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# SERVICE MODULE ENTRY CHARACTERISTICS

By Richard E. Kincade,
Flight Analysis Branch



MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
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# PROJECT APOLLO

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## SUMMARY

Many studies have been performed by the Mission Planning and Analysis Division to describe the characteristics of the Apollo service module (SM) when entering from near-earth orbital and lunar missions. This document summarizes these studies and presents the most probable SM motion during entry and the methods in which these entries can be simulated. Entry characteristics for both an intact SM and SM fragments following structural breakup are considered.


## INTRODUCTION

A knowledge of the SM entry conditions and subsequent motion is necessary for mission planning. This information is essential in eliminating recontact problems between the command module (CM) and the SM during entry and in determining the hazards to earth's inhabitants as the result of impacting fragments of the SM.

The nominal separation of the CM from the SM is defined herein as the separation of a nearly fuel-depleted SM with all reaction control system (RCS) thrusters in operation. The RCS thrusters burn to fuel depletion approximately 150 seconds after CM/SM separation. As the result of mass asymmetries, the nominal roll-up of the SM imparts a certain degree of oscillation. The resultant oscillations of the RCS thrust vector reduce translational efficiency to some extent. The vehicle essentially performs two oscillations about the origin following each large amplitude oscillation. The majority of the motion is near the origin with very little degradation of the relative velocity. The SM should in effect experience essentially zero lifting during entry as a result of the "corkscrew" type motion.

ENTRY CHARACTERISTICS OF AN INTACT SM

Reference 1 has considered how the CM/SM separation $\Delta V$'s, SM lift-to-drag ratios (L/D), and SM bank angle during entry affect the impacts of the SM in comparison with the CM. It presents the results of a study of the SM entry conditions computed as functions of the CM entry conditions. The CM entry conditions were specified by the RCS and service propulsion system (SPS) target lines for the low velocity (25 400 to 27 000 fps) and for the high velocity (30 000 to 37 000 fps) entries. Spacecraft weights were selected to coincide as closely as possible to the $\Delta V$ capabilities of the SM RCS. Comparisons of the touchdown points of the CM and SM were made for various SM L/D's and a fixed one-half lift entry of the CM. An SM L/D of 0.3 and a bank angle of $60^\circ$ were used to obtain maximum crossranges.

The data derived in this study can be used to estimate relative landing points of the SM and CM and dispersion areas of the SM impact points (IP). The data indicates that for an SM L/D of 0.3, the SM will have a touchdown point in front of the CM half-lift point unless higher than nominal separation $\Delta V$'s are used. For lower SM L/D's the SM impacts behind the CM. In the event of CM entries on either of the target lines, the SM downranges decrease as the CM entry flight-path angle and velocity increase.

A more sophisticated analysis of the motion of the SM during entry is presented in reference 2. It discusses the results of the six-degrees-of-freedom motion study for both the fully propellant-loaded and empty entering SM. These analyses were conducted in order to obtain a clearer understanding of SM motion during entry and to verify that this motion can be approximated by a point-mass simulation.

Entry inertial velocities ($V_i$) of 10 000 to 25 000 fps, inertial flight-path angles ($\gamma_i$) of $-4^\circ$ to $-15^\circ$, and a representative range of values for weight (fully loaded and empty), moments of inertia, spin rate at entry, and attitude at entry were used in simulating the atmospheric entry of the SM.

The results of this analysis indicate that for the altitude range of 400 000 ft to 200 000 ft, differences between trajectories of tumbling, non-spinning and spin-stabilized SM's are insignificant (fig. 1). Below 200 000 ft, the tumbling drag point-mass trajectory for the empty SM (based on a drag coefficient of 1.8) and the trajectories simulated for all spin-stabilized empty SM's are nearly identical. This condition is also true of the fully propellant-loaded SM.

