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Evaluating a Complex Debris Dispersion Model Using Experimental Design Techniques

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I. Introduction

Over the past several years there has been a steady increase in space launch operations and forecasters conservatively predict slight growth in future launch rates. New technologies, national security, and the development of new markets in the commercial space transportation industry could further accelerate this growth. Although the September 11, 2001 attacks have reduced the current level of operations, the FAA expects the long-term growth in air travel to resume in the 2004 to 2013 timeframe.[1] These trends will require a safe and efficient integration of both air and space transportation vehicles operating in shared airspace.

The Federal Aviation Administration (FAA) and NASA are developing operational concepts that will seamlessly integrate air and space launch/reentry operations while ensuring that the highest levels of safety, security, and efficiency are maintained. The current procedure for ensuring aircraft are safely distanced from the spacecraft during a launch is to restrict all air traffic from flying in a very large region of Special Use Airspace (SUA) and/or Altitude Reservations (ALTRV) within the range.[2] Figure 1 presents a debris hazard zone within a hypothetical SUA/ALTRV. During a launch, aircraft that would normally fly through this airspace simply take a longer, alternate route to their destination. This procedure accommodates today's launch rates and the air traffic around the launch site. However, this procedure will probably not be acceptable if launch rates significantly increase, or when

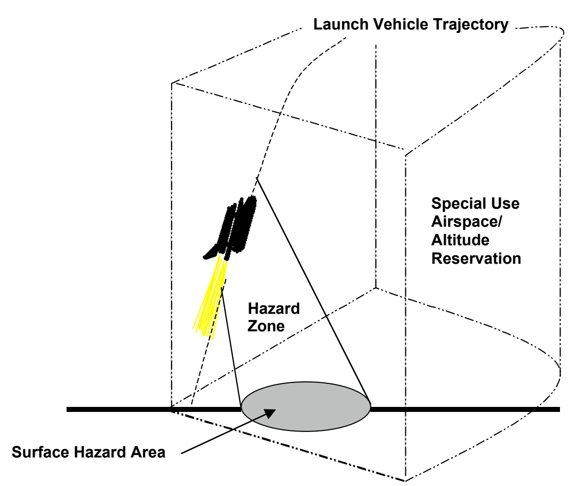

Fig. 1 Conceptual illustration of a launch hazard zone within a hypothetical SUA/ALTRV.

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there is a greater demand for this airspace to accommodate growth in air travel. To accommodate these growing demands on National Airspace System (NAS) capacity, air and space transportation system developers and integrators will need to investigate the impact of space launch and return operations on surrounding air traffic.

A range has many command and control systems that monitor a large surface area and region of airspace surrounding a launch site, up to where a space vehicle enters orbit. For launches at Kennedy Space Center and Cape Canaveral, range safety is maintained from the Range Operations Control Center (ROCC) located at Cape Canaveral Air Force Station.[2] To calculate and help manage risks within the range, range operators use the Common Real-Time Debris Footprint (CRTF) program.[3] The CRTF program can model debris dispersion, which can result from a catastrophic failure of the launch vehicle. The debris model calculates the motion, fragment distribution, impact locations, and hazard areas associated with debris falling within a finite area. Using the space shuttle as an example, this paper applies experimental design techniques in the study of the CRTF debris dispersion model. The methodology and results from this analysis could be used in launch system design, airspace and air traffic decision support tool design, and for developing and evaluating range safety procedures.

II. Debris Model Description

Debris dispersion is a key safety consideration for a launch decision and understanding the vehicle design characteristics, atmospheric conditions, and other factors that can affect a hazard area is very important to range operators. In general, a debris dispersion model calculates the motion, size distribution, and the impact probabilities and risks associated with debris resulting from a catastrophic failure or intentional destruction of a launch vehicle. The CRTF debris dispersion model is based on launch vehicle velocity, weight, explosion energy, and other physical and aerodynamic characteristics of the debris. Other factors such as vehicle design, wind, and launch trajectory affect the output of this model. The CRTF program is composed of six uncertainty models that estimate the free-fall dispersion and impact location of debris fragments resulting from a vehicle breakup. Of the six uncertainty models, four models employ a Monte Carlo technique to generate a Gaussian distribution of random samples. The CRTF program includes the following six models:[4]

1) A real-time vehicle state vector that contains position and velocity uncertainty (metric tracking error) for three orthogonal axes and six degrees-of-freedom (Monte Carlo).

