Impact and Casualty Prediction for Malfunctioning Multi-Stage Vehicles

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IMPACT AND CASUALTY PREDICTION
FOR MALFUNCTIONING MULTI-STAGE VEHICLES

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ABSTRACT

Presented is a rather general explanation of an automated method for determining, by Monte Carlo techniques, the probabilities of impacting populated land masses and causing a casualty when a malfunctioning multi-stage vehicle deviates from its normal instantaneous earth impact pattern. The generation of this data is explained through the use of illustrative material which describes the necessary flow of information and computational operations. The economic advantages of the method discussed are compared, in terms of manpower, computer time, and total elapsed time requirements, with those of a forerunning method used to generate such data.

CREDIT

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INTRODUCTION

The support of a space vehicle launch requires the generation of a considerable amount of data for use in range safety operations. These data are supplied to the range safety office at the intended range facility so that the proposed flight plan can be evaluated and appropriate destruct criteria established to insure that adequate safety will be afforded to life and property during the flight of a vehicle. Among the data often required is an impact hazard study, containing probability of impact and casualty expectation data associated with a number of possible vehicle malfunctions.

Such analyses are generally accomplished by first assessing the modes of failure and assigning a probability of occurrence to each mode. Second, a probability density function is assigned to each of those vehicle state parameters which characterize particular modes of failure. Then, using the applicable equations of motion, the points of stage impact resulting from a number of failure mode simulations are determined, and the probability of impact is computed for each land mass (e.g. a country, city, etc.) subject to impact in the event of a malfunction. Finally, using the population density of each land area and the lethal area of the impacting stage(s), the casualty expectation is computed.
Except for selected failure modes, these probability calculations do not lend themselves to simple analytic solutions. Graphical procedures require generation of large amounts of trajectory data which must be subsequently manipulated to arrive at the final results. This approach is very tedious, especially if repeated analyses are to be made. Such is the case, for example, on the Delta program where a wide variety of missions are flown, including escape, highly elliptical, circular and high and low inclination orbits.

This paper discusses a simple approach to the problem, using the Monte Carlo technique, which has been found to significantly reduce the elapsed time and the computer time required to produce an impact hazard study report. In formulating and solving the problem several simplifying assumptions are made. For example, it is assumed that

a. certain vehicle failures may be grouped into selected failure modes,
b. the rate of occurrence of each failure mode is known, and
c. the probable behavior of the vehicle can be predicted in the event of a malfunction.

Other assumptions will become apparent in reading the discussion. These assumptions are fairly standard for this type of analysis, having little to do with the fact that a Monte Carlo technique is used. Therefore, the probability results obtained using the Monte Carlo technique are believed to be as valid as those which might be produced by other methods. The principle aim of developing the method presented in this paper was to provide a means whereby the analyses could be performed on a repeated basis with a minimum expenditure of time and effort on the part of the engineer.

DISCUSSION

General

The availability of high speed computers makes possible the use of the Monte Carlo technique for determining the probability of impact and casualty expectation of a malfunctioning vehicle. The basic steps followed in generating the data are summarized below:

a. for a particular mode of failure, a time of failure and the associated set of variables describing the state of the vehicle are determined using random number tables and the probability density function assigned to each of the state variables,
b. stage "burnout" conditions are computed, using the sample state variables and a set of dynamical equations which are assumed to describe the behavior of the vehicle when under the influence of a given failure mode,
c. the earth coordinates (latitude and longitude) of the impacting stage(s) are determined using the sample "burnout" conditions and standard two-body conic equations,
d. the country(ies) impacted is identified using a country search routine,
e. having completed steps (a) through (d) for a large number of simulations, the conditional probability of impacting each country, given that a malfunction has occurred, is computed simply by dividing the number of impacts recorded for each country
by the total number of possible impacts which could result from the failure mode in question. (The number of possible impacts is dependent on the sample size, the number of stages, and the nature of the failure mode.),

g. the probability of impacting in each country in a given failure mode is then computed by multiplying the conditional probability determined in step (e) by the probability of failure for that mode,

h. steps (a) through (g) are repeated by each assumed failure mode,

i. the total impact probability and casualty expectation for each country is determined by summing the probabilities computed for the individual failure modes.

The above steps are illustrated in figure 1.

