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AN ANALYTICAL METHOD FOR STUDYING THE LATERAL MOTION OF ATMOSPHERE ENTRY VEHICLES

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SUMMARY

An analytical method for studying the lateral motion of entry vehicles is presented. The method is applicable for small entry angles and results obtained with the method are compared with results from numerical integration of the complete equations of motion. The method is found useful for studying maneuvers of vehicles with aerodynamic lift-drag ratios up to about 1.5. Thus, the method should be useful for vehicles of current practical interest. It is found that bank angles of about 45° are sufficient to utilize the near maximum lateral-range potential of a vehicle without overly penalizing entry heating effects.

INTRODUCTION

Many authors have investigated the motion and heating of vehicles entering the earth's atmosphere (see, e.g., refs. 1, 2, 3). In these investigations, the effects of vehicle aerodynamic and mass characteristics on entry heating, deceleration, and range have been studied, and several convenient and useful simplified methods for analyzing entry trajectories have been developed. Primarily, attention has been devoted to the trajectories of entry vehicles which do not maneuver laterally. However, for the purposes of recovery or landing of the entry vehicle at a specified point on the earth's surface, the vehicle should be able to maneuver laterally. In fact, the lateral range of a vehicle during entry may be as important as the longitudinal range. The objective of the present paper is to develop approximate analytical methods which are useful for studying the lateral motion of entry vehicles.

SYMBOLS

A	vehicle reference area
C_D	drag coefficient
D	drag

G	resultant deceleration in g's
g	local acceleration of gravity
H	total heat
L	vertical component of lift
l	lateral displacement
m	mass of vehicle
r	distance from the center of the earth
r_o	radius of the earth
s	distance along the flight path
t	time
V	velocity
V_s	local circular satellite velocity
$\bar{V}$	normalized velocity, $\frac{V}{V_s}$
x	longitudinal displacement
Y	side force
$\left(\frac{L}{D}\right)_o$	vehicle lift-drag ratio in an unbanked attitude
β	logarithmic rate of decay of density with altitude
γ	flight-path angle with respect to local horizontal
ξ	side-force parameter
ρ	air density
Φ_n	function defined by equation (14)
φ	roll angle
ψ	lateral deflection angle

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Subscripts

E entry conditions

i conditions at initiation of maneuver

ANALYSIS

Equations of Motion

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The equations of motion for a lifting vehicle in unpowered flight are given as

$$\frac{dV}{dt} = \frac{dV}{ds}\frac{ds}{dt} = V\frac{dV}{ds} = \dot{V}$$

$$mV \frac{dV}{ds} = -D - mg \sin \gamma \tag{1}$$

$$\frac{d\gamma}{dt} = \frac{d\gamma}{ds}\frac{ds}{dt} = V\frac{d\gamma}{ds} = \dot{\gamma}$$

$$mV^2 \frac{d\gamma}{ds} = L - m \cos \gamma \left(g - \frac{V^2}{r}\right) \tag{2}$$

$$mV^2 \frac{d\psi}{ds} = Y \tag{3}$$

In this coordinate system, the drag, D, is opposite in direction to the instantaneous velocity, the lift, L, lies in the plane containing the center of the earth, and the side force, Y, is normal to L and D. If the side force, Y, is developed by banking the lifting vehicle, then for a vehicle which develops a constant aerodynamic lift-drag ratio of $(L/D)_o$ and for a bank angle φ we have

$$\frac{L}{D} = \left(\frac{L}{D}\right)_o \cos \varphi \tag{4}$$

$$\frac{Y}{D} = \left(\frac{L}{D}\right)_o \sin \varphi \tag{5}$$

In general, solution of the above set of equations involves numerical methods. For trajectories suitable for the entry of manned vehicles, that is, trajectories which tend to minimize decelerations and heating rates, the flight path angle, γ, must be restricted to moderate values. Thus, the usual approximations made to simplify the above equations are $|mg \sin \gamma| \ll D$ and $|\gamma| \ll 1$. Such assumptions lead to equations whose solutions give a good description of the portion of the trajectory where decelerations and heating are important (e.g., see ref. 1). With these approximations, combining equations (1) and (3) results in

$$d\psi = -\frac{Y}{D}\frac{dV}{V} \tag{6}$$

which integrates, for constant Y/D, to

$$\psi = \frac{Y}{D}\, \ln \frac{\overline{V}_i}{\overline{V}} \tag{7}$$

The subscript i refers to the point for which $\psi = 0$, and the velocity has been made dimensionless in terms of satellite velocity; that is, $\overline{V} \equiv V/V_s$. The equation gives the angle ψ through which the vehicle has turned laterally from the flight direction at the initiation of the maneuver.[1] Note that although the turn angle, ψ, does depend on the mass and the size of the vehicle and on the atmosphere, combining equations (1) and (3) to obtain equation (7) eliminates this explicit dependence so that it is possible to express ψ merely in terms of velocity and Y/D.

