DISCRETE SIMULATION APPLIED TO MARS LANDER

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Abstract

NASA plans for a sophisticated Mars lander mission during the 1973 opportunity present a rigorous deceleration system design problem due to uncertainties in the environment in which the retardation must be effected. Selection of design characteristics such as ballistic coefficient, aeroshell diameter, parachute size and deployment altitude, and propulsion thrust level and initiation altitude is critical, for if a "worst case" design philosophy is adopted for all parameters, weight is not available to perform an interesting science mission. To establish a proper design, a certain risk with respect to environment must be accepted; this paper discusses a digital simulation tool as it has been applied to parameter trades to specify retardation design.

1. INTRODUCTION

NASA plans for a sophisticated Mars lander mission during the 1973 opportunity present a rigorous deceleration system design problem due to uncertainties in the environment in which the retardation must be effected. NASA-Langley has assembled data,(1) in a probabilistic format, which represents a current description of the Mars environment. Deceleration will likely be a three stage process (Figure 1); atmospheric drag will be used to decelerate the vehicle to a velocity which permits deployment of a subsonic parachute. The parachute separates the lander from the heatshield and further retards the lander until the final, Surveyor-type, propulsive phase is initiated. Selection of design characteristics such as ballistic coefficient, aeroshell diameter, parachute size and deployment altitude, and propulsion thrust level and initiation altitude is critical, for if a "worst case" design philosophy is adopted for all parameters, weight is not available to perform an interesting science mission. To establish a proper design, a certain risk with respect to environment must be accepted; this paper discusses a digital simulation tool as it has been applied to parameter trades to specify retardation design.

To maintain a manageable scope, only a part of the problem will be discussed in this paper: the interaction of the hypersonic aerodynamic phase and the parachute deceleration phase. Naturally, this limitation precludes quantitative discussion of how the overall optimization was accomplished, but the method will be indicated. In a mathematical sense, however, this paper will produce a statistical description of the parameters important to design of the propulsive phase systems (initiation path angle, velocity, and slant range) as a function of the following design values characteristic of the first two deceleration stages:

1. Nominal entry path angle
2. Hypersonic ballistic coefficient
3. Entry weight
4. Parachute diameter

5. Parachute deployment altitude (above local terrain)
6. Propulsion initiation altitude (above local terrain)

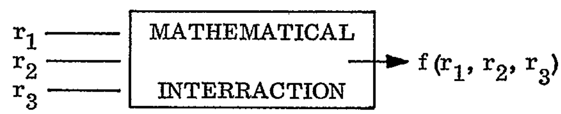
The computational technique accounts for the "environment" uncertainties:

1. Atmosphere characteristics
2. Entry path angle dispersions
3. Aerodynamic coefficient uncertainties
4. Local terrain elevation
5. Wind velocity and direction

Figure 1 summarizes the major constraints accepted for retardation design; these constraints represent judgment as to how far one should plan design beyond current experience on a complex program with severe time and cost restraints. Other constraints indicated are representative of the planned 1973 mission. The simulation does not directly address the hardware reliability problem, but is oriented to determination of the likelihood that a given design will experience certain unfavorable combinations of environmental parameters (which cause marginal operation even with perfect hardware performance). For example, the probability distribution of parachute deployment dynamic pressure is computed and serves as an indicator, in a statistical sense, of the rigors to which a specific retardation design subjects the parachute.

2. SOLUTION TECHNIQUE

A simulation design to establish lander system performance within a random environment for a range of design parameters will necessarily be required to integrate a large number of ballistic and parachute trajectories. Of course, if one is very fortunate, the integrations can be accomplished in closed form (in some sense). Many trajectory problems, however, are not amenable to closed form solution and the computer time needed for numerical integration renders a simulation useless for establishing multi-parameter design sensitivities. In order to reduce the impact of integration time on utility of the simulation, a technique called discrete modeling was adopted. In discrete modeling the random variables are characterized by discrete probability density functions, that is, the random variable is made to take on only a finite number of values each with an associated probability. Once a discrete representation is selected for all the random variables, the computer simulation merely considers every possible occurrence within the framework of the simulation. The following simplified problem will illustrate the procedure. Let R_1, R_2, R_3 be random variables where R_1 takes on L discrete values, R_2 has S values, and R_3 has T values. Also let r_i be a specific value of R_i and let p_i be the probability associated with r_i. The simulation output $f(r_1, r_2, r_3)$



is one possible outcome with probability $p_1 \cdot p_2 \cdot p_3$ of occurring. The total number of outcome events is $L \cdot S \cdot T$. These outputs can now be collected in a histogram to characterize the statistical distribution. The above discrete simulation technique differs from a Monte Carlo simulation in the following ways:

(1) Random sampling is avoided; the sample values and their probabilities are selected prior to the simulation rather than randomly generated during the simulation.

(2) The output probabilities, resulting from the discrete input densities, are exact.

In the limit as the number of discrete values in each density function becomes large, the discrete modeling technique approaches results which would be obtained from continuous distributions. For certain kinds of problems, discrete modeling appears to provide computational advantages over a conventional Monte Carlo formulation.