Deviations from the tumbling drag and spin-stabilized trajectories resulted when the spin rates were approximately zero for the empty SM. This is due to the motion brought about by the highly nonlinear aerodynamic forces and moments for the non-spinning SM. Differences between the full non-spinning SM trajectories and the tumbling drag and spin-stabilized trajectories were also noted. However, these differences are much smaller than those resulting from the empty SM. Figure 2 presents an example of the differences between the tumbling, non-spinning and spin-stabilized trajectories for the empty SM, and figure 3 represents the deviations between the three simulations for the fully loaded vehicle.

Based on the results of this analysis of SM motion during entry from 400 000 to 100 000 ft in altitude, the following can be concluded:

1. Point-mass trajectory simulations, using a tumbling drag coefficient of 1.8, are acceptable representations of the actual entry trajectories for reasonable SM spin rates (2 rad/sec for the empty SM and 0.5 rad/sec for the full SM).

2. Six-degrees-of-freedom simulations are required when the empty SM is not spin-stabilized before entry because the actual entry trajectory deviates significantly relative to its tumbling drag simulated trajectory. The fully loaded SM trajectory is far less affected by spin-stabilization, indicating a tumbling drag trajectory simulation is probably acceptable.

Reference 3 extends the analysis in reference 2 to include an entry $V_i$ = 36 300 fps and $\gamma_i = -7.3^\circ$ for the SM. A comparison of a six-degrees-of-freedom simulation of a spinning SM and a point-mass simulation using a drag coefficient of 1.8 is presented in figure 4. The comparison of the two trajectory simulations reveals that the error in range with the point-mass solution is less than 5 n. mi. throughout the entire trajectory to an altitude of 80 000 ft, while the difference in altitude is less than 1000 ft. The errors encountered for skip trajectories were approximately the same as those indicated above. Therefore, a tumbling drag point-mass simulation for the spin-stabilized SM is applicable for superorbital entry velocities.

## ENTRY CHARACTERISTICS OF THE SM FOLLOWING STRUCTURAL BREAKUP

All of the preceding sections supply a good knowledge of how the SM will act during entry if the SM does not experience structural breakup. However, theoretical analyses have been performed for Apollo orbital debris hazard evaluations which show that the SM does not impact as an intact vehicle. Figure 5 presents a representative pictorial view of the breakup and dispersion of entry debris. Actual tracking of a fragment of the entering AS-201 SM verifies these analyses. The following sections describe the methods which should be employed in order to define the structural breakup and impact of SM debris.

In the SM six-degrees-of-freedom trajectory studies performed in reference 4, a Newtonian pitching moment was computed about the center of gravity for angles of attack ($\alpha$) from $0^{\circ}$ to $180^{\circ}$. One of the trim points near $\alpha = 30^{\circ}$ was stable and a relatively strong trim point was indicated by the slope of the pitching moment curve. Since the mass properties of the vehicle and the initial angular rates were known, a six-degrees-of-freedom trajectory calculation was used to determine the entry motion. One of the Apollo missions evaluated for SM entry was AS-204, in which the motion of the intact SM was found to be a circular precession about a mean angle of attack that was $60^{\circ}$ at altitudes above 200 000 ft and decreased to $20^{\circ}$ at altitudes below 150 000 ft. Because of changes in entry conditions and in order to accurately determine the prediction of the vehicle breakup altitude, six-degrees-of-freedom trajectory simulations-to-impact for the intact vehicle are required for each mission.

Once the intact SM trajectory-to-impact has been calculated, aerodynamic loads and temperature histories at critical structural locations are then determined. Structural analyses are performed to establish primary breakup modes and the altitudes at which they occur. Aerodynamic, thermal, and structural analyses are repeated to determine secondary breakup modes and associated altitudes for the resulting pieces of the primary breakup mode. Conditions are then reached at which it can be assumed that all vehicle internal components are exposed to the entry environment and the vehicle is completely broken up.

After the SM has been completely broken up, survivability analyses are conducted on the vehicle components. This requires a detailed knowledge of sizes, shapes, weights, materials, and aerodynamic characteristics of the components in order to determine which objects will survive to impact and which will burn up in the atmosphere.