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The quasi-horizontal projection of the trajectory on the earth's surface is represented in figure 1. The incremental longitudinal and lateral displacements are

$$\left.\begin{aligned} dx &= ds \cos \psi \\ dl &= ds \sin \psi \end{aligned}\right\} \tag{8}$$

To obtain the total displacements, it is necessary to write ds as a function of velocity for the entry flight. This function depends on the particular trajectory flown. If the exact expression is known, equations (8) may be integrated numerically. However, at present, we are interested in certain approximate analytical solutions for various types of entry trajectories.

Entry Trajectories

Equilibrium-glide trajectory.- One class of trajectories of interest which may be treated analytically is the so-called equilibrium-glide entry where the vehicle weight is balanced by the lift plus centrifugal force in the vertical direction. This is consistent with the previously made assumptions of small flight-path angles and may be written in our notation as

$$\frac{ds}{r_o} = \left(\frac{L}{D}\right)\frac{\overline{V}\, d\overline{V}}{\overline{V}^2 - 1} \tag{9}$$

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[1]Actually ψ is in the plane of the instantaneous trajectory, but we neglect this for small γ.

Combining this equation with equations (7) and (8), we obtain

$$\frac{dl}{r_o} = \left(\frac{L}{D}\right) \frac{\overline{V}\, d\overline{V}}{\overline{V}^2 - 1} \sin\left[\frac{Y}{D}\left(ln\, \overline{V}_i - ln\, \overline{V}\right)\right] \tag{10}$$

If the lateral deflection angle, ψ, is small and the maneuver is initiated at satellite speed ($\overline{V}_i = 1$), equation (10) then reduces to

$$\frac{dl}{r_o} = \left(\frac{L}{D}\right)\left(\frac{Y}{D}\right) \frac{\overline{V}\, ln\, \overline{V}\, d\overline{V}}{1 - \overline{V}^2} \tag{11}$$

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which integrates, for the limits $\overline{V}_i = 1$ to $\overline{V} = 0$, to

$$\frac{l}{r_o} = \frac{\pi^2}{24}\left(\frac{L}{D}\right)_o^2 \sin\varphi \cos\varphi \tag{12}$$

and gives maximum lateral range at $\varphi = 45^\circ$. This particular result agrees with that given in reference 1.

In general, however, the lateral deflection is not restricted to small angles nor is the maneuver restricted to initiation at satellite speed and the integration of equation (10) is not straightforward. (Note that integration of eq. (11) is nonanalytic for limits between those given.) Consider, then, the series expansion of $\sin\psi$. For our purposes, retention of three terms is sufficient for accuracy of 1 percent up to angles of 90°. With the definition $\xi \equiv (Y/D)\, ln\, \overline{V}$, expansion of equation (10) gives

$$\frac{dl}{r_o} = \left(\frac{L}{D}\right) \frac{\overline{V}\, d\overline{V}}{\overline{V}^2 - 1}\left[\left(\xi_i - \frac{\xi_i^3}{3!} + \frac{\xi_i^5}{5!}\right) + \left(-1 + \frac{3}{3!}\xi_i^2 - \frac{5}{5!}\xi_i^4\right)\xi + \left(-\frac{3}{3!}\xi_i + \frac{10}{5!}\xi_i^3\right)\xi^2 + \left(\frac{1}{3!} - \frac{10}{5!}\xi_i^2\right)\xi^3 + \frac{5}{5!}\xi_i\xi^4 - \frac{1}{5!}\xi^5\right] \tag{13}$$

