NASA/TM-2001-211246

An Approach to Simulation of Extreme Conditions for a Planetary Lander

Eric M. Queen, Scott A. Striepe, and Richard W. Powell
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National Aeronautics and
Space Administration

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1 Abstract

A "Monte Carlo-like" design analysis tool is developed and applied to an aeromaneuvering Mars entry vehicle. This tool provides realistic but challenging design cases using many fewer cases than a full Monte Carlo analysis. The problem of random input variables that are provided a priori (as opposed to being drawn from a given distribution) is addressed and a solution is found that shows prospects for future improvement.

2 Introduction

The engineering design of a flight vehicle is often based on a "worst case" combination of external conditions and manufacturing defects which the vehicle must be able to overcome to achieve its mission. A better name for this case might be a "design case", because a worse case can always be imagined, though perhaps not a realistic one. Thus, a balance must be maintained between designing to a case that is too severe, leading to overdesign (higher weight, higher cost) and a design case that is not severe enough and subjecting the vehicle to a failure that could have been prevented. One approach that addresses this issue is the use of Monte Carlo analysis as a design tool. In this approach, one determines a realistic range of values for each variable that will affect the final design (e.g. atmospheric dispersions, materials defects, measurement errors, etc.) and simulates the system with many different combinations of input variables (typically thousands.) This design approach has been used for the entry guidance system design of the Mars 2007 "Smart" Lander.

A disadvantage of Monte Carlo design is that the extreme cases are the cases that drive the design. Typically, a system performs very well for conditions that are near the nominal, but not as well for conditions that are far from the nominal. For a large number of inputs, many cases are near the nominal, because relatively few cases fall far from the mean and of those, fewer still occur in variables that are strong contributors to the final output. Thus, in order to get a sufficient number of extreme cases, many thousands of Monte Carlo cases often need to be run. The goal of the current work is to demonstrate a technique for simulating extreme cases that are consistent with the Monte Carlo analysis, but requires fewer runs.

The Monte Carlo simulation used in this study is similar to that described in [Striepe et al], except that the vehicle model has been changed to reflect the new mission. Notice that not all of the inputs have the same type of distribution. Some are Gaussian, some are Uniform and some are provided as-is and are not necessarily represented by any standard distribution. Notably the initial position and velocity are results of another random process based on the interplanetary trajectory and are provided by the NASA Jet Propulsion Laboratory (JPL).

3 Background

The vehicle used in this study is the proposed 2007 "Smart" Mars Lander. Of primary interest will be the portion of the mission that involves entry from interplanetary approach orbit until the parachute is deployed near Mach 2. This vehicle is a blunt body with a heatshield forebody very similar to the Viking and Pathfinder forebodies.

The purpose of the onboard guidance system is to direct the vehicle safely to a predetermined target point. The ability of the guidance system to do this is strongly affected by the interplanetary navigation; that is, the accuracy with which the spacecraft achieves its target atmospheric entry condition. Two types of navigation were considered. In the first, the standard radiometric measurements by the Deep Space Network were assumed. In the second, additional optical measurements of Phobos and Deimos by the onboard star tracker are incorporated, providing increased accuracy. The first data type is referred to as “radiometric” and the second as “optical”. For both types of navigation, sets of 100,000 delivery positions and velocities were provided by JPL. Additionally, an estimate of the vehicles position and velocity as determined for use by onboard navigation systems was provided by JPL.

Since Pathfinder,[1] the authors have assumed that 2,000 cases were adequate to characterize Monte Carlo results. But over the last several years, the simulations have become more complex and have more input variables. Also, as confidence in the methods increased, higher order statistics were utilized from the simulations. The concern is that 2,000 cases may be insufficient for statistical analyses. Therefore, a Monte Carlo with 100,000 cases was run to determine the minimum number of cases required for reliable statistics.

Figure 1 shows the mean true range to target and mean navigated range to target for the radiometric only data as a function of number of cases run. Both means are very well behaved and reach a steady state after about 15,000 cases.

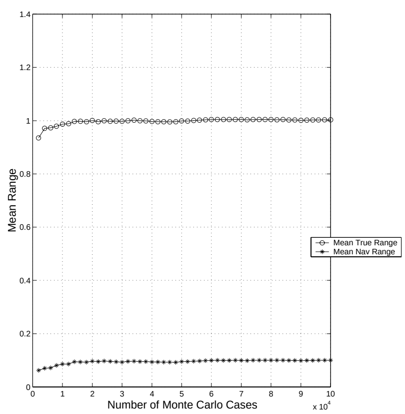

Fig. 1. Radiometric Mean Range to target at Parachute Deploy

Figure 2 shows the standard deviations of range to target for the radiometric only data, true and navigated. These statistics are much more volatile, with 10% changes after 50,000 cases. To some extent this result is to be expected, since the standard deviation is a higher order statistic than the mean.

