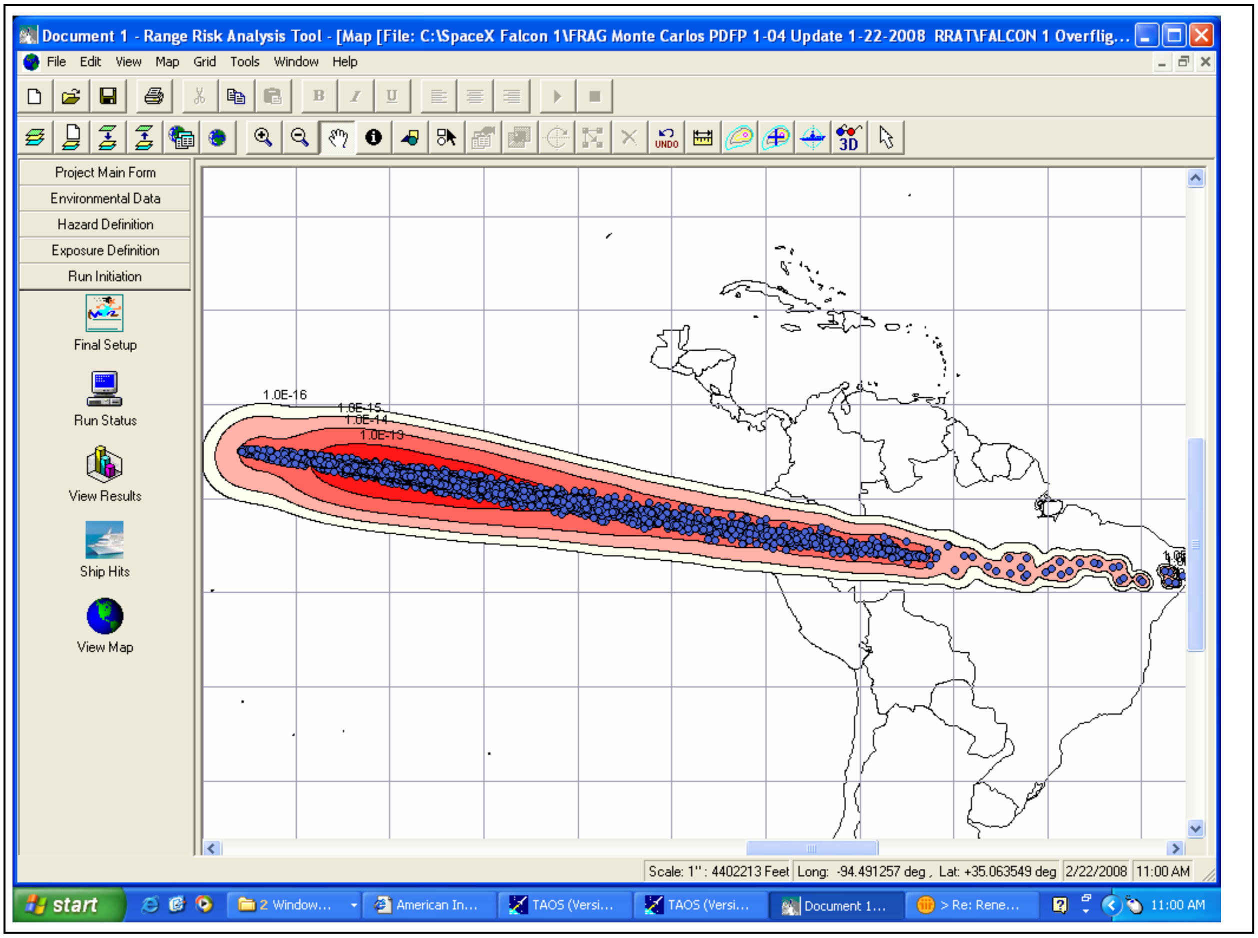

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Figure 12. Impacts and probability contours using FAA malfunction turns and KDE option at a failure time of 557 seconds.