If we also define

$$\Phi_n = \int_{\overline{V}_i}^{\overline{V}} \frac{\eta(ln\, \eta)^n}{1 - \eta^2}\, d\eta \tag{14}$$

then

$$\frac{l}{r_o} = \left(\frac{L}{D}\right)\left[\left(-\xi_i + \frac{\xi_i^3}{3!} - \frac{\xi_i^5}{5!}\right)\Phi_o + \left(1 - \frac{3}{3!}\xi_i^2 + \frac{5}{5!}\xi_i^4\right)\left(\frac{Y}{D}\right)\Phi_1\right.$$

$$+ \left(\frac{3}{3!}\xi_i - \frac{10}{5!}\xi_i^3\right)\left(\frac{Y}{D}\right)^2\Phi_2 + \left(-\frac{1}{3!} + \frac{10}{5!}\xi_i^2\right)\left(\frac{Y}{D}\right)^3\Phi_3$$

$$\left. - \frac{5}{5!}\xi_i\left(\frac{Y}{D}\right)^4\Phi_4 + \frac{1}{5!}\left(\frac{Y}{D}\right)^5\Phi_5\right] \qquad (15)$$

for $\xi_i = 0$, this equation reduces to

$$\frac{l}{r_o} = \left(\frac{L}{D}\right)\left[\left(\frac{Y}{D}\right)\Phi_1 - \frac{1}{3!}\left(\frac{Y}{D}\right)^3\Phi_3 + \frac{1}{5!}\left(\frac{Y}{D}\right)^5\Phi_5\right] \qquad (16)$$

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For completeness, we include here the expression analogous to equation (15) for longitudinal range

$$\frac{x}{r_o} = \left(\frac{L}{D}\right)\left[\left(-1 + \frac{\xi_i^2}{2!} - \frac{\xi_i^4}{4!}\right)\Phi_o + \left(-\frac{2}{2!}\xi_i + \frac{4}{4!}\xi^3\right)\left(\frac{Y}{D}\right)\Phi_1\right.$$

$$\left. + \left(\frac{1}{2!} - \frac{6}{4!}\xi_i^2\right)\left(\frac{Y}{D}\right)^2\Phi_2 + \frac{4}{4!}\xi_i\left(\frac{Y}{D}\right)^3\Phi_3 - \frac{1}{4!}\left(\frac{Y}{D}\right)^4\Phi_4\right] \qquad (17)$$

Values of Φ_n are tabulated in table I. For $n = 0$, the integration is explicit

$$\Phi_o = \frac{1}{2}\, l n \frac{1 - \bar{V}_i^2}{1 - \bar{V}^2} \qquad (18)$$

With this result and with $Y/D = 0$, equation (17) gives the equilibrium-glide result for longitudinal range

$$\frac{x}{r_o} = \frac{1}{2}\left(\frac{L}{D}\right) l n \frac{1 - \bar{V}^2}{1 - \bar{V}_i^2} \qquad (19)$$

The limits of integration for Φ_n are determined from equation (7), which can be rewritten as

$$\overline{V} = \overline{V}_i e^{-\psi/(Y/D)} \tag{20}$$

where $\overline{V}_i$ is the velocity at initiation of the maneuver. Each Φ_n is, of course, the difference between the tabulated values at $\overline{V}$ and $\overline{V}_i$.

Entry at bank angles near 90°.- The foregoing analysis is useful for trajectories of the equilibrium-glide type. However, this analysis is not expected to give an accurate representation of the trajectory for vehicles which develop low lift in the vertical direction (L/D less than 1/4, say). Such is the case for entries at a large roll angle. Consider then, a trajectory with zero lift in the vertical plane, representing a decay from satellite orbit (see ref. 1, footnote p. 13-25). This may be written in our notation as

$$\frac{ds}{r_o} = -\frac{\sqrt{6}}{4\sqrt{\beta r_o}} \frac{d\overline{V}}{\overline{V}(-ln\ \overline{V})^{3/2}} \tag{21}$$

where β is the logarithmic rate of decay of air density with altitude. Combining equations (21), (7), and (8) for $\overline{V}_i = 1$ and $\sin\psi \approx \psi$, we obtain

$$\frac{dl}{r_o} = -\frac{\sqrt{6}}{4\sqrt{\beta r_o}} \left(\frac{Y}{D}\right) \frac{d\overline{V}}{\overline{V}(-ln\ \overline{V})^{1/2}} \tag{22}$$