2) Tumble-turn course changes that can be caused by flight control malfunctions or other events that cause vehicle trajectory uncertainties prior to breakup (Monte Carlo).

3) Explosion velocity uncertainty of fragments along three orthogonal axes (Monte Carlo).

4) Ballistic coefficient uncertainty for each fragment type that is defined by fragment size and shape, which determine the drag effects during free-fall (Monte Carlo).

5) A lift force model used to predict two impact points for each fragment; one for zero lift and one for constant lift.

6) Wind measurement uncertainties.

These uncertainties are applied to the input variables used in the model's deterministic equations. The input variables being studied include:

A. Wind
B. Metric Tracking Error (vehicle state vector)
C. Fragment ballistic coefficient
D. Fragment lift-to-drag ratio
E. Initial explosion velocities of the fragments
F. Altitude of vehicle at failure

The predicted debris impact area from CRTF is the primary output used in this analysis. The size of the impact area, called the "hull" in the CRTF program, is the area contained by impact ellipses that are calculated from the uncertainty matrices for each fragment type. Fragment types or categories define how major vehicle components are expected to breakup. For example, the space shuttle has about 50 fragment types for which lift-to-drag ratios can range from between 0.00 (sphere-shaped) and 0.05 (flat plate) (Ref. 4). This fragment data, which is provided by the launch vehicle manufacturer, is defined by variables C, D, and E in the previous list. Variables A and B are measured, and variable F is selected for arbitrary altitudes between 20,000 and 41,000 ft were used, which are typically within en route airspace. For the debris analysis, shuttle mission parameters for STS-75 were applied. The launch site was located at Kennedy Space Center with a launch azimuth of 90 deg (due east).

III. Analysis

For the six variables of interest in studying the debris model, 64 (2^6) independent runs were required for a two-level full factorial analysis. Each experiment run contains a set of different combinations of high and low values, such as {++++++, -+++++, +-++++,…}. Each variable, and all possible combination of variables {A, B, …, AB, AC, …, …, ABCDEF} were evaluated for main effects and interaction effects. The results were evaluated for statistical significance using analysis of variance (ANOVA) techniques. For the analysis, it was assumed that factor variations have a Gaussian distribution, not all factors exert the same influence on the output, and the prediction equation satisfies normality and independence.[5]

The predicted debris impact area (miles^2) is the primary output used in this analysis. Applying a two-level full factorial design, the CRTF debris model was run with the shuttle vehicle parameters, and the six input variables were analyzed for main effects and possible interaction effects. Table 1 summarizes the full factorial analysis results for the shuttle.

Table 1 Shuttle results of two-level full factorial analysis & t-test

Factors	Variables	Effect	Half Effect	t-Test $\|t\| > 1.67$	Null Hypothesis
A	Wind	1487.6	743.8	5.35	Reject
C	Ballistic Coefficient	-1044.0	-522.0	-3.83	Reject
F	Altitude	1387.8	693.9	4.85	Reject
AC	Wind & Ballistic Coef.	-677.1	-338.6	-2.08	Reject
AF	Wind & Altitude	886.4	443.2	2.80	Reject
CF	Ballistic Coef. & Altitude	-609.9	-305.0	-1.86	Reject

A two-tailed t-test evaluation of the null hypothesis (Ho: the factors do not affect the mean Hull area), with a 95 percent confidence level (T* = 1.67) was used to evaluate statistical significance.[5] The t-test was used to determine whether the differences in the means were truly caused by the factors, or if the differences resulted from inherent sampling variations in the model's uncertainty processes. To further illustrate these results graphically, Fig. 2 presents the normal probability plot of half effects for the shuttle.