4. *Sensitivity to Population Exposure and Explosive Impact*

In this analysis, the FAA examined two exposure models for over-flight assuming that the second stage would remain intact and impact with as much as 400 lbs of propellant and as little as 190 lbs of propellant. For the first stage flight the FAA only considered explosive impact with no propellant venting. The first sheltering model assumed that all of the people would be unsheltered and in the open. In this model an overpressure of 10 psi is considered to produce a casualty from inner organ trauma[3]. The second sheltering model assumed that the population would be sheltered in a typical single family residence consisting of a wood frame and about 30 percent windows. Glass breakage can produce a casualty at an overpressure as low as 1. For the first stage flight and over-flight assessment, the conservative sheltering model considering explosive debris was found to increase the expected casualties by a factor 10 to 20 depending upon whether the RRAT or RESOLV tool was used. Examination of the propellant yield factors used by RRAT and RESOLV showed that RESOLV used a greater propellant yield factor, by a factor of 2, than RRAT. For the over-flight assessment modeling explosive debris as opposed to inert debris resulted in a factor of 3 increase in expected casualties. When the sheltering of the population is uncertain the FAA would suggest that the risk assessment consider the more conservative sheltering model as opposed to the unsheltered model. In addition, if it is not clear that the over-flight reentry will result in a breakup of the vehicle prior to ground impact, the risk assessment should consider explosive debris as opposed to inert debris.

C. Launch Area Assessment

The FAA used the KDE method and RESOLV tools to examine the risk to the public in the launch area using the Landscan population for the Oceania area. Figure 13 shows the impact locations for each of the malfunction turn trajectories evaluated from 6 to 66 seconds after launch. After 66 seconds the launch area risk was insignificant. Only one thousand Monte Carlo malfunction turns were run for each failure time due to database size considerations. The probability of impact contours shown are per square foot area. Comparison of the results obtained with RRAT using an KDE method and RESOLV as seen in Figures 14 and 15 show a similar trend for expected casualties versus failure time and approximately the same number of total expected casualties of $17\text{x}10^{-6}$ using the sheltering model and assuming that none of the propellant would be vented and that the vehicle would impact intact. The six second time skew in the KDE and RESOLV results is a consequence of the time reference used in the RRAT assessment. This expected casualty assumes the malfunction turn is the only failure. Research Triangle[7] Institute has shown the probability of a malfunction turn trajectory failure in the first stage could be as low as .21, which would reduce the expected casualties considerably. The Landscan population data considered as many as 300 public on the islands. An additional mitigation measure for Falcon 1 is that only 10 mission essential personnel will be on any island within the impact contours and that these people will be in sheltered bunkers. With these considerations in mind the expected casualties to the public in the launch area become less than $1\text{x}10^{-9}$ casualties.