Integration from $\overline{V}_i = 1$ results in

$$\frac{l}{r_o} = \frac{\sqrt{6}}{2\sqrt{\beta r_o}} \left(\frac{Y}{D}\right) \left(-ln\ \overline{V}\right)^{1/2} \tag{23}$$

From equation (7)

$$\frac{l}{r_o} = \left[\frac{3}{2\beta r_o} \left(\frac{Y}{D}\right) \psi\right]^{1/2} \tag{24}$$

This result is the lateral displacement expected for a lifting vehicle which enters the atmosphere from satellite speed in a roll attitude of 90° (i.e., $\frac{Y}{D} = \left(\frac{L}{D}\right)_o$).

Entry at escape speed.- The present method is also applicable to entries at other than satellite speed. For example, consider a vehicle which grazes the atmosphere, entering at escape speed and exiting at satellite speed. Equation (7) yields

$$\psi = \left(\frac{Y}{D}\right)\frac{ln\ 2}{2} \tag{25}$$

The plane of the resulting near-earth satellite orbit is thus deflected from the plane of the original entry trajectory by the angle ψ.

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RESULTS AND DISCUSSION

To test the validity of the present approximate analytical method, comparisons have been made with numerical solutions to the complete equations of motion (see, e.g., ref. 4). These solutions were obtained by use of a high-speed digital computer. The program included the effects of a rotating earth and atmosphere and the effects of geometric and gravitational oblateness. Characteristics of the atmosphere used in the program were obtained from reference 5. The results presented apply to entry at a constant bank angle (constant Y/D) held until a heading of $\psi = 90^\circ$ is reached. At this point, the vehicle may be rolled out to zero bank angle and the additional range which will result is given by the familiar equilibrium-glide result, equation (19). However, for small lift-drag ratios, the additional range is small. For example, numerical results for a vehicle with $(L/D)_o = 1.5$, $\overline{V}_i = 1$, $\Phi = 45^\circ$, and $C_DA/m = 0.5$ which enters from an easterly equatorial orbit indicate that the velocity at the end of the 90° turn is approximately 5,000 feet per second. From equation (19) then, the additional range potential is approximately 100 nautical miles or less than 10 percent of the lateral displacement which resulted from the banked turn to $\psi = 90^\circ$. For smaller lift-drag ratios, the percentage increase in lateral displacement is less. Thus in most of the following discussion, the lateral range to 90° heading was used as a basis of comparison with numerical results to the same heading.

Effect of Bank Angle

The effect of bank angle on the lateral range is shown in figure 2. The results were computed for a vehicle of constant $C_DA/m = 0.5$ sq ft/slug and $(L/D)_o = 1$ entering the atmosphere at satellite velocity in a banked attitude.[2] The lateral ranges presented for the numerical solutions

[2]Note that the analysis has indicated the lateral range is independent of C_DA/m. Numerical computations have shown that this is substantially correct if trajectories with different C_DA/m are compared at points where the velocities are equal.

and for equation (16) correspond to the point on the trajectory where the deflection angle ψ is 90°; whereas, the lateral ranges presented for the small-angle approximation (eq. (12)) correspond to the point on the trajectory where the velocity drops to zero. Numerical data are presented for entry from an equatorial orbit, both for entry east to west, and for entry, west to east. The east to west entry results in a greater lateral range since the velocity relative to the atmosphere and, hence, the dynamic pressures acting on the vehicle are greater. We see that a maximum lateral range occurs for a roll angle in the neighborhood of 45° and this angle is used in subsequent calculations. It is also observed that the equilibrium-glide analysis (eqs. (12) and (16)) gives zero lateral range at a bank angle of 90°. This result is, of course, in error. A more accurate estimate is obtained with the zero-lift entry analysis (eq. (24)). The later method gives results which agree within about 15 percent with those obtained numerically.