From Fig. 2, variables that are off the normal probability line suggest the presence of real effects. The plot also shows the order of factors having the greatest influence on hull area. For the shuttle, variables A, C, and F produced the main effects, and two-factor interaction effects were found with AC, AF, and CF. From these results, which were also consistent with t-test results, the first order prediction equation was developed:

$$\_ = 1176.4 + 743.8A - 522.0C + 693.9F - 338.6AC + 443.2AF - 305.0CF$$

Using the first order prediction equation, a graphical analysis of the residuals, calculated from the predicted and observed values, were studied to evaluate the performance of the prediction equation. Figure 3 present the plots of residuals against predicted values.

Reviewing Fig. 3, residuals appear to fall within a horizontal band around zero, which indicates that predicted values are close to observed values. However, the residuals do not appear to randomly fluctuate around zero. This distribution suggests second-order effects are present. Although the first-order prediction equation produced a satisfactory value for R_a^2, further analysis is prudent to investigate the possible presence of second order effects.[5]

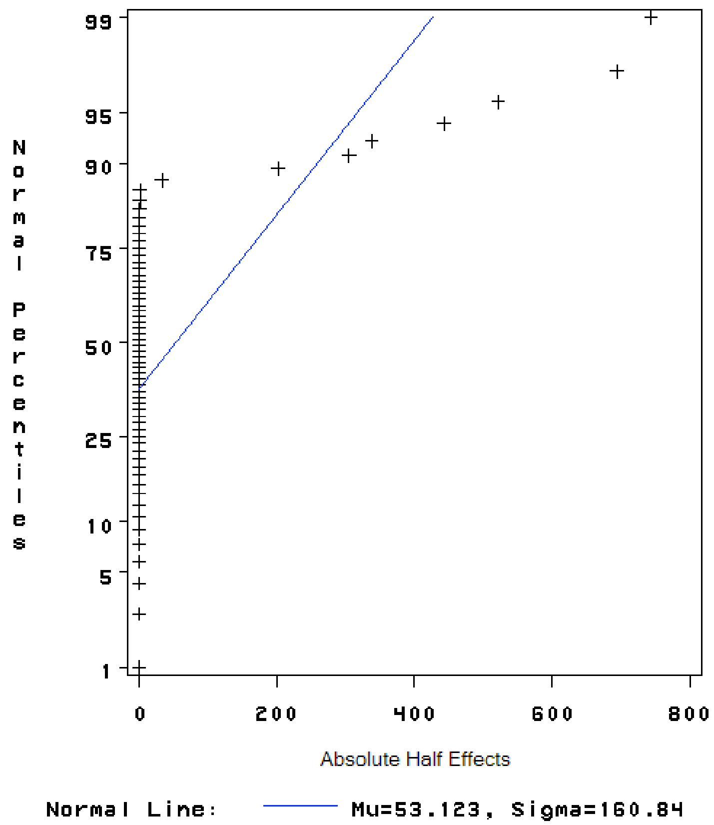

Fig. 2 Normal probability plot of half effects for the shuttle.