Figures 3 and 4 show the same statistics as figures 1 and 2 but for the optical data set. Here the standard deviation is slightly slower to converge than the mean, but both are settled by 12,000 cases. It is not clear why the standard deviation of the optical data shows so much less variability than the radiometric data.

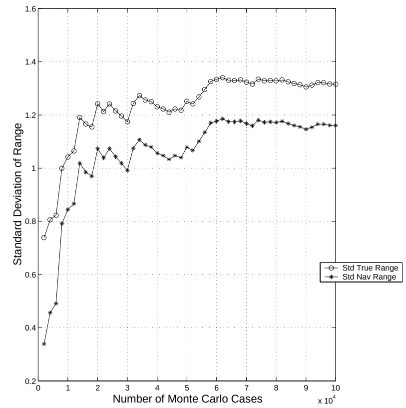

Fig. 2. Radiometric Standard Deviation Range to target at Parachute Deploy

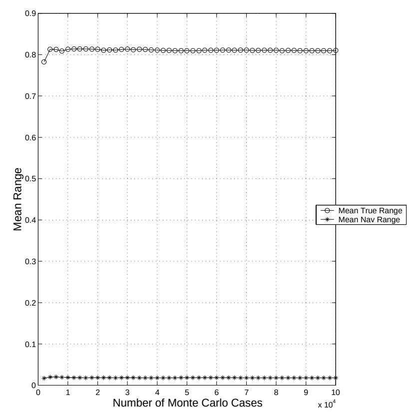

Fig. 3. Optical Mean Range to target at Parachute Deploy

Figure 5 shows the 99.7% range for the two navigation types, again as a function of number of cases. The difference between the two navigation types is even more pronounced for this statistic. The radiometric takes 50,000 cases to converge within 10% of the final result while the optical is within 2% from 2,000 cases on.In the runs using radiometric data, the initial vehicle state is a much larger contributor to the range than for the optical data. It has been conjectured that the larger variation in the initial state values may contribute to the slow convergence of the radiometric data.

Not knowing the reason for the slow convergence, a conservative approach would require at least 60,000 cases to estimate the standard deviation of

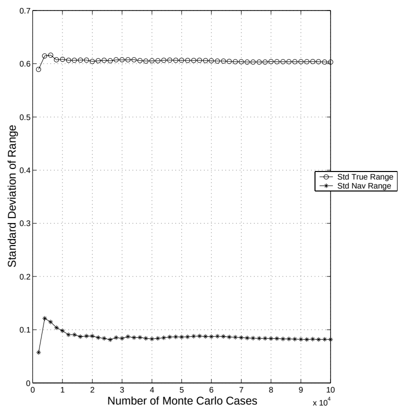

Fig. 4. Optical Standard Deviation Range to target at Parachute Deploy

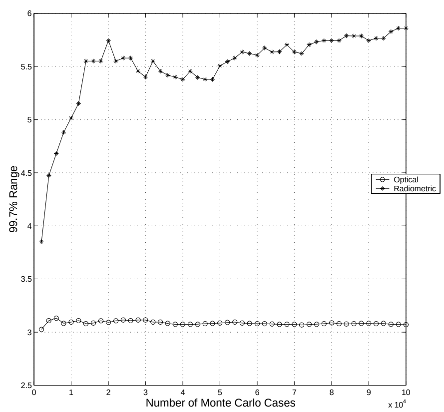

Fig. 5. 99.7% Range to target at Parachute Deploy

the final range.

4 Robustness Simulation

As a final check, a 60,000 case Monte Carlo simulation might be acceptable for a three degree-of-freedom (3DoF) problem. As a design tool, a 60,000 cases run is not practical with current computers. Fortunately a design tool need not estimate the standard deviation or 99.7% range values. Since the design is driven by the most severe cases, it is only necessary to simulate those cases.

The current approach is "Monte Carlo-like" in that it is based on random values for key simulation parameters. The distributions of the random inputs are modified so that the most extreme realistic cases result. For the normally distributed variables, only values more than 2σ from the mean are used. For uniform variables, only the endpoints of the distribution were used. In this manner, extreme (but reasonable) combinations of parameters were investigated. These extreme values of inputs are referred to as "robust" inputs.