3. MATHEMATICAL MODELING

Because of the uncertainty in environment, a highly accurate trajectory integration scheme is judged unwarranted (and undesirable from a computer time standpoint). The program uses first order Runge-Kutta integration with 0.2 and 2.0 second time intervals selected by the deceleration level. The planar point mass equations for the ballistic trajectory are:

$$\ddot{h} - (R_o + h)\dot{\theta}^2 = -\frac{R_o^2 g_m}{(R_o+h)^2} - \frac{\rho V \dot{h}}{2\beta}$$

$$2\dot{h}\dot{\theta} + (R_o + h)\ddot{\theta} = -\frac{\rho V}{2\beta}(R_o + h)\dot{\theta}$$

$$V = \left[\dot{h}^2 + (R_o + h)^2 \dot{\theta}^2\right]^{1/2}$$

where:

g_m = Mars gravitational acceleration

h = Altitude of entry vehicle

θ = Central angle

R_o = Mean radius of Mars

ρ = Atmospheric density

V = Velocity of entry vehicle

β = Ballistic parameter (drag coefficient is assumed independent of Mach number)

The parachute trajectory equations are written in a rectangular reference frame because at relatively low parachute deployment altitudes, curvature effects are negligible.

$$\dot{V} = \frac{\rho V^2}{2\beta} + g_m \sin\gamma$$

$$\dot{\gamma} = \frac{g_m \cos\gamma}{V}$$

$$\dot{h} = -V \sin\gamma$$

where:

γ - angle velocity vector makes with local horizontal.

These equations provide the framework for processing the significant random events that occur during entry. The philosophies used to select the discrete probability density functions are:

3.1 ATMOSPHERE MODELS

The environmental document issued by NASA-Langley(1) specifies five atmosphere models which are intended to bound the actual Martian atmosphere as well as to indicate a most probable model. A probability distribution is not specified; the probabilities selected are:

Atmosphere Model	Probability
Minimum Scale Height	.15
Minimum Surface Density	.15
Most Probable	.40
Maximum Surface Density	.15
Maximum Scale Height	.15

These probability weightings are based upon the following rationale:

1. The most probable atmosphere should have more weight than the other models.
2. It is dangerous to assign low probabilities to the extreme atmospheres without proper justification, since a design for this weighting may not be acceptably tolerant to future data indicating an extreme atmosphere.

3.2 ENTRY PATH ANGLE AND HYPERSONIC DRAG COEFFICIENT

Studies indicate that with careful design and manufacturing, the uncertainty in hypersonic drag coefficient can be controlled to approximately $\pm$ 7.5% (3σ). This uncertainty in drag coefficient has an effect on parachute deployment conditions similar to entry path angle dispersions. To conserve computational time, uncertainties in drag were combined with entry path angle dispersions. The entry path angle error, based upon error analyses, is approximately normally distributed about the nominal entry angle with a standard deviation of $\pm .7^{\circ}$ (3σ). This deviation coupled with an uncorrelated normally distributed hypersonic drag coefficient uncertainty extended the effective entry path angle deviation to $\pm 1^{o}$ (3σ). Figure 2 illustrates the method used to approximate this continuous probability density function by discrete values. The area under the normal curve between $-.5\sigma$ and $+.5\sigma$ was combined into a delta function at 16 degrees, the area from $\pm .5\sigma$ to $\pm 1.5\sigma$ included in a delta function at 1σ, etc. All area above 2.5σ was combined into an impulse function at the 3σ value.

3.3 TERRAIN ELEVATION

The discrete model of local terrain elevation is derived directly from the LRC Mars model (1) by replacing each bar in the histogram by an impulse function (representing the area of the bar) located at its center; specific values are shown in Figure 3. The implementation of the program presumes that the atmosphere and terrain models are referenced to the same datum.

3.4 PARACHUTE DRAG UNCERTAINTY

Parachute drag uncertainty is estimated to be normally distributed with deviation $\pm 15\%$ (3σ). The discrete drag values selected are based on the rationale applied to the entry path angle:

Drag	Probability
.85 of Nominal	.0062
.9 of Nominal	.0606
.95 of Nominal	.2417
Nominal	.383
1.05 of Nominal	.2417
1.1 of Nominal	.0606
1.15 of Nominal	.0062

3.5 WIND MAGNITUDE

The wind model proposed by NASA-Langley(1) has the following characteristics: (1) The maximum wind speed at the edge of the boundary layer (V_{max}) is 63.6 mps; the actual wind speed is then statistically distributed in terms of V_{max} as illustrated in Figure 4. (2) The maximum wind speed gradient ($\dot{V}_{max}$) is specified as 8.3 mps for each kilometer of altitude above the boundary layer; the actual wind speed gradient is then satistically distributed as a function of $\dot{V}_{max}$ as illustrated in Figure 5. In order to ascertain the wind speed at the propulsion initiation altitude, the statistical distribution of the random variable S is needed:

S = V + VG

V - wind speed at boundary layer based on V_{max} of 63.6 mps

VG - wind speed added due to gradient times initiation altitude.

It was assumed that the propulsion initiation occurs at approximately 1.3 km. Thus the additional maximum wind speed added to the gradient is:

$$VG_{max} = (8.3) \cdot (1.3) = 10.8 \text{ mps}$$

Based on the above, the convolution of the histograms in Figures 4 and 5 was carried out and the following discrete points selected:

Wind Speed at Vernier Initiation meters/second	Probability
2.5	.0076
7.5	.0490
12.5	.1123
17.5	.1887
22.5	.2410
27.5	.2067
32.5	.1259
37.5	.0462
42.5	.0125
47.5	.0040
52.5	.0025
57.5	.0017
62.5	.0014
67.5	.0005

3.6 WIND DIRECTION

The wind was assumed to have eight possible directions in a plane parallel to the Martian surface; each of these directions was assigned probability .125. The simulation assumes that the lander and parachute have reached steady-state with the wind. This is a conservative approach; however, in a more detailed simulation, the force due to the wind should be incorporated into the integration of the parachute trajectory equations.