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Effect of Lift-Drag Ratio

The effect of lift-drag ratio on lateral range is shown in figure 3. The results shown are for vehicles with a C_DA/m of 0.5 square foot per slug at a constant bank angle of 45°. Results are presented for both the small ψ approximation (eq. (12)) and for the more complicated equation (16) which resulted from a series expansion. Again, the lateral range shown corresponds to the point in the trajectory where $\psi = 90^{\circ}$ except for equation (12). When compared to the numerical results, both equations (12) and (16) give overestimates of the lateral range at higher lift-drag ratios. It would be expected that equation (12) would overestimate the lateral range since not only is the range computed at the point where $\overline{V}$ is zero instead of at the point where $\psi = 90^{\circ}$, but also the assumption that ψ is small is violated at the higher lift-drag ratios. The inaccuracy of the present methods is also attributed partly to the use of "flat-earth" coordinates in the analysis. This approximation introduces significant errors when the lateral range becomes appreciable compared to the earth's radius which is the case for lift-drag ratios of 2 or more. It appears, however, that at least equation (16) yields adequate results for lift-drag ratios up to 1.5. Since lift-drag ratios up to about this value are of most practical interest at present, it does not appear that the inaccuracies of the present method are a serious limitation of its usefulness.

From the numerical results on figure 3, it is also noted that the westerly equatorial entry may yield lateral displacements as much as 20 percent greater than that of the easterly entry. It is expected that entry from orbits of other inclinations will yield values between these extremes.

Entry Flight-Path Angle

Since entry may not necessarily be along an equilibrium-glide flight path, it is of interest to determine the effect of departure from this type of entry trajectory. This effect was studied numerically by changing γ_E and computing the lateral displacement, and the results are shown in figure 4. The lateral range is decreased for steeper entries but the effect is less than 10 percent for entry angles up to -5°. At the same time, however, the longitudinal range is decreased 40 percent for a change in γ_E from -2° to -5° (ref. 2). Therefore, even though the longitudinal range is sensitive to entry angle, moderate departures from the equilibrium-glide flight path do not invalidate the present results for lateral range.

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Velocity at Initiation of Maneuver

The effect on lateral range of the velocity at the beginning of a roll maneuver was also studied. It was found that the lateral range capability is quite sensitive to the velocity at which the maneuver is initiated. Figure 5 shows this effect for a lift-drag ratio of 1.0 and a roll angle of 45°. The results shown were obtained with equation (15) and comparison is made with results obtained numerically. For the numerical results, the abscissa was obtained from the inertial velocity rather than the relative velocity. In general, the results obtained with equation (15) are in good agreement with the numerical results. Note that the maneuver must be initiated at close to satellite speed if the maximum lateral range potential is to be realized. For example, it is indicated that delay of the maneuver until the critical heating point ($\bar{V}_i \approx 0.8$) results in a loss of lateral range of 50 percent.

Deceleration and Heating

The deceleration and heating for entry in a banked attitude are summarized in figure 6. The curves presented are taken from reference 1. The maximum deceleration varies inversely with $\cos \varphi$ and the total heating and maximum heating rate vary directly and inversely with the square root of $\cos \varphi$, respectively. Also shown on figure 6 are numerical data for the equatorial west to east entry. It is noted that for bank angles up to 45°, the increases in maximum heating rate and maximum deceleration are not severe (the maximum heating rate is increased approximately 20 percent at $\varphi = 45^{\circ}$). However, heating considerations may limit the use of bank angles greater than 45°.

CONCLUDING REMARKS

An investigation has been made of the lateral motion of satellite vehicles which enter the earth's atmosphere. Simple analytical methods appear to be adequate for studying small entry-angle trajectories for lift-drag ratios up to about 1.5. Bank angles of 45° tend to yield the maximum lateral range. The use of higher bank angles may be limited by heating considerations. It was found that the velocity at which the banked maneuver is initiated bears importantly on the resultant lateral displacement and that delay in initiation of the maneuver to a velocity 80 percent of satellite velocity may result in a loss of lateral range potential of 50 percent. The effect of entry angle on lateral range was
A found to be small in comparison with its strong effect on longitudinal
3 range. Numerical studies indicated that neglect of the earth's rotation
7 in calculations may introduce errors of as much as 10 percent in the
9 resultant lateral range.