Failure Modes

Because of the large number of possible vehicle malfunctions which may lead to unintentional earth impacts, those malfunctions which affect the motion of a vehicle in a similar manner are grouped and considered as a single "mode of failure". Otherwise, the magnitude of the problem would render it beyond practical analysis. The probability of failing in a given mode is then computed based on the probability density functions and inter-relationship of each of the component failures which make up that failure mode. All resulting failure modes are assumed to be mutually exclusive.

A detailed failure mode analysis is not considered within the scope of this paper, since the resulting failure modes will be dependent upon the vehicle system being analyzed. A listing of the failure modes considered in analyzing the Delta vehicle will suffice to illustrate the types of failure modes which can be analyzed:

Mode 1: Premature Stage I Thrust Termination
Mode 2: Premature Stage II Thrust Termination
Mode 3: Stage II Constant Nozzle Deflection
Mode 4: Stage II Thrust Termination Due to Propellant Depletion
Mode 5: Stage III Ignition During Stage II Thrust Phase
Mode 6: Stage III Ignition During Stage II Coast Phase
Mode 7: Failure to Achieve Stage III Spin-up
Mode 8: Loss of Stage II Coast Phase Attitude Control
Mode 9: Large Stage III Thrust Misalignment
Mode 10: Premature Stage III Thrust Termination
Dynamical Equations

Several thousand partial trajectory simulations are necessary to determine, by Monte Carlo techniques, the impact probability and casualty expectation for a given land mass. Solutions to the dynamical equations describing the behavior of the vehicle, when a failure mode is simulated, are approximated by closed form methods in order to minimize the time required to compute the trajectories. The inherent error resulting from the use of such methods has been found to be acceptable, since the equations represent, at best, an assumed behavior of the vehicle when a malfunction has occurred. The small errors which do exist may be thought of as adding to the randomness of the failure. Certainly, the accuracy of the equations is consistent with many of the other assumptions which have been made.

The equations which have been developed are not presented in this paper since a separate set is required for each failure mode and a presentation of all the equations would be rather lengthy. Also, such details are not required for an understanding of the basic approach. Furthermore, such equations will be dependent on the vehicle system under consideration and will differ from vehicle to vehicle.

Impact Coordinate Prediction

Once the burnout conditions of a stage have been calculated, the longitude and latitude of the resulting earth impact point are determined using standard two-body conic equations. For the sake of expedience, the effects of drag on re-entry are neglected. While this produces a shift in the resultant impact pattern, the overall effects on the probability calculations will, in general, be small. Planned revisions to the existing program include incorporation of the effects of atmospheric drag on the impact range to eliminate any possible discrepancies which might exist.

The use of the closed form two-body conic equations, excluding drag, has been justified since only the upper stages present a hazard to populated land areas in the event of a malfunction. Standard destruct criteria preclude impact on land for malfunctions occurring early in first stage flight. The malfunctions of concern predominantly occur after the vehicle is out of the atmosphere.

Country Search Routine

Once the impact coordinates of a malfunctioning stage have been computed it is necessary to determine the country that was impacted, if any. Three simple tests are performed to make this determination.

The first test isolates a small region of the earth's surface containing the impact point in question. Only those countries lying within this region are tested. This is done to minimize the number of countries required to be examined on any given search. The second test checks to see if the impact point is within the latitude and longitude extremes of each country (see figure 2). If it is not, the point is not in the country being examined. If it is, the third and final test is performed. Points (B), (C), (D) and (E) of figure 2 all would satisfy the second test. However, satisfying the second test does not necessarily mean that the point is in that country as can be seen by examining points (C) and (E). The third test is accomplished by computing the number of times the boundary of a country is crossed by that segment of the meridian joining the North Pole and the impact point in question. If the number is odd, the impact point lies within the boundaries of the country being tested. If even, it does not lie within the boundaries of the country being tested, and the searching process reverts to the second test for the next country to be tested.
Two cases arise which require special consideration. One has to do with islands or small countries and the other with countries that are contained wholly within the boundaries of another country.