Since the initial states were provided as-is and not generated from a known distribution, it was necessary to select an appropriate set from the 100,000 states available. A set of 2,000 cases was chosen, made up of five distinct subsets. The first subset consisted of the 400 states with the largest position delivery errors. The second subset consisted of the 400 states with the largest velocity delivery errors. The third subset consisted of the 400 states with the largest position knowledge errors. The fourth subset consisted of the 400 states with the largest velocity knowledge errors. The final subset consisted of the 400 states with the largest sum of absolute value of the error in each of the 12 state components (3 position, 3 velocity, 3 knowledge position, 3 knowledge velocity). That is, while the first four subsets were vector magnitudes, the fifth subset summed the absolute value of each component of the other four vectors. This fifth subset is referred to as the 12-state magnitude error subset.

There is considerable correlation between the five subsets. From the radiometric data 68 states occurred in only one subset, 447 states occurred in exactly two subsets and 346 states occurred in exactly 3 subsets, for a total of 861 different states used in the 2,000 runs. Figures 6 and 7 show the delivery latitude and longitude of the 100,000 states and the

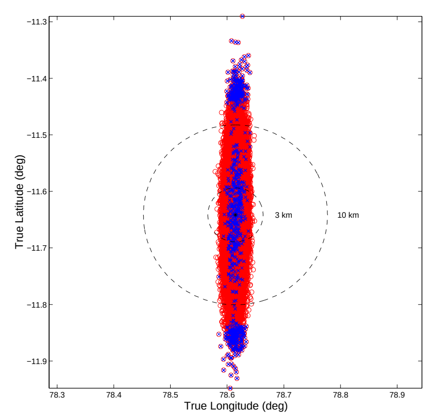

Fig. 6. Initial Distribution of 100,000 radiometric states and robust states.

861 selected. The endpoints of the 100,000 states are included (usually multiple times) in the reduced

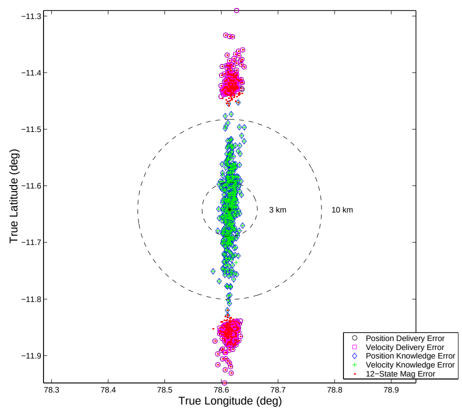

Fig. 7. Initial Distribution of robust radiometric states by subset.

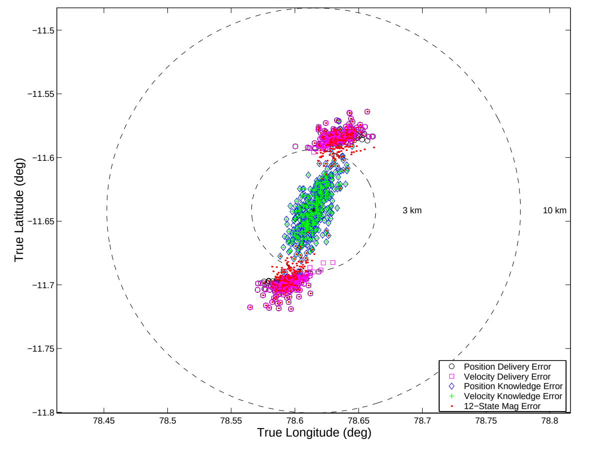

Fig. 9. Initial Distribution of robust Optical states by subset.

set.

The states chosen from the optical data overlapped as well. They included 240 states in exactly one subset, 532 states that occurred in exactly two subsets, 229 in exactly three subsets, 1 in exactly four subsets and 1 in exactly five subsets, for a total of 1,003 different states. Figures 8 and 9 show the distribution of the 100,000 optical states and of the

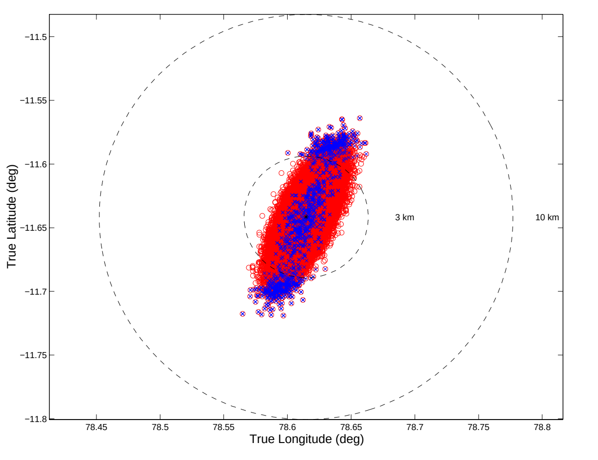

Fig. 8. Initial Distribution of 100,000 Optical states and robust states.