Ames Research Center
National Aeronautics and Space Administration
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TABLE I.- VALUES OF THE FUNCTION Φ_n

$\bar{V}$	Φ_0	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	$\bar{V}$	Φ_0	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5
1.00	∞	0	0	0	0	0	0.49	0.1373	0.2492	-0.0773	0.0341	-0.0175	0.0097
.99	1.9585	.0050	.0000	.0000	.0000	.0000	.48	.1309	.2538	-.0806	.0366	-.0192	.0109
.98	1.6145	.0100	-.0001	.0000	.0000	.0000	.47	.1248	.2584	-.0840	.0391	-.0211	.0123
.97	1.4143	.0150	-.0002	.0000	.0000	.0000	.46	.1189	.2629	-.0875	.0417	-.0231	.0139
.96	1.2730	.0200	-.0004	.0000	.0000	.0000	.45	.1131	.2674	-.0910	.0445	-.0253	.0156
.95	1.1640	.0250	-.0006	.0000	.0000	.0000	.44	.1076	.2719	-.0947	.0475	-.0277	.0176
.94	1.0754	.0300	-.0009	.0000	.0000	.0000	.43	.1022	.2764	-.0984	.0506	-.0303	.0197
.93	1.0009	.0350	-.0012	.0001	.0000	.0000	.42	.0970	.2808	-.1022	.0538	-.0331	.0221
.92	.9367	.0400	-.0016	.0001	.0000	.0000	.41	.0920	.2852	-.1061	.0572	-.0361	.0247
.91	.8804	.0450	-.0021	.0001	.0000	.0000	.40	.0872	.2896	-.1100	.0608	-.0393	.0276
.90	.8304	.0500	-.0026	.0002	.0000	.0000	.39	.0825	.2940	-.1140	.0646	-.0428	.0309
.89	.7853	.0550	-.0031	.0002	.0000	.0000	.38	.0780	.2983	-.1182	.0685	-.0466	.0345
.88	.7445	.0600	-.0038	.0003	.0000	.0000	.37	.0736	.3026	-.1224	.0726	-.0506	.0384
.87	.7071	.0649	-.0044	.0004	.0000	.0000	.36	.0694	.3068	-.1266	.0769	-.0549	.0428
.86	.6728	.0699	-.0051	.0005	-.0001	.0000	.35	.0653	.3110	-.1310	.0814	-.0596	.0477
.85	.6410	.0749	-.0059	.0006	-.0001	.0000	.34	.0614	.3152	-.1354	.0862	-.0646	.0530
.84	.6114	.0799	-.0068	.0008	-.0001	.0000	.33	.0576	.3193	-.1400	.0911	-.0700	.0589
.83	.5838	.0848	-.0076	.0009	-.0001	.0000	.32	.0540	.3234	-.1445	.0963	-.0758	.0654
.82	.5580	.0898	-.0086	.0011	-.0002	.0000	.31	.0505	.3274	-.1492	.1016	-.0821	.0726
.81	.5337	.0948	-.0096	.0013	-.0002	.0000	.30	.0472	.3314	-.1540	.1073	-.0888	.0806
.80	.5108	.0997	-.0107	.0016	-.0003	.0000	.29	.0439	.3354	-.1588	.1132	-.0959	.0893
.79	.4892	.1047	-.0118	.0018	-.0003	.0001	.28	.0408	.3393	-.1636	.1193	-.1036	.0990
.78	.4688	.1096	-.0130	.0021	-.0004	.0001	.27	.0378	.3431	-.1686	.1257	-.1119	.1097
.77	.4493	.1146	-.0143	.0024	-.0005	.0001	.26	.0350	.3469	-.1736	.1324	-.1207	.1214
.76	.4309	.1195	-.0156	.0028	-.0006	.0001	.25	.0323	.3506	-.1787	.1393	-.1303	.1344
.75	.4133	.1245	-.0170	.0032	-.0007	.0002	.24	.0297	.3543	-.1839	.1466	-.1405	.1488
.74	.3966	.1294	-.0185	.0036	-.0008	.0002	.23	.0272	.3579	-.1891	.1541	-.1514	.1647
.73	.3806	.1343	-.0200	.0041	-.0009	.0002	.22	.0248	.3614	-.1944	.1620	-.1632	.1822
.72	.3653	.1392	-.0216	.0046	-.0011	.0003	.21	.0226	.3649	-.1997	.1702	-.1757	.2015
.71	.3507	.1441	-.0232	.0051	-.0013	.0004	.20	.0204	.3683	-.2051	.1787	-.1892	.2229
.70	.3367	.1490	-.0249	.0057	-.0015	.0004	.19	.0184	.3716	-.2105	.1876	-.2037	.2466
.69	.3232	.1539	-.0267	.0064	-.0017	.0005	.18	.0165	.3748	-.2160	.1968	-.2192	.2728
.68	.3103	.1588	-.0285	.0071	-.0020	.0006	.17	.0147	.3780	-.2214	.2063	-.2359	.3019
.67	.2979	.1637	-.0304	.0078	-.0023	.0007	.16	.0130	.3810	-.2269	.2162	-.2538	.3341
.66	.2860	.1686	-.0324	.0086	-.0026	.0009	.15	.0114	.3840	-.2325	.2265	-.2730	.3699
.65	.2745	.1734	-.0345	.0095	-.0030	.0010	.14	.0099	.3868	-.2380	.2372	-.2936	.4097
.64	.2635	.1782	-.0366	.0104	-.0034	.0012	.13	.0085	.3896	-.2435	.2482	-.3157	.4540
.63	.2528	.1831	-.0388	.0114	-.0039	.0014	.12	.0073	.3922	-.2490	.2597	-.3394	.5034
.62	.2426	.1879	-.0411	.0125	-.0044	.0016	.11	.0061	.3948	-.2544	.2715	-.3650	.5585
.61	.2327	.1927	-.0434	.0136	-.0049	.0019	.10	.0050	.3972	-.2598	.2836	-.3924	.6023
.60	.2231	.1975	-.0458	.0148	-.0055	.0022	.09	.0041	.3994	-.2651	.2961	-.4218	.6896
.59	.2139	.2023	-.0483	.0161	-.0062	.0026	.08	.0032	.4015	-.2703	.3089	-.4534	.7676
.58	.2050	.2071	-.0509	.0175	-.0069	.0030	.07	.0025	.4035	-.2754	.3220	-.4874	.8556
.57	.1964	.2118	-.0535	.0190	-.0077	.0034	.06	.0018	.4053	-.2803	.3354	-.5238	.9553
.56	.1881	.2166	-.0562	.0205	-.0086	.0039	.05	.0013	.4069	-.2849	.3488	-.5628	1.0686
.55	.1801	.2213	-.0590	.0222	-.0096	.0045	.04	.0008	.4083	-.2892	.3623	-.6046	1.1981
.54	.1724	.2260	-.0618	.0239	-.0106	.0051	.03	.0005	.4094	-.2932	.3754	-.6488	1.3466
.53	.1649	.2307	-.0648	.0257	-.0118	.0058	.02	.0002	.4104	-.2966	.3880	-.6950	1.5176
.52	.1576	.2353	-.0678	.0276	-.0130	.0066	.01	.0001	.4110	-.2992	.3990	-.7415	1.7134
.51	.1506	.2400	-.0709	.0297	-.0144	.0075	.00	.0000	.4112	-.3005	.4059	-.7777	1.9075
.50	.1438	.2446	-.0740	.0319	-.0159	.0085							