Figure 6 illustrates the simulation logic.

4. RESULTS

For a particular set of lander design parameters the simulation exposes this design to a total of 356,672 combinations of "environmental" events:

(5 atmospheres) · (7 path angles) · (13 elevations)

(7 parachute drag values) · (14 wind magnitudes) ·

(8 wind directions) = 356,672 individual events.

These events each have an associated probability and results can be accumulated in histogram format. Note that, in a statistical sense, this deals with a very large number of "trials", but the number of time consuming trajectory integrations is not unreasonable. In the simulation, only 35 hypersonic and 3185 parachute trajectories must be integrated to generate 356,672 sample points.

4.1 BALLISTIC PARAMETER AND NOMINAL ENTRY PATH ANGLE SELECTION

One of the significant factors that constrains the ballistic parameter and entry path angle is the requirement that the parachute be deployed at a safe Mach number and dynamic pressure. Figure 7 shows a typical simulation output of the correlation of Mach number and dynamic pressure at parachute deployment. Several runs were made to parametrically evaluate the effect of path angle and ballistic parameter on deployment Mach number (Figure 8). A parachute deployment altitude of 4 km (above local terrain) represents a practical lower limit with respect to terminal propulsion constraints. From recent successful tests in the Planetary Entry Parachute Program, parachute deployment in the Mach 3 range merits consideration; however, a more conservative design goal of deployment below Mach 2 is appropriate to lower risk on planetary missions. A ballistic parameter of .31 slugs/ft^2 is required along with a nominal entry angle at the lower end of the range shown to ensure a high probability (> .98) of deployment below Mach 2. These probabilities are only an indication of successful deployment - the results of a parachute test program could be used to establish performance curves to convert deployment conditions into probability of successful parachute operation.

4.2 PARACHUTE SIZE AND DEPLOYMENT ALTITUDE SELECTION

In this simulation the terminal propulsion phase was initiated in accordance with an altitude/altitude rate criterion, $h = a + b\dot{h}$. The conditions at the end of the parachute phase have been formulated in terms of slant range - velocity and path angle - velocity correlation histograms. Utilizing this data in conjunction with a terminal guidance procedure (gravity turn using acceleration control), trade studies may be carried out to determine optimum landed weight. The following are considerations that must be statistically evaluated for the parachute selection: (1) the design and development risk inherent in deployment at higher dynamic pressures caused by higher deployment altitudes. (2) a reduced probability of intersecting the chosen parachute release criterion resulting from a lower deployment altitude; (3) the increased landing radar acquisition difficulties caused by shallower initial flight path angles resulting from lower deployment altitudes; and (4) the increased probability of successful landing, when local terrain discontinuities are considered, with higher deployment altitudes. To illustrate how the above are evaluated with simulation output consider Figures 9 and 10. Both of these histograms are for the same basic lander design, however, in Figure 9, the parachute deployment altitude is 3km and in Figure 10, the deployment altitude is 4 km. The 3km deployment results in a small probability of missing the $h/\dot{h}$ curve and also has very high velocities due to non-terminal conditions on the parachute. Increasing the deployment altitude to 4km removes the $h/\dot{h}$ intersection difficulty and substantially reduces the velocities at the beginning of terminal descent.

These are only a few examples of the statistical data that is generated by the simulation. The intent is to show the practicality of discrete modeling and how results offer a consistent numerical comparison of various deceleration designs based on the balancing of risk (from environment) and capability (from system parameters).

5. EVALUATION OF DISCRETE MODELING TECHNIQUE

Since the discrete modeling technique uses only a finite number of values to describe continuous random variables, the probabilities generated are merely an approximation. A numerical evaluation of the closed form solution of probability of parachute deployment below Mach 2 was developed in order to ascertain the numerical significance of the probability computations. For each atmosphere model the altitude at which Mach 2 occurs can be accurately expressed as a linear function of entry path angle and ballistic parameter in a restricted region:

$14.5^{\circ} \leq$ Entry Path Angle $\leq 17.5^{\circ}$

$.28$ slugs/ft^2 $\leq$ Ballistic Parameter $\leq .34$ slugs/ft^2

Since it is assumed that the entry path angle and ballistic parameter are independent normal random variables, the altitude where Mach 2 occurs is obtained by a linear transformation; therefore it becomes a normal random variable. If we assume a deployment altitude of 4km above the local terrain, the probability of parachute deployment below Mach 2 is given by:

Prob. $(HM_2 \leq TE + 4km)$

where:

HM_2 - Altitude of Mach two (normal random variable)

TE - Terrain Elevation (Histogram, Figure 3)

The above equation was solved by convolution, for each atmosphere model, and the results were:

	Probability Development is Below Mach 2
Discrete Modeling	.984
Closed Form	.979

This comparison indicates that the discrete modeling technique appears to generate numbers that are of sufficient quality to perform trade studies.