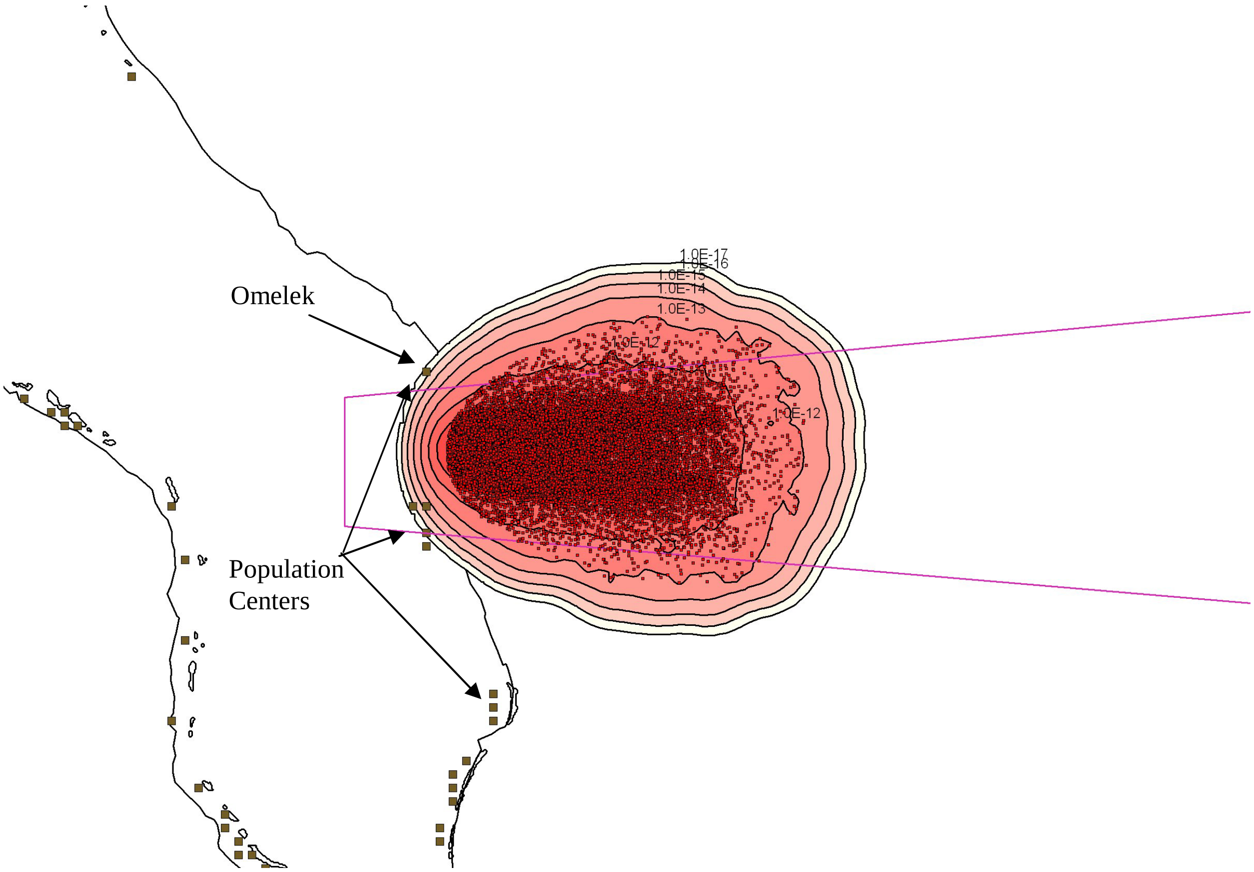

Figure 13. Falcon 1 launch area impact and contours using FAA malfunction trajectories and KDE.