Trajectories are generated for each surviving piece to determine their zero-lift impact locations. Impact dispersions of each surviving piece of debris are determined by assuming a constant L/D and orienting the lift vector to provide the maximum downrange, uprange, and crossrange deviations from the non-lifting impact point. This is accomplished by positioning the lift vector, relative to the velocity vector, upward at $90^{\circ}$ and away from the earth, downward at $90^{\circ}$ and toward the earth, and sideward at $45^{\circ}$ to the plane of the trajectory and away from the earth. It should be noted that impact dispersions computed in this manner are not realistic, but because of all the uncertainties associated with the mass properties, shapes, and L/D for each surviving piece, it does represent a fixed-lift vector orientation that gives the maximum dispersion that could take place.

A summary of SM structural breakup and the number of surviving pieces of debris information for various Apollo missions are shown below. A more complete description can be found in the designated references.

| Mission | $V_i$ at entry, fps | $\gamma_i$ at entry, deg | Weight at entry, lb | Primary breakup altitude, ft | Secondary breakup altitude, ft | Number of impacting pieces, n.d. |
|---|---|---|---|---|---|---|
| AS-201 (ref. 5) | 25 262 | -7.59 | 9 430 | Not calculated prior to mission. | Not calculated prior to mission. Actual is 212 000 ft based on radar observation. | Not calculated prior to mission. |
| AS-202 (ref. 5) | 28 462 | -3.67 | 10 670 | 239 500 | 234 500 | 48 |
| AS-204 (ref. 6) | | | | | | |
| SPS deorbit with SM tumbling | 25 758 | -1.48 | 10 820 | 260 000 | 255 000 | 69 |
| SPS deorbit with SM trimmed at $90^{\circ}$ | 25 758 | -1.48 | 10 820 | 271 000 | 266 000 | 69 |
| RCS deorbit with SM tumbling | 25 831 | -0.93 | 11 105 | 281 000 | 271 000 | 67 |
| AS-501 (ref. 7) | 36 309 | -7.23 | 20 158 | 231 500 | 226 500 | 44 |
| AS-502 (ref. 8) | 36 334 | -7.13 | 9 980 | 230 000 | 225 000 | 44 |

## CONCLUSIONS

The nominal SM motion during entry can be defined as a circular precession about a mean angle of attack until it reaches its structural breakup altitude. The majority of the motion is spent near the origin ("corkscrew" motion) with little degradation of the relative velocity. As a result, the SM should experience essentially no lift until the vehicle breaks up.

For either the fully propellant-loaded or empty SM, the entry trajectory of a spin-stabilized SM can be adequately simulated by assuming the body to be a point mass with tumbling drag. The entry trajectories of the empty non-spinning SM are not properly represented by point-mass simulations and would require six-degrees-of-freedom motion studies to simulate this type of entry. The fully propellant-loaded vehicle with zero spin can probably be simulated successfully as a point-mass body with tumbling drag.

Estimations of landing points of the SM (assuming the vehicle does not breakup) relative to the CM and estimations of SM dispersion areas can be made by varying the CM/SM separation $\Delta V$'s, SM bank angles, and SM L/D's. For an L/D of 0.3, the SM will impact in front of the CM half-lift point unless high separation $\Delta V$'s are used. For lower L/D ratios, the SM has a touchdown point behind the CM. For CM entries on either of the target lines, the SM downranges decrease as the CM entry flight-path angle and velocity increase.

In order to present a true picture of SM entries, the breakup of the vehicle in the earth's atmosphere must also be considered. To simulate this requires a much more detailed analysis than those required for the entering intact SM. A knowledge of aerodynamic, thermodynamic, and structural properties of the intact vehicle is required to perform breakup analyses. Then, thermodynamic and aerodynamic characteristics of the pieces of the SM must be known to predict their survivability and dispersions. These evaluations are required for each Apollo mission because of differences in velocity, flight-path angle, and weight at entry. In these calculations six-degrees-of-freedom trajectory simulations are required.

All of this information can be utilized, according to the user's requirements, to simulate the entry trajectory of the SM. For real-time planning and other time-critical studies, the best method to employ in determining the nominal intact SM trajectory to impact is a tumbling drag point-mass simulation. Then, to account for the breakup of the SM, transfer the position of the dispersion ellipse (determined previously for the particular mission's operational trajectory SM impact point) to the new calculated tumbling drag point-mass impact point.