6. CONCLUSION

This paper represents two possible contributions to the simulation art. First, it documents an effort to use simulation to optimize, in a sense, a multi-parameter system for operation in a highly uncertain environment. Presumably, this represents a class of design problems important in many fields. Secondly, it demonstrates the use of discrete modeling, which, for certain problems, seems to present an attractive alternative to other simulation techniques. The approach is intuitively satisfying and characterized by conceptual simplicity although a theoretical question of how to best represent a continuous distribution by a discrete distribution is unresolved — from a computation standpoint, it is extremely relevant to attempt to minimize the number of discrete values while still producing adequate answers. In the Mars lander simulation, we were more concerned with relative performance of various designs than with calculation of absolute probabilities. Thus, we were satisfied to expose each design to the same set of environments (which are judged to encompass the entire spectrum of expected environments) in order to make design decisions. A study was conducted to estimate the error produced by the discrete approximation of continuous distributions; this error was not significant in an engineering sense although no theoretical basis exists at this time for establishing a confidence band for the results. However, by judicious selection of the discrete points (e.g. at the minimum or at the maximum of a region) one can determine statistical bounds.

REFERENCE

1. Mars Engineering Model, Viking Project Office, NASA-Langley Research Center, Document M73-106-0, February 6, 1969.

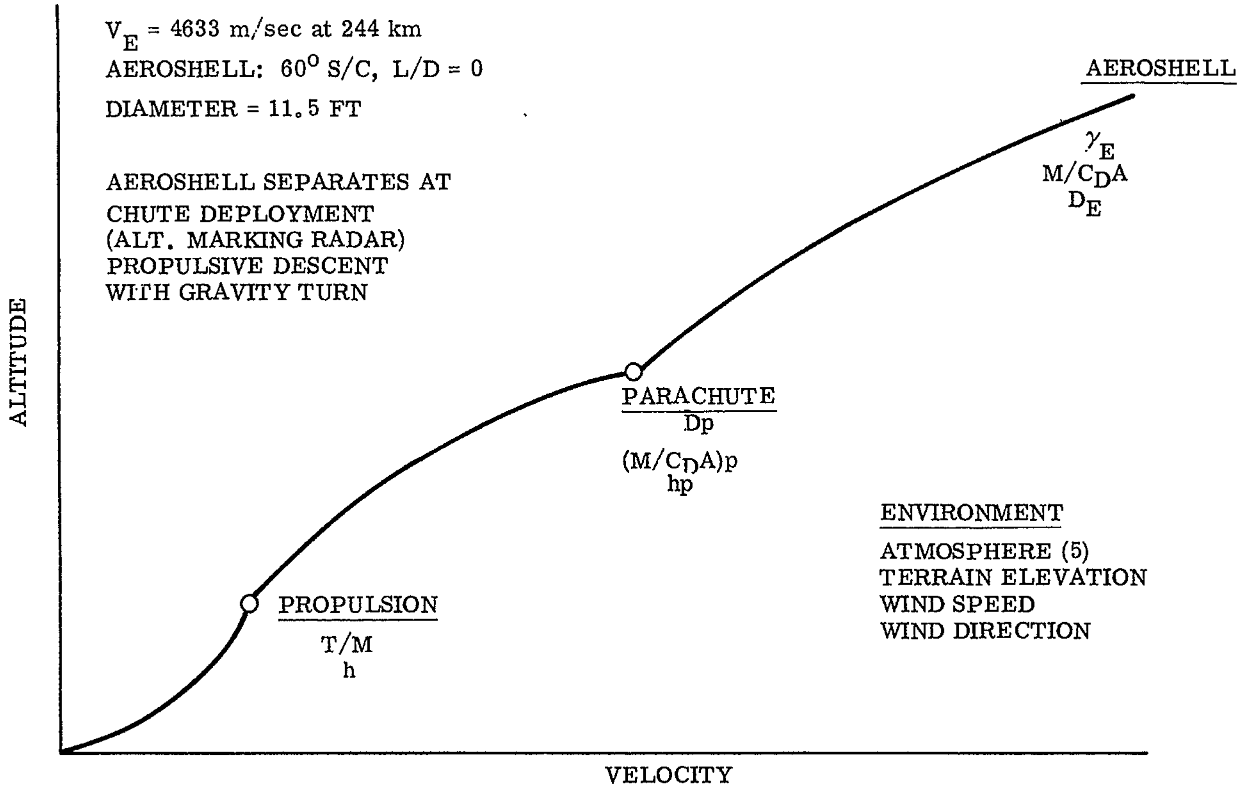


FIGURE 1. RETARDATION PROCESS

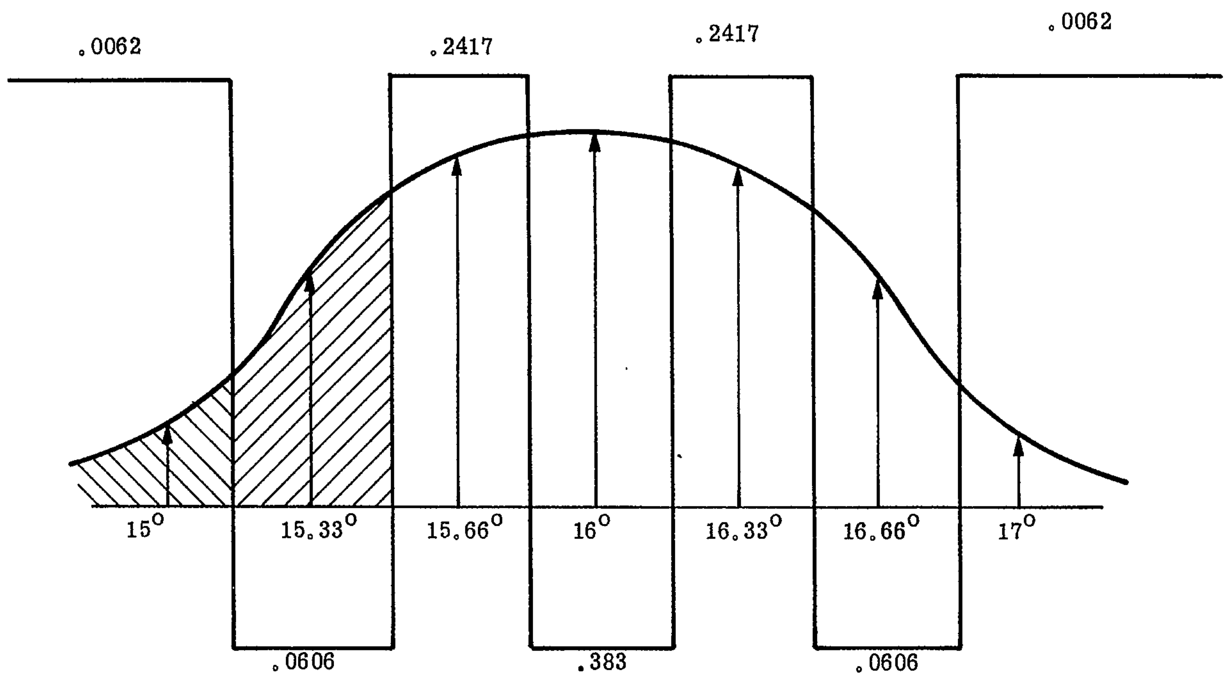


FIGURE 2. ASSUMED ENTRY ANGLE DISTRIBUTION

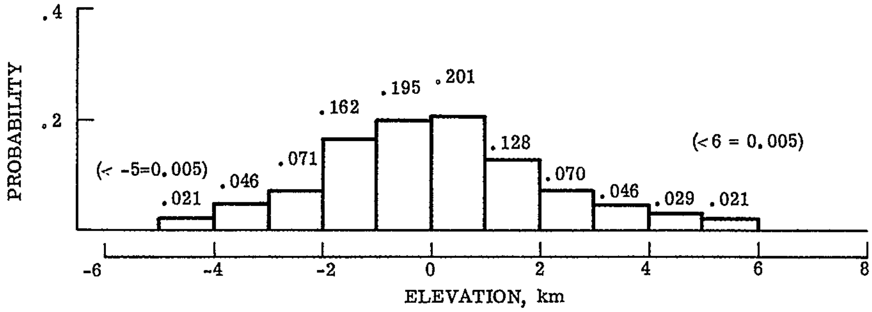


FIGURE 3. ASSUMED SURFACE ELEVIATION DISTRIBUTION

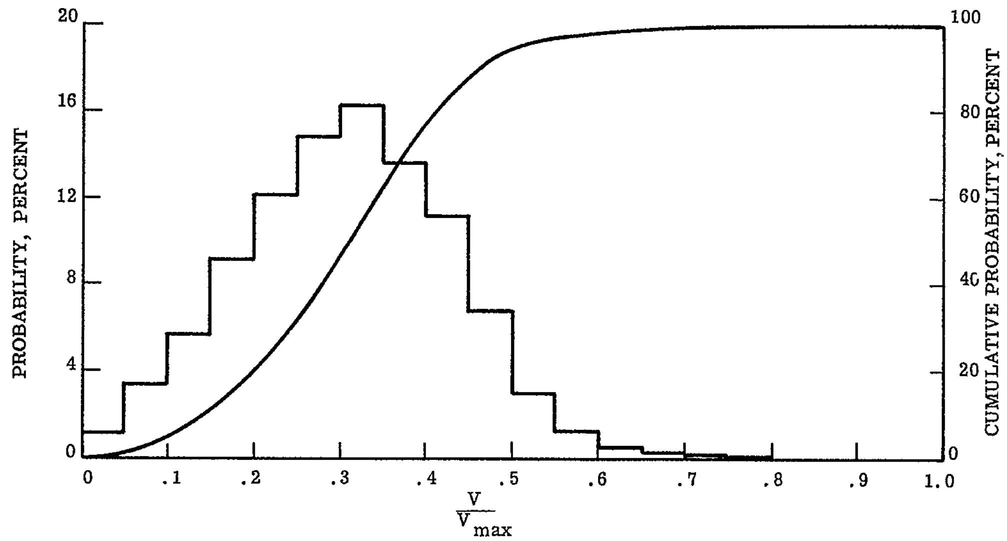


FIGURE 4. PROBABILITY DISTRIBUTION OF NEAR-SURFACE WIND SPEED ON MARS BETWEEN ± 28° LATITUDE NEAR THE VERNAL EQUINOX IN THE NORTHERN HEMISPHERE.[1]