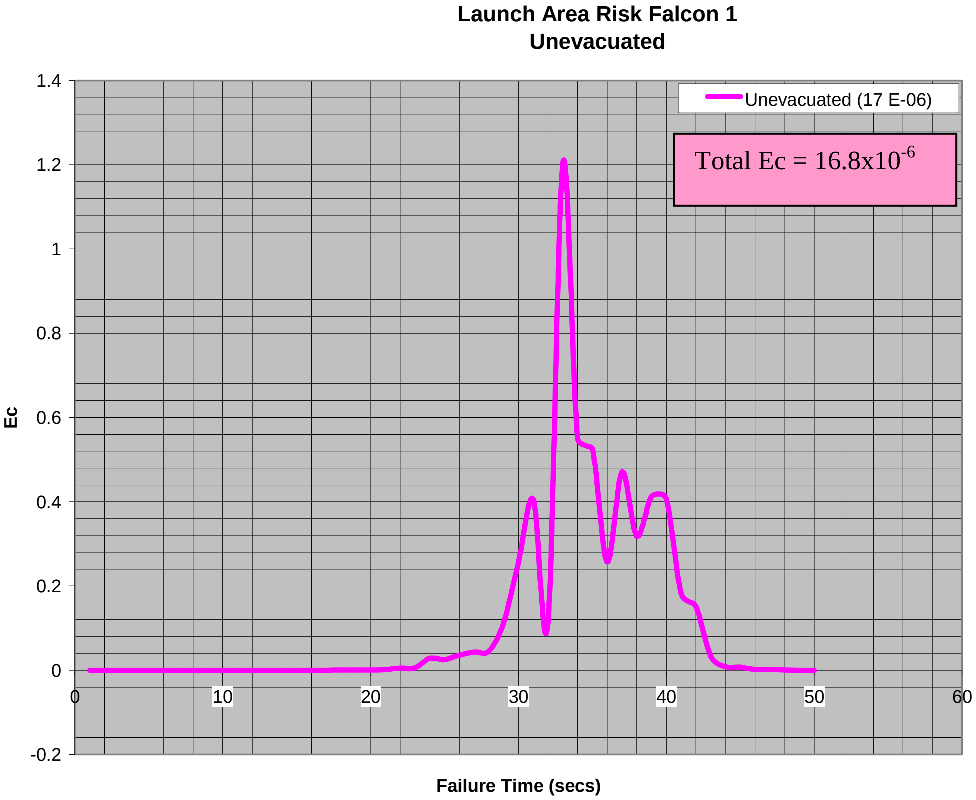

Figure 14. KDE launch area expected casualties versus failure time

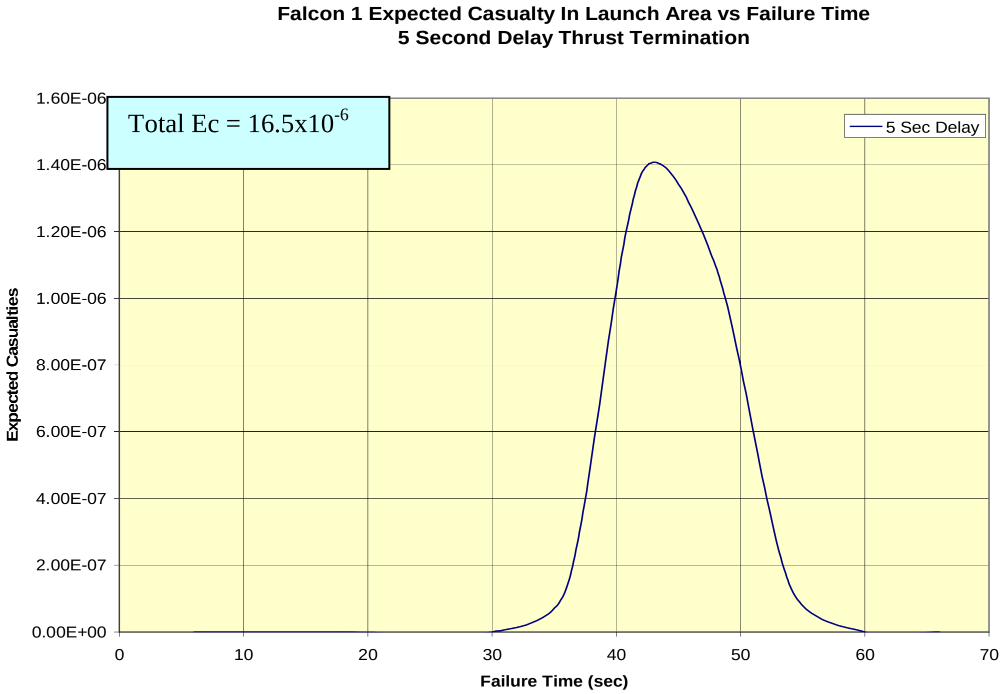

Figure 15. RESOLV launch area expected casualties versus failure time

D. First Stage Over-Flight Assessment

The author observed that the flight path of the Falcon 1 nominal first stage trajectory caused it to pass over the Atoll Islands of Erikub and Maloelap for failure times from 115 to 130 seconds. Assuming explosive debris and a sheltering model, the FAA calculated an expected casualty of 570×10^{-6}, assuming a malfunction turn as the only failure, as shown in Figure 16. Further examination of the Island of Erikub and Maloelap showed that Erikub is visited but does not contain any dwellings and that the population on the Island of Maloelap should be considered as unsheltered reducing the expected casualties by a factor of 20. Thus the only real consideration for expected casualties is Island of Maloelap. A further reduction in expected casualties is realized if one considers the probability of a malfunction turn failure as .21 as Research Triangle Institute suggests. With these considerations a reasonable value of expected casualties to the uninvolved public in the first stage launch area is 6.0×10^{-6} casualties.