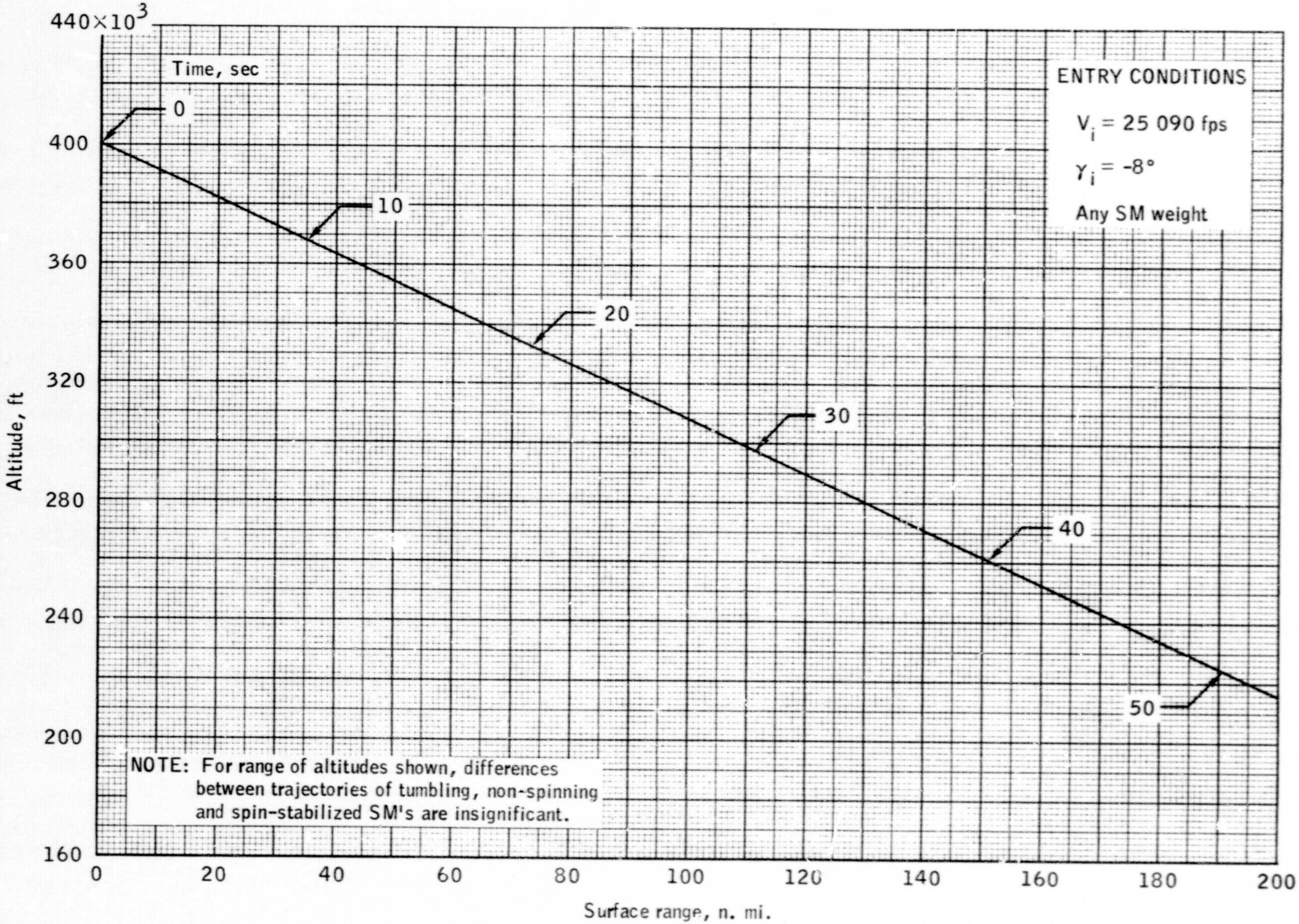


Figure 1.- Comparisons between entry trajectories of tumbling, non-spinning and spin-stabilized SM's.