First, except for very large sample sizes, small islands, cities, and small countries may not record any impacts even though the impact probability is finite. This problem is eliminated by defining an arbitrary boundary about such an area, sufficiently large as to include likely impact samples. The probability of impacting within the smaller area then is computed as the product of the probability of impacting within the larger, arbitrarily defined boundary and the ratio of the smaller area to the larger area. This assumes the impacts are uniformly distributed over the larger area.

Second, when one country is wholly within the boundaries of another country, the outer country's boundaries are not uniquely defined. The boundaries of such a country must be redefined by constructing two closely spaced parallel line segments extending from the natural boundary of one country to the natural boundary of the second country as shown in figure 3. The outer country is now a closed region which excludes the inner country.

Probability Calculations

The probability data are very easily computed. The conditional probability of impact in a particular country given a failure has occurred, \( P(I/F) \), is equal to the number of impacts recorded for that country divided by the total number of possible impacts which could result from the failure mode in question. The impact probability, \( P(I) \), for a given failure mode in a given country is equal to the failure probability, \( P_f \), multiplied by the conditional probability of impact given the failure occurs. That is,

\[
P(I) = P_f \cdot P(I/F).
\]

The casualty expectation, \( P(C) \), for a given failure mode and country is computed as the product of the impact probability, the population density, \( d \), for that country, and the lethal area, \( A_L \), of the impacting stage(s).

\[
P(C) = P(I) \cdot d \cdot A_L.
\]

The population of each country is assumed to be uniformly distributed, throughout the country.

Total impact and casualty expectation probabilities for a given country are computed by summing the probabilities calculated for the individual failure modes. In addition, the total probabilities for each failure mode summed over all countries are computed. Further, the combined total impact probability and casualty expectation for all failure modes and countries are computed by summing the individual totals.

Data Input

Vehicle Data. Since the state of a vehicle at the initiation of a failure mode must be supplied for each simulation of a failure, and because the time of occurrence of most modes of failure is a variable, extremely large amounts of input data are required. To efficiently handle this data, and to guarantee the minimization of input data error opportunities, pre-prepared magnetic data tapes are used. Such tapes supply position, velocity, acceleration, and attitude data of a given vehicle from launch
until payload insertion into orbit. To account for the effect of expected variations in vehicle performance, not only data for the desired (nominal) trajectory, but also data for three-sigma deviation trajectories must be recorded on these tapes.

For program versatility, a second group of data is input via load sheets or punched data cards. This group includes such information as simplified vehicle thrust, weight and attitude history simulation data, failure mode probabilities, and stage lethal areas.

Country Boundaries. The longitude and latitude of each corner of polygon approximations to the boundaries of all countries, cities, and other land areas of interest are stored along with area and population density data on a semi-permanent magnetic tape. These data are automatically retrieved when required during operation of the program. Figure 4 shows a typical polygon approximation of the boundaries of a country.

Data Output

Program output is provided in the form of probability tables and graphical displays, ready for immediate insertion into formal range safety reports. The tabular data give impact probability and casualty expectation by country and continent for each mode of failure. The graphical display data is a plot, on a world map, of the impact points used to determine the probability data. The shaded effect created by the impact points provides a clear picture of the impact distribution resulting from each mode of failure. The regions of highest impact density are clearly depicted. A sample output of the computer program is presented in the following section, describing the analysis of a typical failure mode.

Analysis of Typical Failure Mode

For illustration, the analysis of a typical failure mode is presented. The failure mode discussed is entitled "Loss of Stage II Coast Phase Attitude Control".

Normally, the vehicle coasts from second stage burnout to second stage apogee where the third stage is spun-up, separated from the second stage, and ignited to inject the third stage and its payload into orbit. During the coast phase the vehicle's attitude is controlled by a cold gas attitude control system. In the event of a failure of the attitude control system, the vehicle's attitude will be improperly aligned at third stage ignition. The resulting departure of the vehicle from its nominal flight path often will lead to an earth impact, as shown in figure 5.