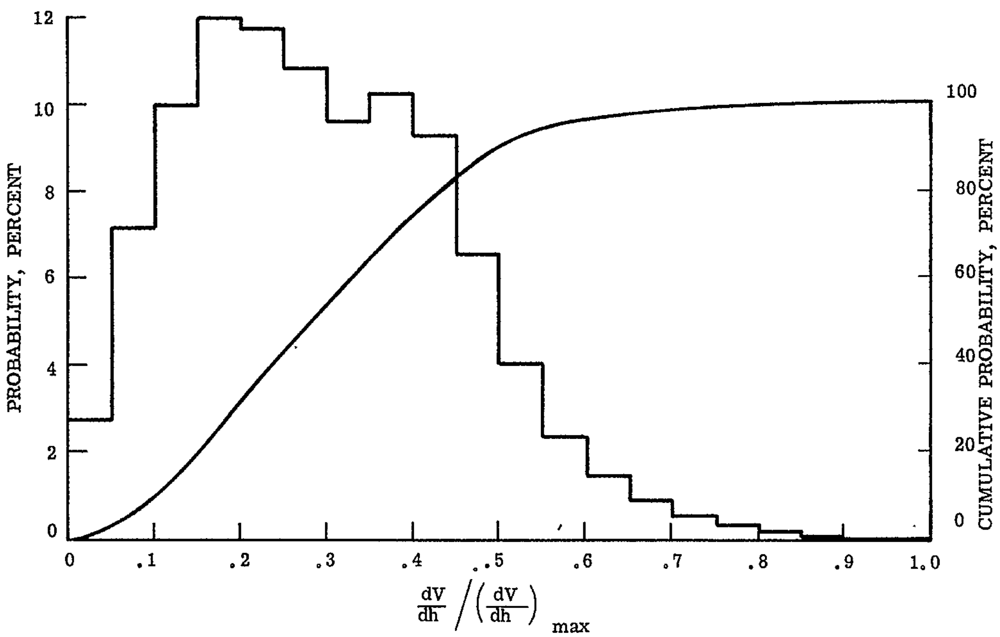


FIGURE 5. -PROBABILITY DISTRIBUTION OF WIND SPEED GRADIENT ON MARS BETWEEN ± 28° LATITUDE NEAR THE VERNAL EQUINOX IN THE NORTHERN HEMISPHERE.[1]