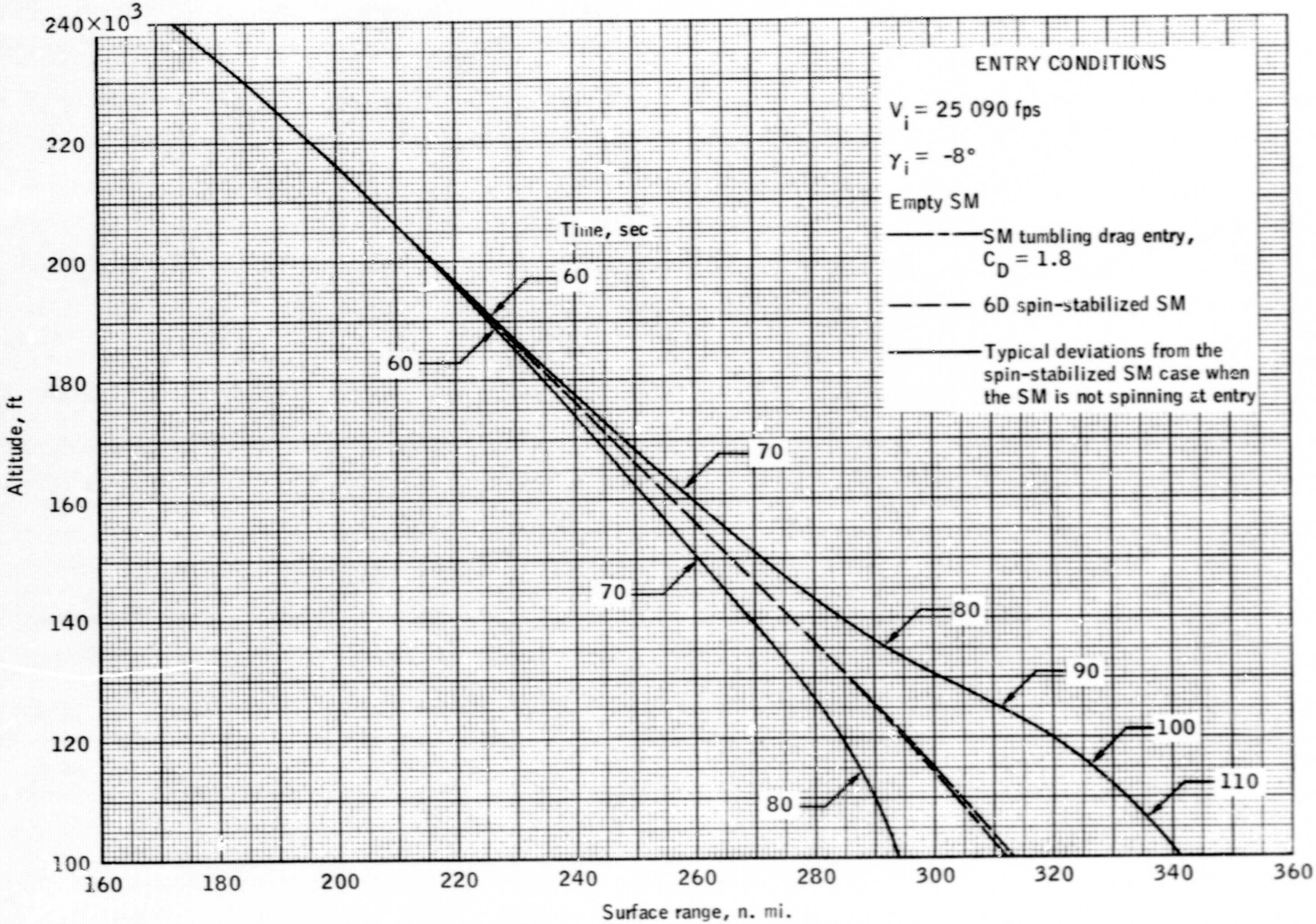


Figure 2.- Comparisons between entry trajectories of tumbling, non-spinning and spin-stabilized empty SM's.