For this failure mode the vehicle's attitude is assumed to be uniformly distributed over a unit sphere about the center of gravity of the third stage. The calculation of each sample begins with the selection, from a uniform distribution, of two random numbers \( (N_{R_1} \text{ and } N_{R_2}) \) ranging from zero to one. One is multiplied by \( 2\pi \) to obtain the sample roll attitude, \( \phi \), and the other is related to the cosine of the sample pitch attitude, \( \theta \). That is,

\[
\phi = 2\pi N_{R_1}
\]

\[
\theta = \cos^{-1} (2N_{R_2} - 1)
\]

An ordered roll-pitch rotation sequence is assumed. The attitude geometry is illustrated in figure 6.
Using the sample roll and pitch attitudes, the vehicle's weight and propulsion characteristics, and the initial position and velocity of the vehicle, the sample burnout conditions and, subsequently, the sample impact coordinates are computed. These calculations are repeated until the desired sample size is obtained. The impact probability and casualty expectation then are computed as described previously. Sample output data as obtained directly from the computer are given in Table I and figure 7. In computing these data, an arbitrary set of trajectory conditions were used and an arbitrary value of 0.01 was assumed for the failure mode probability. The output data are for illustrative purposes only; the data do not reflect actual values for any particular mission.

Sample Size Requirements

The Monte Carlo technique requires a fairly large sample size to insure that the probability data have been determined within specified accuracy limits at a specified confidence level. However, the sample size should be as small as possible in order not to require excessive amounts of computer time.

To date, the investigation of sample size requirements is limited to the running of several test cases at varying sample sizes for an arbitrarily selected failure mode. The failure mode examined was the one discussed in the previous section of this paper ... Loss of Stage II Coast Phase Attitude Control. Sample sizes of 1000, 5000, 10,000 and 15,000 were chosen for this comparison. Examination of the data revealed that a sample size of 5000 is adequate for this mode of failure. The impact pattern for this mode of failure covers a greater area than any other mode. For this reason, it is believed that a sample size of less than 5000 will provide adequate data for the other modes of failure.

This analysis was done for one mode of failure and one mission; however, it showed qualitatively and, to a certain extent, quantitatively that reasonably accurate impact probability data can be determined using the Monte Carlo technique without requiring excessively large sample sizes.

Program Operating Cost

The advantages of a program of this nature are apparent when its operation costs are compared with those of methods used prior to its development. Completion of the impact probability and casualty expectation data for a typical mission, including formal documentation, presently requires less than two weeks whereas five to six weeks were previously required to complete this task. Despite the fact that a Monte Carlo technique has been used, the IBM 7094 computer time requirements necessary to complete the analysis have been reduced by a factor of greater than four. Furthermore, significant reductions in the manpower requirements needed to do the analysis have been realized.

The impact hazard study for the SYNCOM III, equatorial, synchronous orbit communications satellite was performed using the technique presented in this paper. A sample size of 5000 was used with the expenditure of 63 minutes of computing time. Eight minutes were required to print the tables and graphs presenting the data.

CONCLUDING REMARKS

The Monte Carlo technique has been successfully employed as a method for doing an impact hazard study in preparation for a space vehicle launch. The solution provides a method whereby the analyses can be completed with a minimum expenditure of elapsed time.
time, computer time, and engineering effort. Data output, in the form of probability tables and graphical displays, are provided by the computer, ready for immediate insertion into formal range safety reports.
### Table I