1,003 selected initial states.

Figures 10 and 11 cover the navigated supersonic parachute deploy condition for the 100,000 case Monte Carlo simulation and the 2,000 case robustness study, respectively. Note that the simulation (exterior to the guidance) forced the parachute to deploy whenever the navigated altitude dropped below 6 kilometers, while the guidance attempted to keep the parachute deployment within Mach and dynamic pressure limits by constraining the parachute deployment to occur at velocity between 370 and 503 m/s.. The footprint of the two studies are very similar. The robustness study resulted in more cases outside of the allowable Mach/Dynamic pressure box. This result is due to the more severe atmosphere in the robustness runs, which was always at either its thinnest or thickest value. Notice the banded structure in the Nav Altitude vs. Nav Velocity plot. This banding will be even more evident in the optical navigation runs and will be discussed later. Figures 12

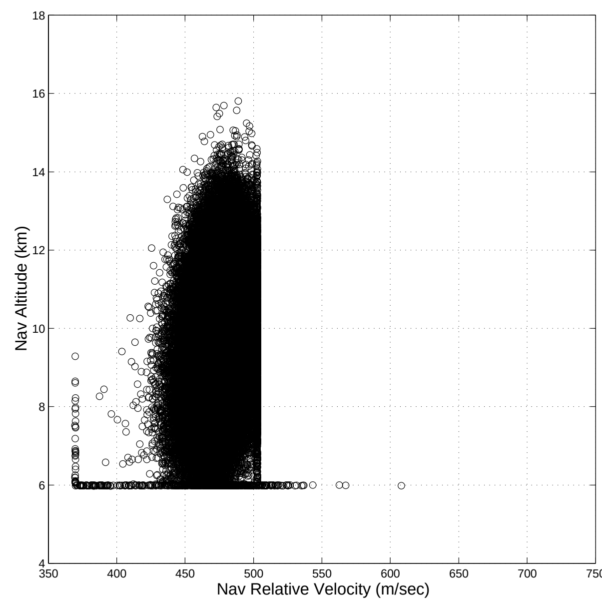

Fig. 10. Radiometric Navigated Conditions at Supersonic Parachute Deploy; 100,000 Monte Carlo cases.

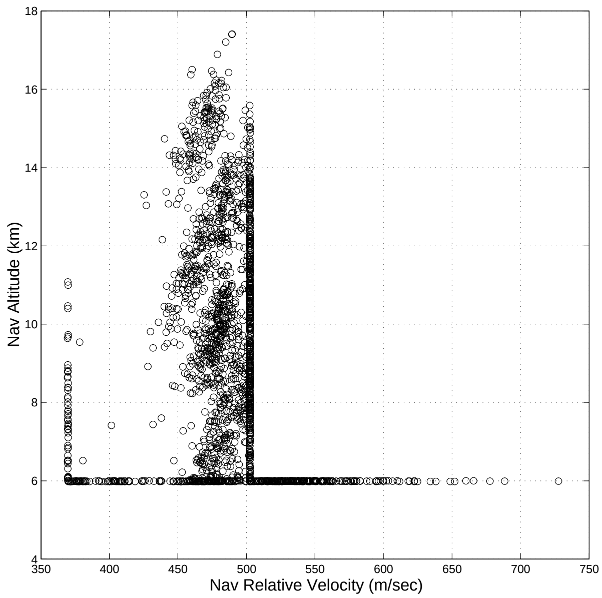

Fig. 11. Radiometric Navigated Conditions at Supersonic Parachute Deploy; 2,000 Robust cases.

and 13 show the actual values to match the navigated values in figures 10 and 11.