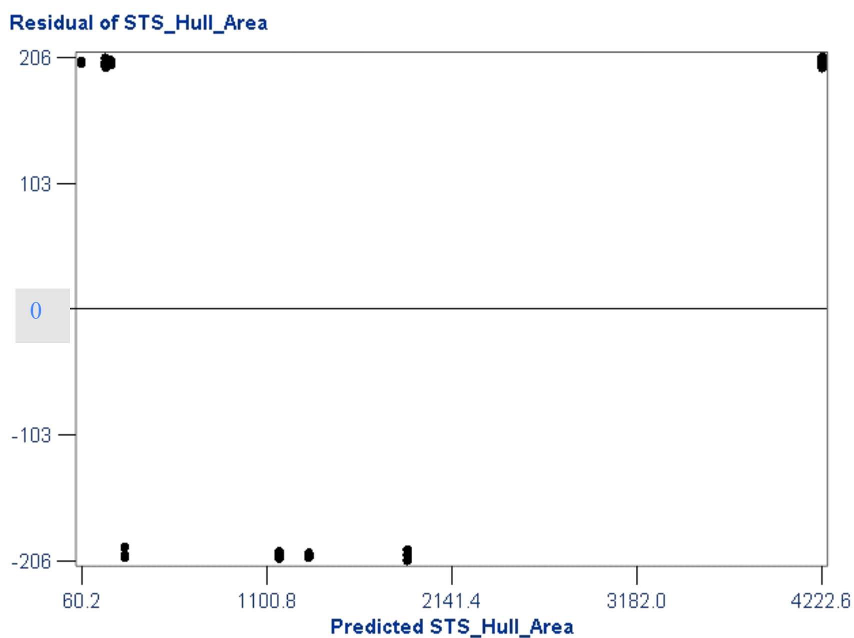

Fig. 3 Plot of residuals against fitted values for the shuttle.

IV. Second Order Analysis

Using the shuttle data for the second-order analysis, a second-order prediction equation was developed for the three variables (A, C, F) and two-factor interactions (AC, AF, CF) that exhibited real effects in the linear analysis. To verify that second-order effects were present, hull areas were plotted against each of the three levels for the three factors being analyzed. Figures 4-6 present the plots of the shuttle hull areas to identify second-order effects.

In Figs. 4-6, there is evidence that there are non-linear properties associated with at least two of the three factors. Plots of factors A and C have possible second-order effects, whereas factor F appears to be nearly linear. Based on these results and the previous first-order analysis, a second-order prediction equation was developed that contained the main effects A, C, and F, two-factor interaction effects AC, AF, and CF, and second-order main effects A2, C2, and F2. To generate the second-order prediction equation, additional data was gathered for a three-level full factorial design that required 27 (3^3) experimental runs.[5] The three factors were used to produce the second-order equation:

$$\_{s}^{2} = 1069.1 + 656.3A - 578.6C + 733.1F - 318.5AC + 399.0AF - 354.1CF - 318.7A^2 + 363.8C^2 + 108.4F^2$$

Similar to the linear case, analysis of variance techniques were applied to examine the performance of the second-order equation. Figure 7 presents the plot of residuals against the predicted values for the shuttle. In Fig. 7, the residuals appear to fall randomly within a horizontal band around zero, which indicates that error terms have constant variance, and that the error terms are independent. A normal probability plot of residuals presented in Fig. 8 was generated to further evaluate the underlying assumptions of the prediction equation.

Referring to Fig. 8, the residuals appear to fall approximately along a straight line in the normal probability plot. This plot suggests that the three factors do not exert the same influence on the output, and that the second-order prediction equation satisfies normality, independence, and constant variance of residuals.

An adjusted coefficient of determination $R_a^2 = 0.978202$ was calculated for the second-order prediction model. This was a slight improvement over $R_a^2 = 0.976813$, which was calculated for the shuttle's linear prediction equation. These R_a^2 values indicate that both the first-order and second-order prediction equations produce a fairly accurate fit for the data.[5] By applying the high (+) or low (–) values to the second-order equation, maximum and minimum debris impact areas were calculated. Second-order prediction results are presented in Table 2.

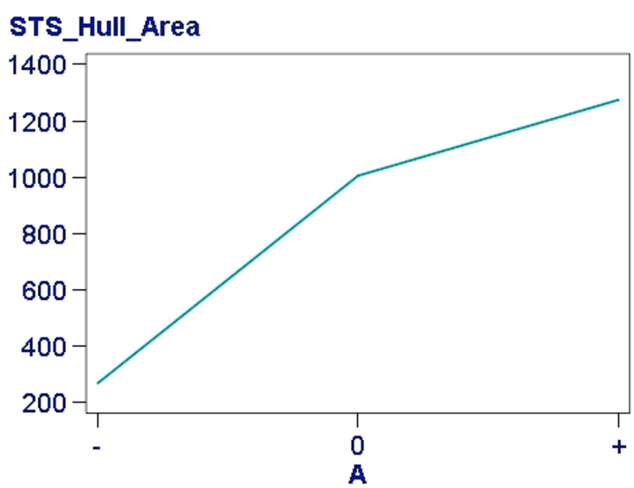

Fig. 4 Three-level plot of hull areas for shuttle - Factor A.