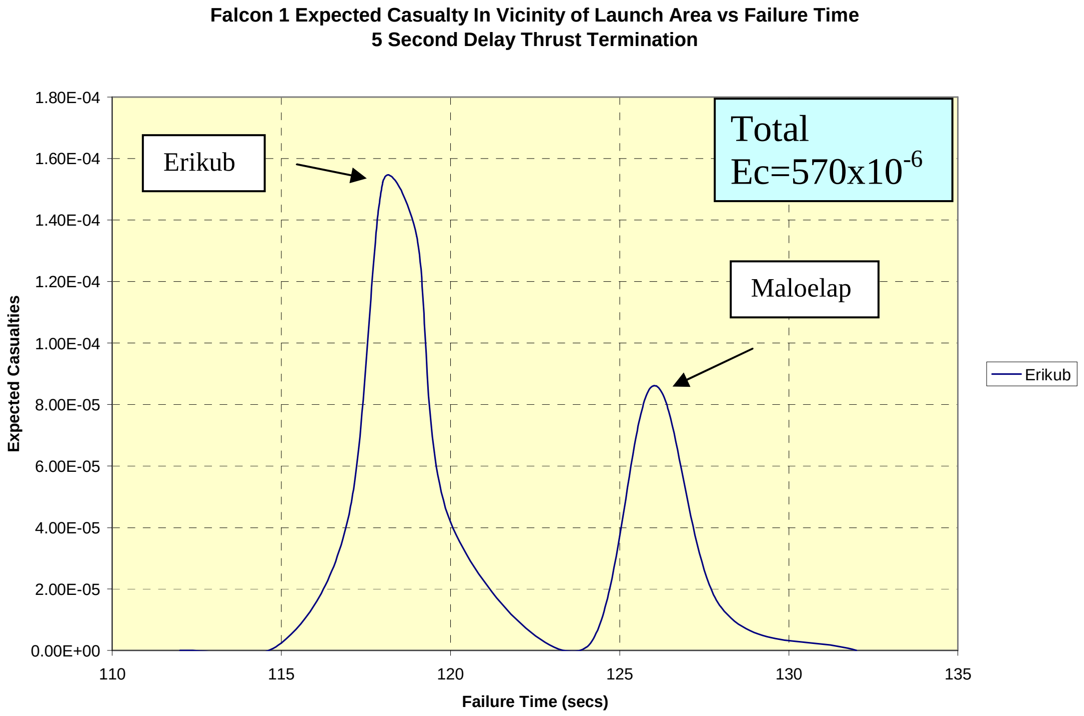

Figure 16. RESOLV first stage over-flight expected casualties versus failure time

VII. Conclusion

This assessment shows that the RESOLV and the RRAT tool (when using a KDE with TAOS input trajectories at ground impact), produce stable and comparable results when investigating over-flight and launch area risk using controlled inputs. Lower resolution population grids were shown to produce more conservative risk values when using the RESOLV and RRAT tools. At the failure time investigated, 557 seconds, both methods calculated risk values of around 1×10^{-8} casualties for inert debris and open sheltering. A risk assessment tool, such as RESOLV, using a bivariate normal distribution may produce less conservative risk for vehicles such as the Falcon 1 in the area of over-flight when compared to a bivariate extreme value distribution when using the RESOLV tool.

Analysis is sensitive to sheltering and the intact explosive debris, increasing the launch area risk by a factor of 20 when a sheltering model is considered and the second stage over-flight risk by a factor of 3 when explosive debris model is considered. In the first stage launch area assessment, measures to evacuate populations from nearby islands and limit essential personnel significantly reduces risk to acceptable values. When one considers the combined risk for second stage over-flight, launch area, and first stage over-flight and reasonable assumptions about sheltering and the probability of a malfunction turn, the assessment shows that the only significant contributor to risk is the Atoll of Maloelap.

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VIII. Acronyms

CFR – Code of Federal Regulation
TAOS – Trajectory Analysis and Optimization Software
FAA – Federal Aviation Administration
AST – Commercial Space Transportation Office
RRAT – Range Risk Assessment Tool (RRAT)
DOF – Degree of Freedom
KDE – Kernel Density Estimation
MBOD – Metric body axis data file
GPSV – Guidance and performance state vector data file
RESOLV – Risk estimator for suborbital launch vehicles
GPW – Gridded population of the world
ELV – Expendable launch vehicle

IX. References

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