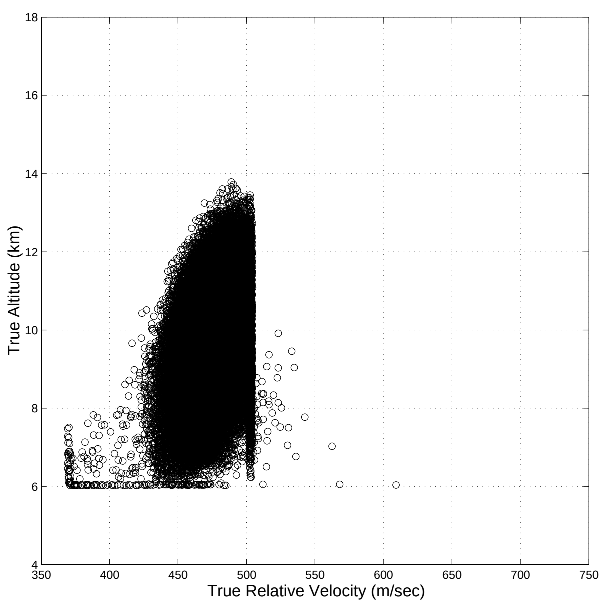

Fig. 12. Radiometric True Conditions at Supersonic Parachute Deploy; 100,000 Monte Carlo cases.

Figures 14 and 15 are similar to the preceding charts, but cover the optical states studies. Again the results are very similar between the 100,000 cases and the 2,000 cases, though the robustness cases have more cases that exceed the parachute deploy

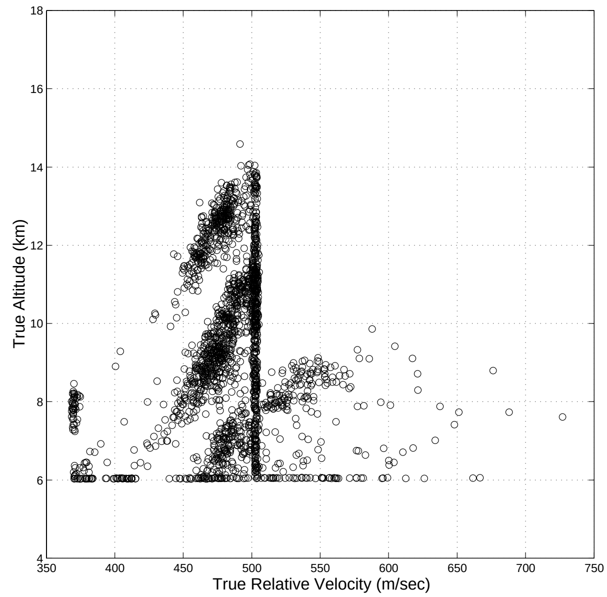

Fig. 13. Radiometric True Conditions at Supersonic Parachute Deploy; 2,000 Robust cases.

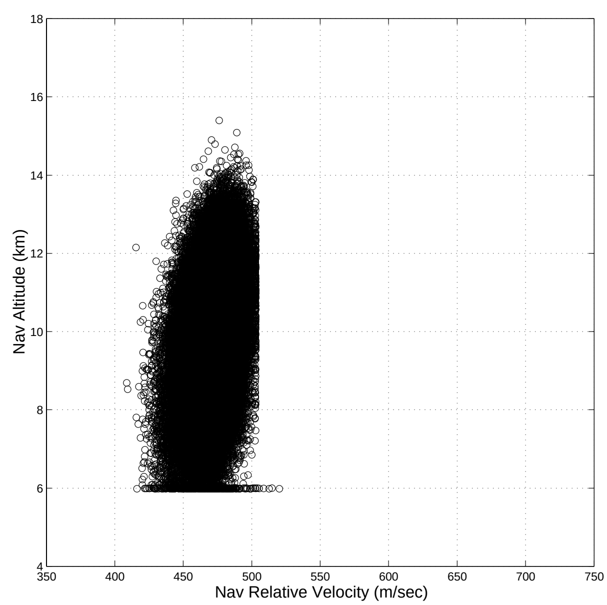

Fig. 14. Optical Navigated Conditions at Supersonic Parachute Deploy; 100,000 Monte Carlo cases.

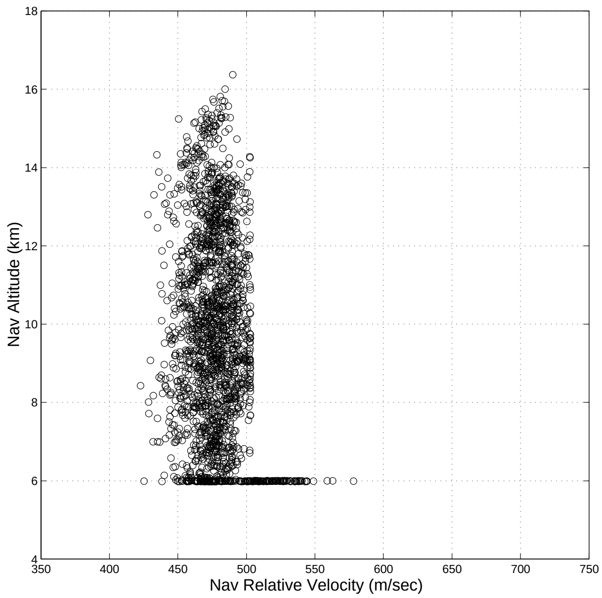

Fig. 15. Optical Navigated Conditions at Supersonic Parachute Deploy; 2,000 Robust cases.