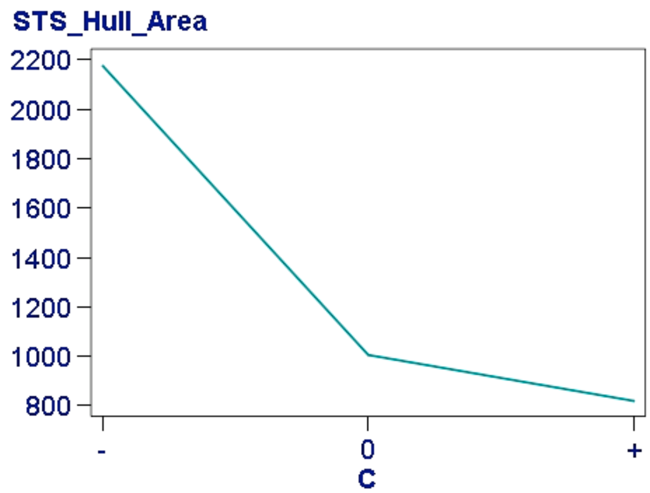

Fig. 5 Three-level plot of hull areas for shuttle - Factor C.

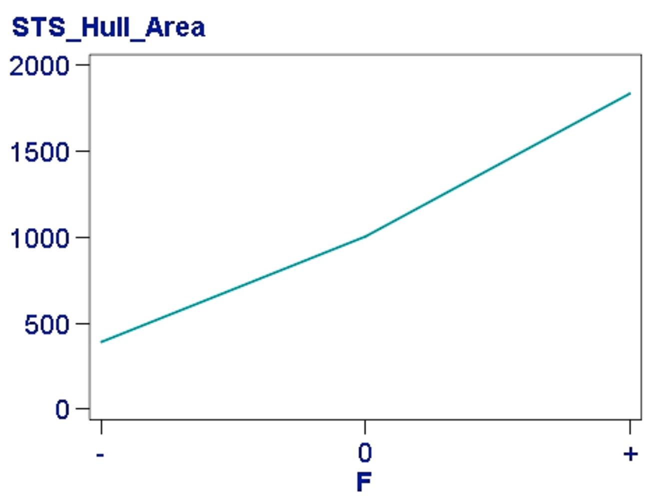

Fig. 6 Three-level plot of hull areas for shuttle - Factor F.

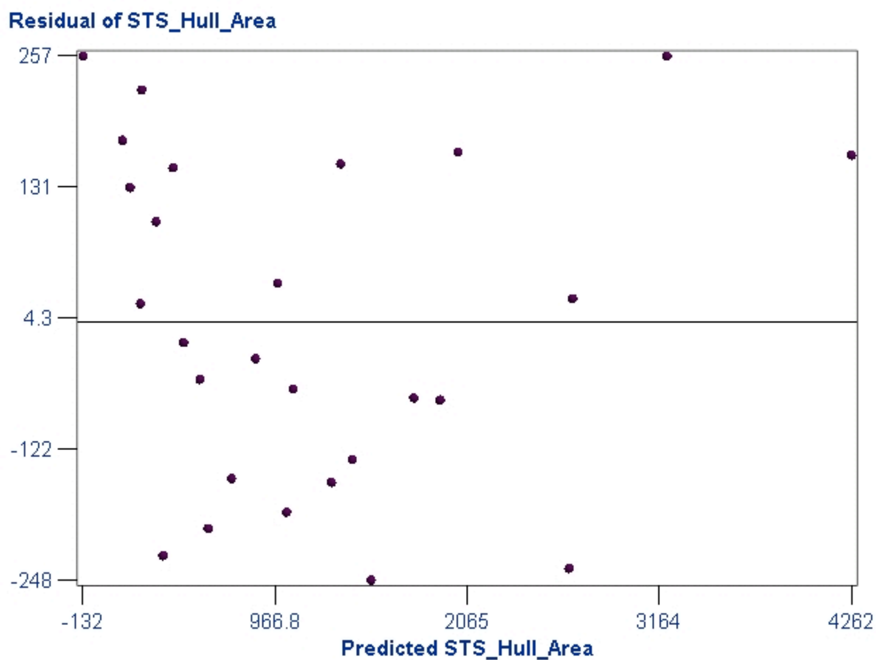

Fig. 7 Plot of residuals against fitted values for second-order analysis.