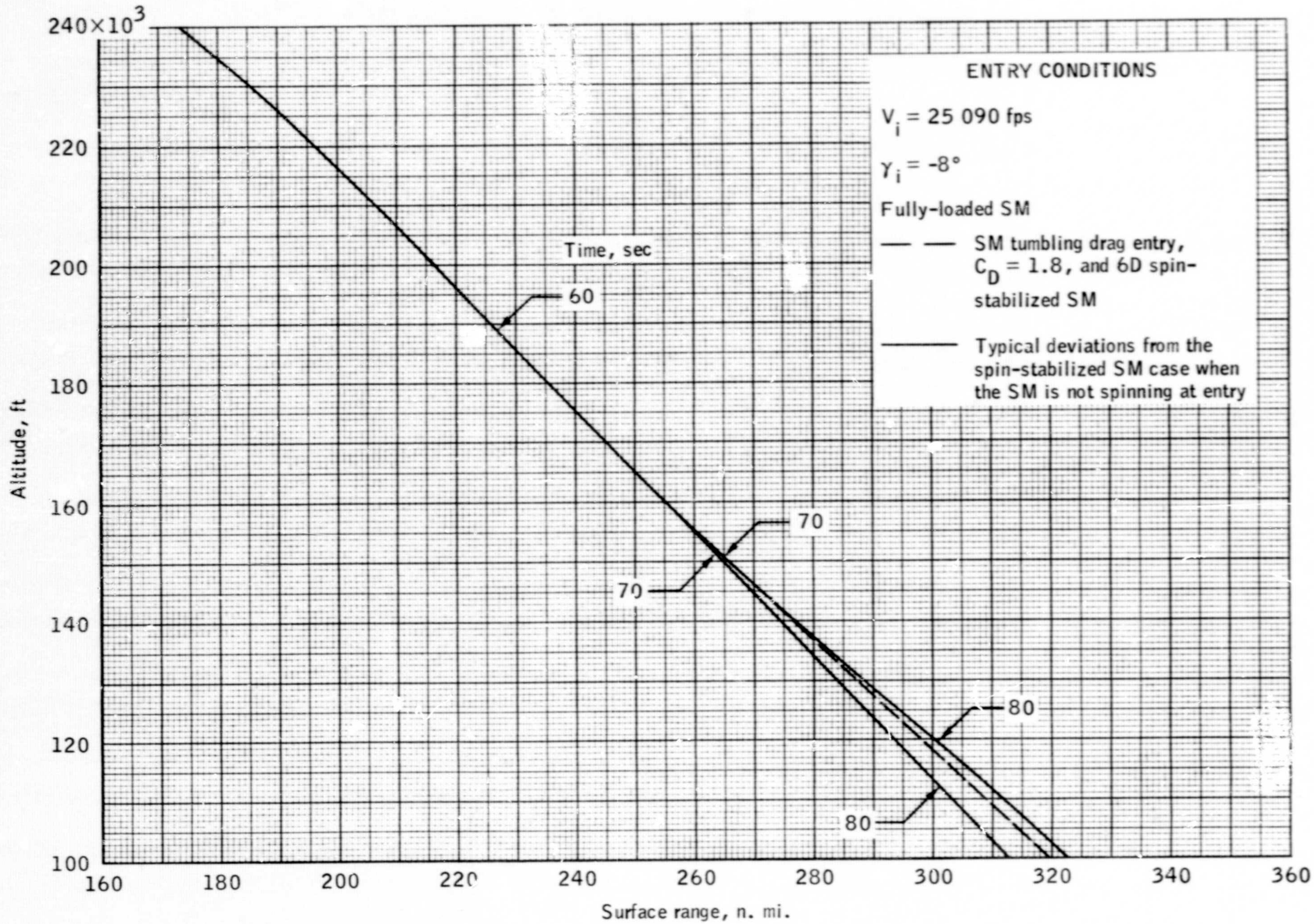


Figure 3.- Comparisons between entry trajectories of tumbling, non-spinning and spin-stabilized fully-loaded SM's.