Mach limit. In figures 16 and 17, which show the

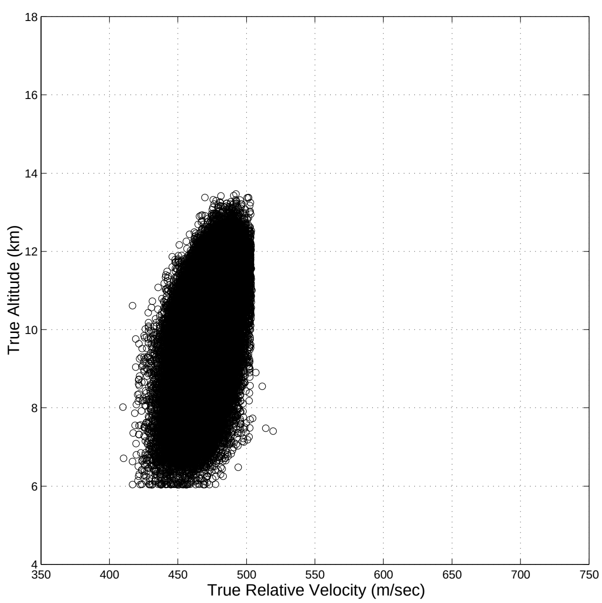

Fig. 16. Optical True Conditions at Supersonic Parachute Deploy; 100,000 Monte Carlo cases.

true altitude and velocity at parachute deploy, the banded structure is very distinct. The banding occurs because the altitude and velocity at parachute deploy are largely determined by two factors: the atmospheric density and the hypersonic axial force coefficient. For this mission the effect of the two factors is approximately equal and in the robust case study,

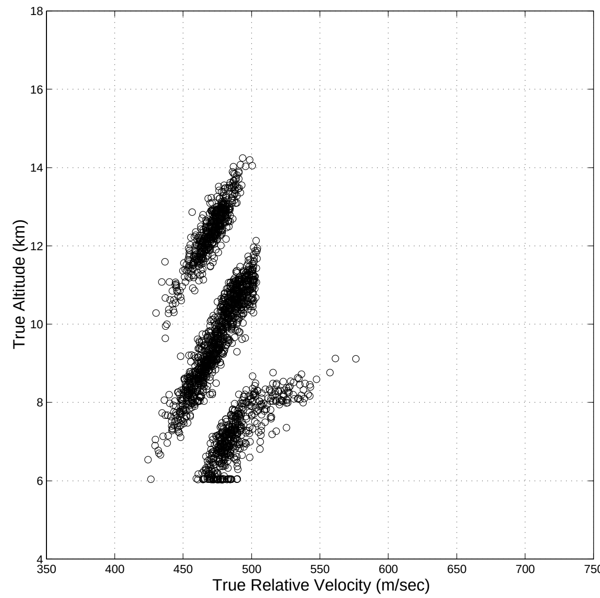

Fig. 17. Optical True Conditions at Supersonic Parachute Deploy; 2,000 Robust cases.

each factor was either at its maximum or its minimum. When a high density atmosphere combined with a high axial force coefficient, the parachute deploy was high and slow. When both factors were low, the deploy was low and fast, and when one was high and the other low, the result was in the middle. This effect is clear from figures 18 and 19 which discriminate between high and low values for each

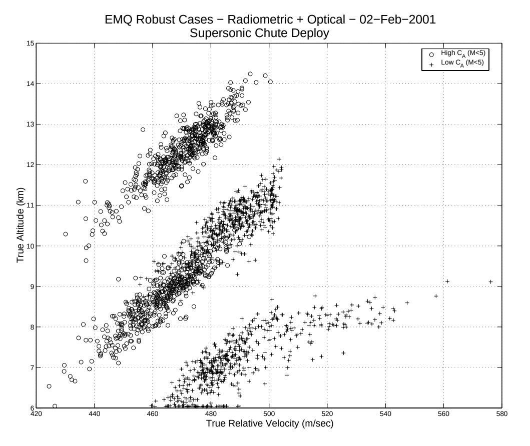

Fig. 18. Conditions at Parachute Deploy sorted by Axial Force Coefficient.

of the factors. Notice that all of the cases with high atmospheric density and high axial force coefficient are on the upper left, all cases with low for both are in the lower right and in the middle each case is low in one and high in the other.