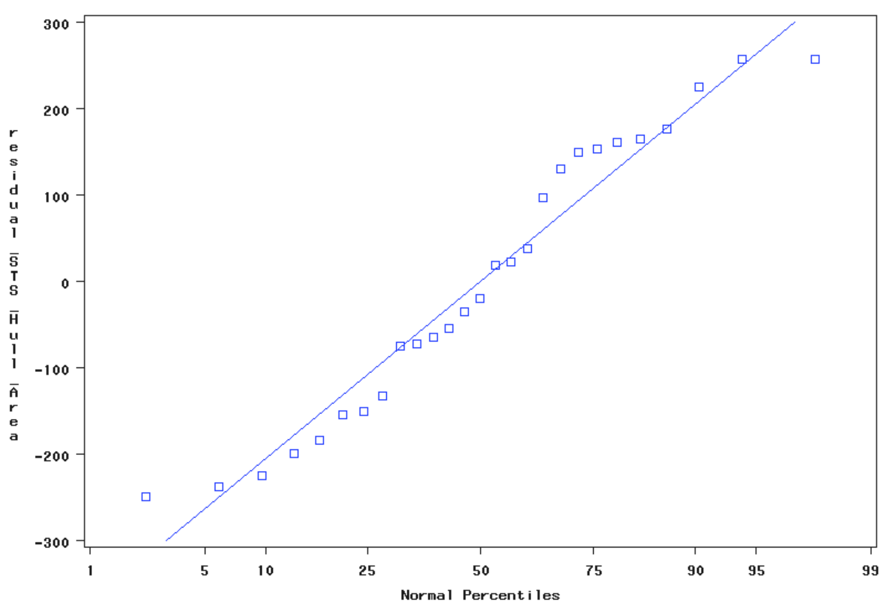

Fig. 8 Normal probability plot of residuals for second-order analysis.

Table 2 Shuttle second-order predicted hull areas

	Prediction Equation Factors									
	A	C	F	AC	AF	CF	A^2	C^2	F^2	(miles^2)
Max	+	-	+	-	+	-	+	+	+	4262.2
Min	-	0	0	0	0	0	+	0	0	94.1

V. Conclusions

By performing a two-level full factorial analysis on the CRTF debris dispersion model, main effects and interaction effects for all possible combinations of factors were found. Results showed that three main effects had statistical significance. The three main factors included wind (A), ballistic coefficient of debris fragments (C), and failure altitude (F), and three two-factor interaction effects (AC, AF, CF).

In evaluating the first-order prediction equation for validity, the plot of residuals against fitted values suggested that second-order effects were present. This could be expected, because the debris model derives the hull area from impact ellipses for each fragment category. Using the three main effect factors from the two-level full factorial analysis, a second-order prediction equation was developed. When using these equations in an optimization study, the second-order predictions would be slightly more accurate because R_a^2 (0.978202) was slightly better than the first-order value of R_a^2 (0.976813).

The second-order prediction equation was used to calculate maximum and minimum hull areas, producing a maximum of 4262.2 miles^2 and a minimum prediction of 94.1 miles^2. The great differences between maximum and minimum hull areas suggest that there could be significant optimization opportunities to minimize the debris impact areas for these vehicles. The minimum prediction factors further suggest that wind (A) has perhaps the greatest influence on hull area for the altitudes studied.

Debris dispersion and other range hazards will be a necessary topic of study to safely and more efficiently integrate aircraft and spacecraft in shared airspace. Results suggest that this type of analysis could be used to possibly gain greater airspace capacity surrounding a launch site. Further studies targeting other operational scenarios could be performed to investigate airspace (SUA/ALTRVs) requirements and range safety procedures. This type of research could also be applied to developing automated decision support tools that support both air traffic and space launch/return operations.

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