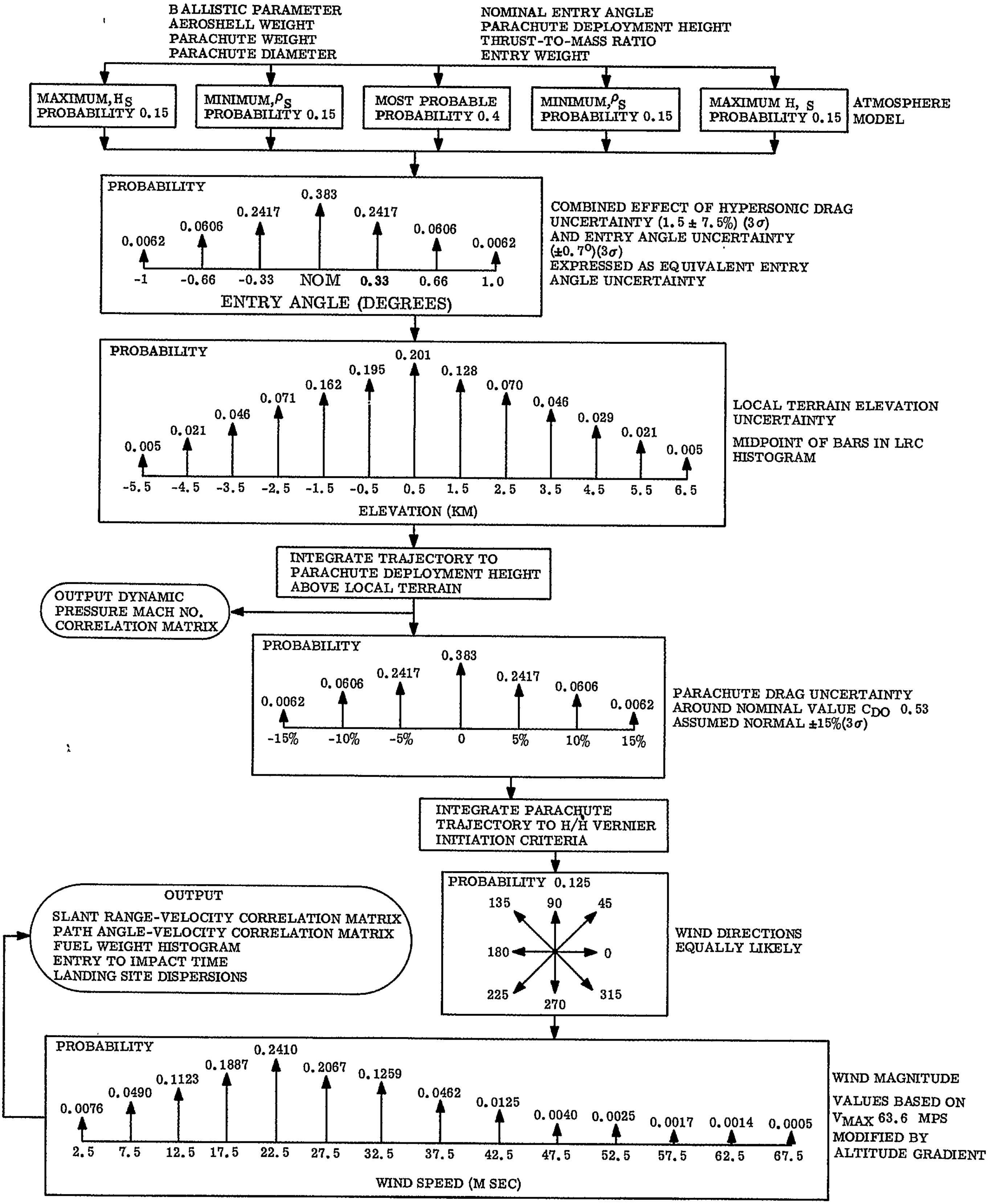


FIGURE 6. LOGIC AND ENVIRONMENTAL INPUTS

MACH #	PROBABILITY										
	ACC.	MAR.									
.25 - .50	.2705	.2705		.2705							
.50 - .75	.5249	.2544		.2544							
.75 - 1.00	.7124	.1875		.1875							
1.00 - 1.25	.8212	.1088		.0485	.0603						
1.25 - 1.50	.9167	.0955			.0955						
1.50 - 1.75	.9692	.0525			.0266	.0259					
1.75 - 2.00	.9843	.0151				.0072	.0079				
2.00 - 2.25	.9897	.0054					.0048	.0006			
2.25 - 2.50	.9927	.0030					.0003	.0027			
2.50 - 2.75	.9961	.0034						.0019	.0015		
2.75 - 3.00	.9984	.0023						.0008	.0012		.0003
3.00 - 3.25	.9993	.0009							.0002	.0007	
3.25 - 3.50	.9998	.0005								.0003	.0002
> 3.5	1.0001	.0003									.0003
MARGINAL				.7609	.1824	.0331	.0130	.0060	.0029	.0010	.0008
DYNAMIC PRESSURE lbs/ft^2			2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	>18
ACCUMULATIVE				.7609	.9433	.9764	.9894	.9954	.9983	.9993	1.0001

ENTRY BALLISTIC PARAMETER = .31 SLUGS/FT^2
NOMINAL ENTRY PATH ANGLE = $15^o \pm 1^o$ (3σ)
PARACHUTE DEPLOYMENT ALTITUDE = 4 KM