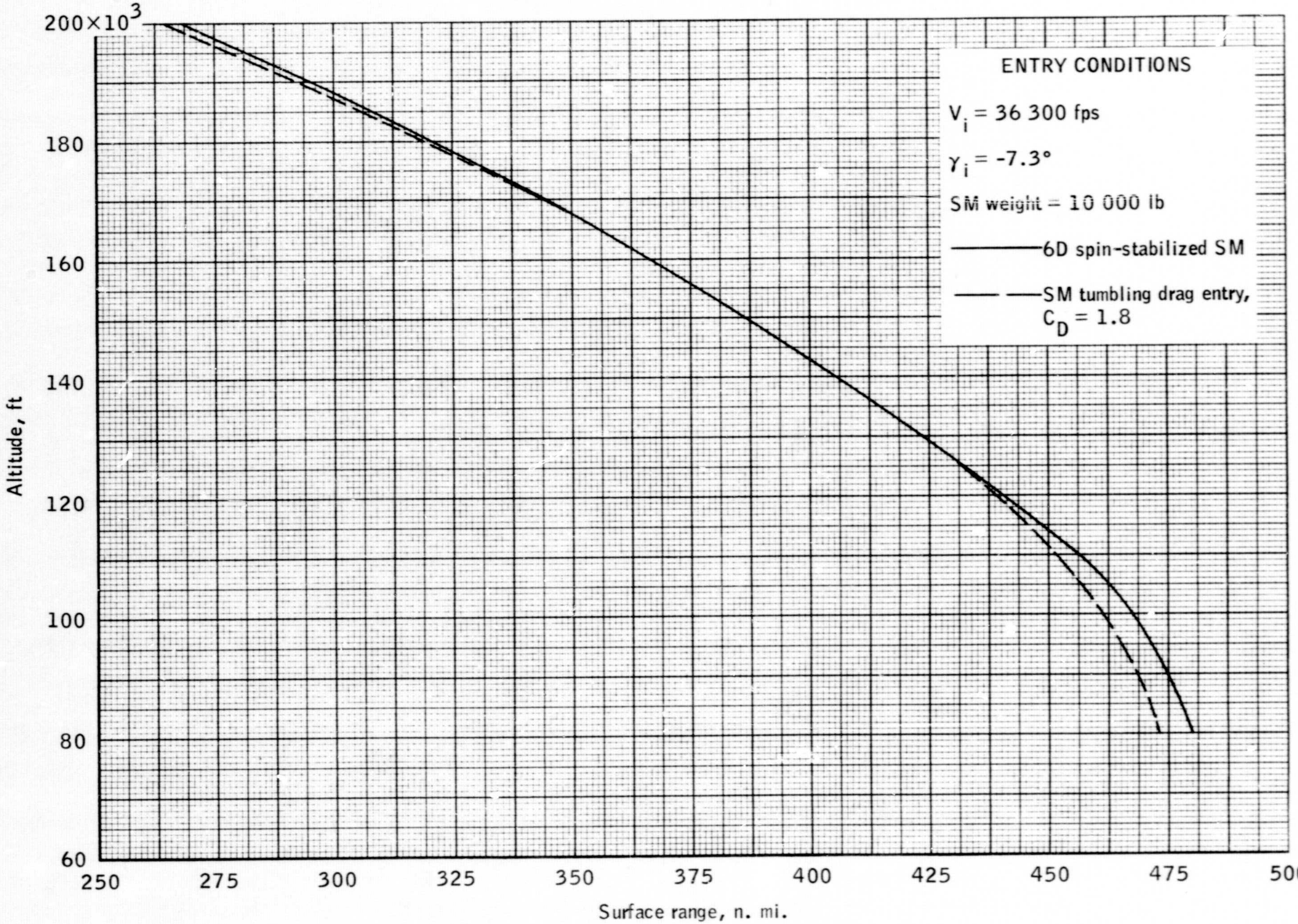


Figure 4.- Comparisons between entry trajectories of tumbling and spin-stabilized SM's.