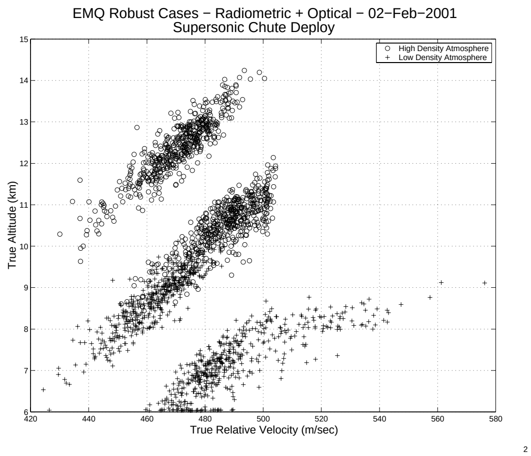

Fig. 19. Conditions at Parachute Deploy sorted by Atmospheric Density.

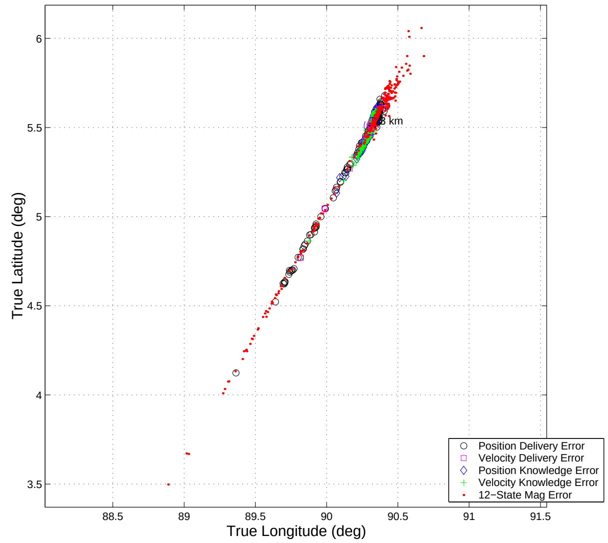

Fig. 20. Radiometric Footprint broken down by initial state subset.

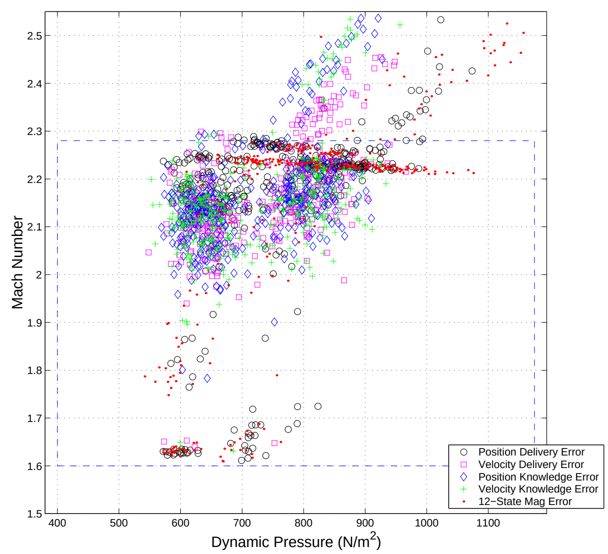

Fig. 21. Radiometric Parachute Deploy Conditions broken down by initial state subset.

Prior to the Monte Carlo study, success criteria were established to determine what constituted a "safe" landing. The maximum safe landing vertical velocity was 4 m/s and the maximum safe landing horizontal velocity was 2 m/s. According to these criteria, 180 cases in radiometric and 175 cases in optical failed the 100,000 case Monte Carlo, while 199 cases in radiometric and 132 cases in optical failed the robustness study.