FIGURE 7. MACH NO. - DYNAMIC PRESSURE CORRELATION MATRIX

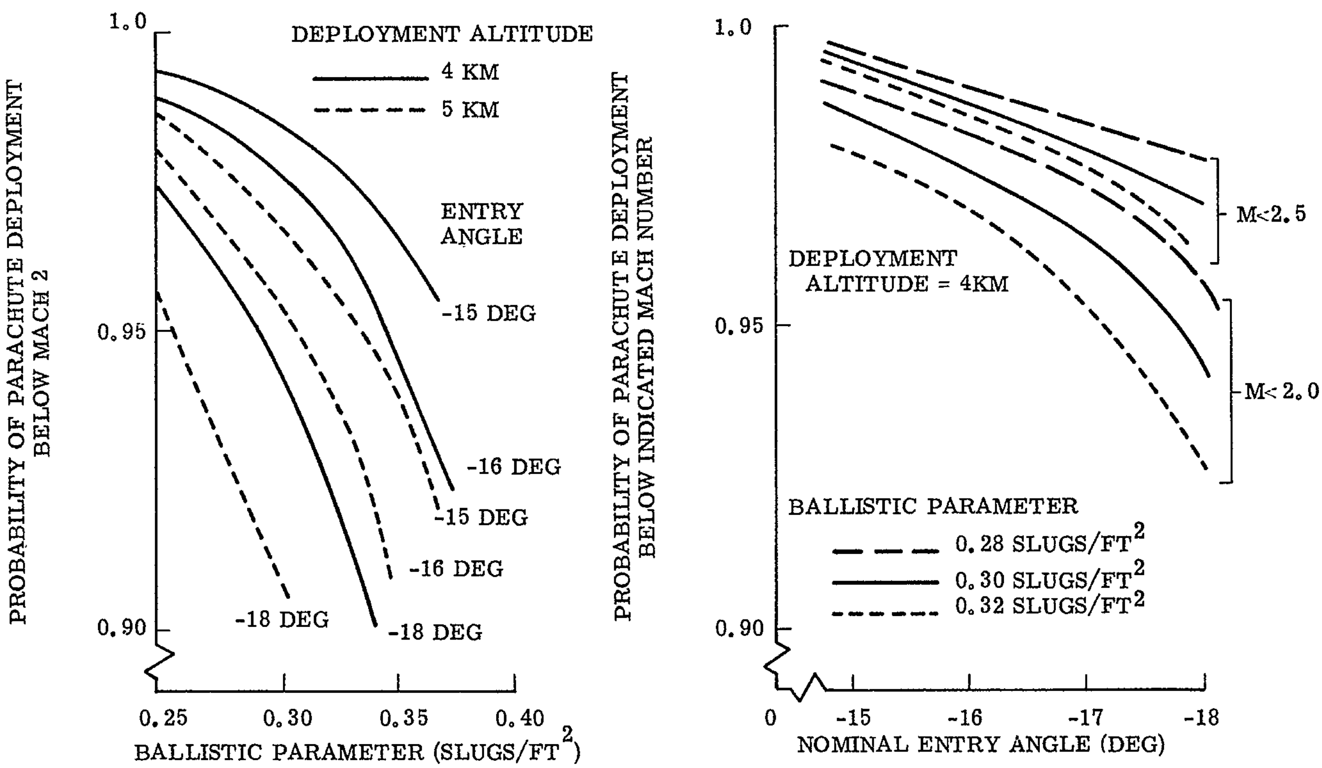


FIGURE 8. EFFECT OF BALLISTIC PARAMETER, ENTRY ANGLE, AND DEPLOYMENT ALTITUDE ON PARACHUTE DEPLOYMENT MACH NUMBER

PATH ANGLE	ACC.	MAR																	
0-5	.0124	.0124	.0000	.0003	.0013	.0020	.0012	.0037	.0031	.0008									
5-10	.0345	.0221		.0006	.0000	.0051	.0059	.0065	.0024	.0016									
10-15	.0869	.0524		.0022	.0087	.0080	.0143	.0129	.0036	.0026	.0001								
15-20	.1866	.0997		.0027	.0067	.0264	.0237	.0212	.0080	.0105	.0005								
20-25	.3277	.1411		.0024	.0152	.0200	.0512	.0267	.0097	.0106	.0051	.0002							
25-30	.5006	.1729		.0030	.0099	.0227	.0728	.0270	.0189	.0076	.0094	.0015	.0001						
30-35	.6872	.1866		.0001	.0220	.0393	.0498	.0266	.0168	.0094	.0148	.0062	.0016						
35-40	.8362	.1490		.0004	.0252	.0258	.0228	.0308	.0075	.0082	.0069	.0150	.0054	.0008	.0002				
40-45	.9224	.0862			.0065	.0210	.0190	.0113	.0029	.0015	.0026	.0048	.0093	.0056	.0013	.0003	.0001		
45-50	.9688	.0464			.0032	.0198	.0074	.0022	.0012	.0006	.0004	.0005	.0010	.0034	.0037	.0023	.0002	.0004	.0001
50-55	.9875	.0187				.0050	.0061	.0016	.0007	.0006	.0003	.0002	.0001	.0001	.0004	.0009	.0014	.0006	.0007
55-60	.9919	.0044				.0006	.0014	.0005	.0005	.0004	.0002							.0002	.0006
60-65	.9929	.0010						.0005	.0002	.0003									
65-70	.9931	.0002							.0001	.0001									
70-75																			
MARGINAL				.0117	.0897	.1957	.2756	.1715	.0756	.0548	.0403	.0284	.0175	.0099	.0056	.0035	.0017	.0012	.0014
ACCUMULATIVE				.0117	.1104	.3061	.5817	.7532	.8288	.8836	.9239	.9523	.9698	.9797	.9853	.9888	.9905	.9917	.9931
VELOCITY-ft/sec			50/75	75/100	100/125	125/150	150/175	175/200	200/225	225/250	250/275	275/300	300/325	325/350	350/375	375/400	400/425	425/450	450/475

AEROSHELL BALLISTIC PARAMETER = .31 SLUGS/FT^2
PARACHUTE BALLISTIC PARAMETER = .030 SLUGS/FT^2
AEROSHELL DIAMETER = 11.5 FEET

PARACHUTE DEPLOYMENT ALTITUDE = 3 KM
NOMINAL ENTRY PATH ANGLE = 15°
AEROSHELL WEIGHT = 300 LBS.

PARACHUTE DIAMETER = 55 FEET
ENTRY WEIGHT = 1550 LBS.

RIGHT OF $\frac{h}{\dot{h}}$ CURVE .0068

FIGURE 9. CONDITIONS AT VERNIER INITIATION

PATH ANGLE	ACC.	MAR.																	
0-5	.0145	.0145		.0003	.0013	.0021	.0011	.0011	.0032	.0054									
5-10	.0464	.0319		.0006	.0001	.0061	.0086	.0056	.0064	.0044	.0001								
10-15	.1117	.0653		.0023	.0087	.0063	.0094	.0112	.0119	.0152	.0003								
15-20	.2250	.1133		.0027	.0066	.0270	.0212	.0198	.0130	.0197	.0033								
20-25	.3864	.1614		.0024	.0152	.0187	.0527	.0261	.0195	.0195	.0072	.0001							
25-30	.5787	.1923		.0030	.0099	.0223	.0769	.0235	.0209	.0149	.0193	.0016							
30-35	.7583	.1796		.0001	.0220	.0394	.0527	.0264	.0097	.0058	.0145	.0088	.0002						
35-40	.8818	.1235		.0004	.0251	.0258	.0221	.0315	.0042	.0023	.0021	.0067	.0032	.0001					
40-45	.9457	.0639			.0065	.0210	.0190	.0108	.0029	.0005	.0003	.0004	.0014	.0010	.0001				
45-50	.9809	.0352			.0032	.0198	.0072	.0022	.0013	.0006	.0003	.0001	.0001	.0002	.0002				
50-55	.9952	.0143				.0050	.0060	.0016	.0007	.0006	.0003	.0001							
55-60	.9988	.0036				.0006	.0014	.0005	.0005	.0004	.0002								
60-65	.9997	.0009						.0005	.0002	.0002									
65-70	.9999	.0002							.0001	.0001									
70-75																			
MARGINAL				.0118	.0986	.1941	.2783	.1608	.0945	.0896	.0479	.0178	.0049	.0013	.0003				
ACCUMULATIVE				.0118	.1104	.3045	.5828	.7436	.8381	.9277	.9756	.9934	.9983	.9996	.9999				
VELOCITY-ft/sec			50/75	75/100	100/125	125/150	150/175	175/200	200/225	225/250	250/275	275/300	300/325	325/350	350/375	375/400	400/425	425/450	450/475

AEROSHELL BALLISTIC PARAMETER = .31 SLUGS/FT^2
PARACHUTE BALLISTIC PARAMETER = .030 SLUGS/FT^2
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PARACHUTE DIAMETER = 55 FEET
ENTRY WEIGHT = 1550 LBS.

FIGURE 10. CONDITIONS AT VERNIER INITIATION

BIOGRAPHIES

E. M. Morgan was born in Philadelphia, Pa. on May 2, 1941. He received the B. S. applied mathematics degree from Lafayette College, Easton, Pa. in 1963, the M. A. Mathematics degree from University of Massachusetts, Amherst in 1965, the M. S. systems science degree Polytechnic Institute of Brooklyn in 1968.

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