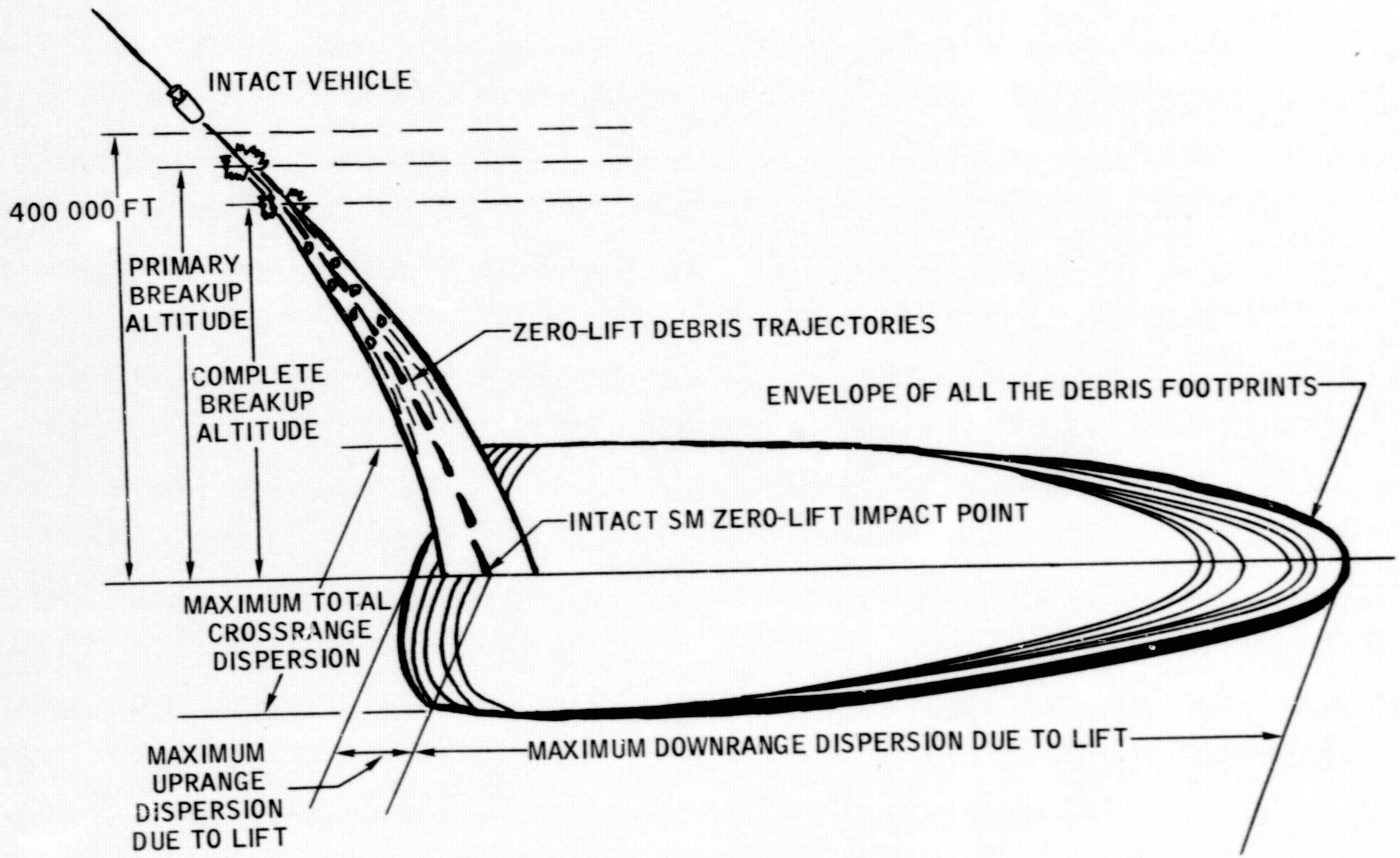


Figure 5.- Pictorial view of the breakup and dispersion of entry debris.

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