5 Postmortem and Future

The means of state selection described above was considered ad hoc. In an effort to make the state selection process better, the footprint and parachute deploy conditions for the robustness study were broken into subsets corresponding to the initial condition subsets. The segregated footprint is shown in figure 20. It is clear that all of the very long cases and most of the very short cases resulted from states in the 12-state magnitude subset. Figure 21 shows the parachute deploy conditions similarly segregated. Here all five subsets contribute to the out-of-bounds cases which are driven largely by the atmosphere. But the 12-state magnitude states seem to cover the range of out-of-bounds cases. Figures 22 and 23 show the same results for the optical cases. In the footprint shown in figure 22, there is more of a mixture of subsets in the very long and very short cases, but most seem to be from knowledge errors and 12-state errors. This result is due to the much smaller state errors for the optical cases, so the knowledge errors become the dominant factor and the 12-state errors include the knowledge errors. Finally, figure 23 shows the deploy condition for the optical cases. Here almost all of the out-of-bounds cases are either knowledge or 12-state.

Figures 20 through 23 show that the 12-state magnitude errors show up consistently in the extreme cases. Suggesting that this method may be a way to select states for future robustness studies, perhaps with some weighting of the various components to find the most effective states.

Another issue is whether the endpoint of a uniform distribution is the worst possible input when it is combined with other inputs. This issue is espe-

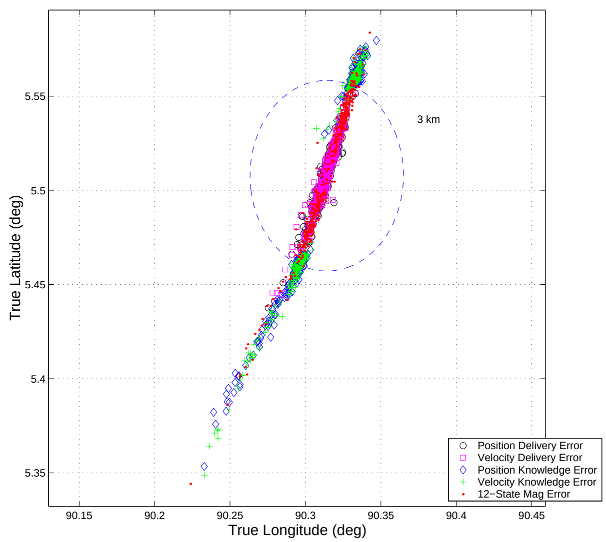

Fig. 22. Optical Footprint broken down by initial state subset.

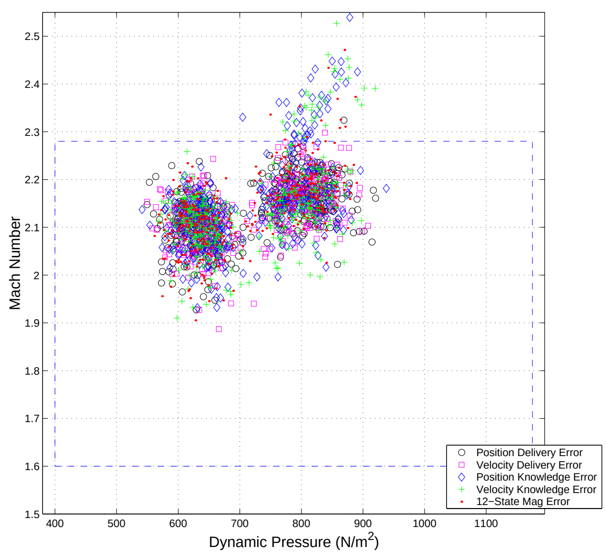

Fig. 23. Optical Parachute Deploy Conditions broken down by initial state subset.

cially a concern for the atmosphere where a very complicated, non-linear system has been parameterized by a single factor, the atmospheric opacity. In the future studies we will replace the endpoints of the uniform variables with "V"-distributed variables. That is, variables that have 0 probability of occurring at the midpoint and linearly increase in probability away from the midpoint.

6 Conclusions

The number of runs needed for a full Monte Carlo analysis has been found to be much too large for its use as a design tool for planetary entry problems. A "Monte Carlo-like" design analysis tool has been developed and applied to a Mars entry vehicle. This tool provides realistic but challenging design cases using many fewer cases than a full Monte Carlo analysis. The problem of random input variables that are provided a priori (as opposed to being drawn from a given distribution) has been addressed and a solution was found that shows prospects of future improvement.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
November 2001

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
A Approach to Simulation of Extreme Conditions for a Planetary Lander

5. FUNDING NUMBERS
WU 896-30-00-03

6. AUTHOR(S)
Eric M. Queen, Scott A. Striepe, Richard W. Powell

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18125

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TM-2001-211246

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 15 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
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14. SUBJECT TERMS
Monte Carlo Design; Mars Lander; Trajectory Analysis

15. NUMBER OF PAGES
13

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z-39-18
298-102