**IMPACTS RESULTING FROM LOSS OF STAGE 2 COAST PHASE ATTITUDE CONTROL - MODE 8**

<table>
<thead>
<tr>
<th>COUNTRY OR TERRITORY</th>
<th>IMPACT 1 PROBABILITY</th>
<th>CASUALTY 1 PROBABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AFRICA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angola</td>
<td>0.3490E-03</td>
<td>0.6284E-07</td>
</tr>
<tr>
<td>Basutoland</td>
<td>1.0000E-06</td>
<td>0.1067E-08</td>
</tr>
<tr>
<td>Bechuanaland</td>
<td>0.8000E-04</td>
<td>0.1502E-08</td>
</tr>
<tr>
<td>Burundi</td>
<td>0.6000E-05</td>
<td>0.1327E-07</td>
</tr>
<tr>
<td>Kenya</td>
<td>0.6000E-04</td>
<td>0.3488E-07</td>
</tr>
<tr>
<td>Malagasy</td>
<td>0.2500E-04</td>
<td>0.1079E-07</td>
</tr>
<tr>
<td>Mozambique</td>
<td>0.4100E-04</td>
<td>0.1628E-07</td>
</tr>
<tr>
<td>Nyasaland</td>
<td>0.8000E-05</td>
<td>0.8462E-06</td>
</tr>
<tr>
<td>Republic of Congo</td>
<td>0.1290E-03</td>
<td>0.1322E-07</td>
</tr>
<tr>
<td>Republic of the Congo</td>
<td>0.4510E-03</td>
<td>0.1265E-06</td>
</tr>
<tr>
<td>Republic of South Africa</td>
<td>0.9700E-04</td>
<td>0.5834E-07</td>
</tr>
<tr>
<td>Rwanda</td>
<td>0.8000E-05</td>
<td>0.3444E-07</td>
</tr>
<tr>
<td>Somalia</td>
<td>0.8000E-05</td>
<td>0.1112E-08</td>
</tr>
<tr>
<td>Southern Rhodesia</td>
<td>0.2500E-04</td>
<td>0.9367E-08</td>
</tr>
<tr>
<td>Southwest Africa</td>
<td>0.1390E-03</td>
<td>0.4188E-08</td>
</tr>
<tr>
<td>Swaziland</td>
<td>1.0000E-06</td>
<td>0.7117E-09</td>
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<tr>
<td>Tanganyika</td>
<td>0.1090E-03</td>
<td>0.5069E-07</td>
</tr>
<tr>
<td>Uganda</td>
<td>0.2600E-04</td>
<td>0.3396E-07</td>
</tr>
<tr>
<td>Zambia</td>
<td>0.6400E-04</td>
<td>0.9897E-08</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>0.1627E-02</td>
<td>0.4915E-06</td>
</tr>
</tbody>
</table>

| **AUSTRALIA**        |                       |                        |
| Queensland           | 0.1600E-04            | 0.6514E-09            |
| South Australia      | 0.1900E-04            | 0.8335E-09            |
| Western Australia    | 0.5500E-04            | 0.7546E-09            |
| No. Ter. of Australia| 0.2800E-04            | 0.2511E-10            |
| **TOTAL**            | 0.1180E-03            | 0.2265E-08            |

| **INDIAN OCEAN ISLANDS** |                       |                        |
| Chagos Islands        | 0.6423E-08            | 0.4356E-11            |
| Cocos Islands         | 0.2525E-09            | 0.5497E-12            |
| Comoro Islands        | 0.3465E-07            | 0.1318E-09            |
| Maldives Islands      | 0.4000E-09            | 0.5614E-11            |
| Mauritius             | 0.6260E-07            | 0.1023E-08            |
| Reunion               | 0.1313E-06            | 0.8141E-09            |
| Seychelles Islands    | 0.5079E-07            | 0.2418E-09            |
| Zanzibar and Pemba    | 0.9150E-07            | 0.4987E-09            |
| **TOTAL**             | 0.3779E-06            | 0.2720E-08            |

1. The numerical values do not reflect actual data for any particular mission.
COMPUTATIONAL FLOW CHART

1. SELECT FAILURE MODE
2. SELECT RANDOM VARIABLES
3. CALL STATE VARIABLES
4. COMPUTE "BURNOUT" CONDITIONS
5. COMPUTE IMPACT COORDINATES
6. IDENTIFY COUNTRY IMPACTED

**REPEAT N TIMES**

**REPEAT FOR EACH FAILURE MODE**

- COMPUTE \( P_c \)
  - SUM \( P_c \)
  - OUTPUT \( P_1 & P_c \)
- COMPUTE \( P_1 \)
  - SUM \( P_1 \)
  - COMPUTE CONDITIONAL \( P_1 \)
COUNTRY SEARCH GEOMETRY

LATITUDE EXTREMES

LONGITUDE EXTREMES

IMPACT POINT

COUNTRY
BOUNDARY DEFINITION FOR NESTED COUNTRIES

COUNTRY A

COUNTRY B
COUNTRY BOUNDARY APPROXIMATION

GEOGRAPHIC BOUNDARY

APPROXIMATION TO GEOGRAPHIC BOUNDARY
LOSS OF STAGE II COAST PHASE ATTITUDE CONTROL

- Attitude error at Stage III ignition
- Nominal Stage III ($\theta = 0$)
- Stage II burnout
- Stage II ignition
- Stage III and payload impact
DISTRIBUTION OF IMPACTS

M-23184