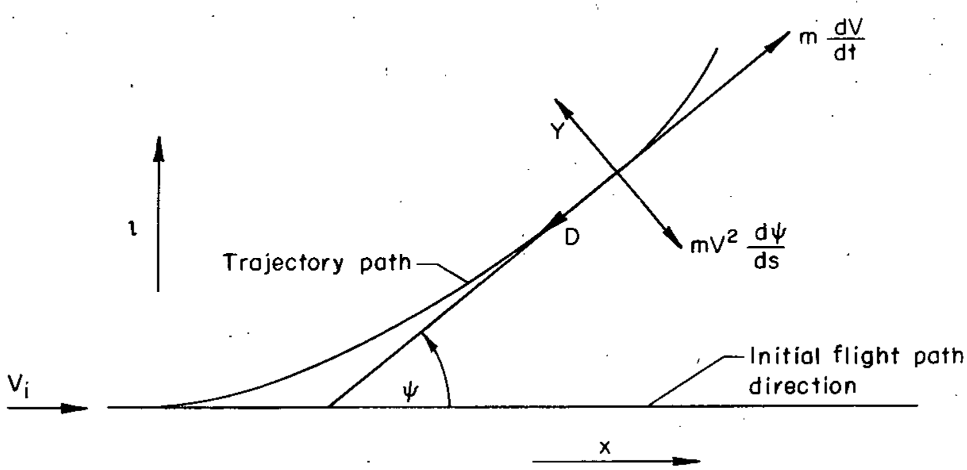

Figure 1.- Coordinate system.

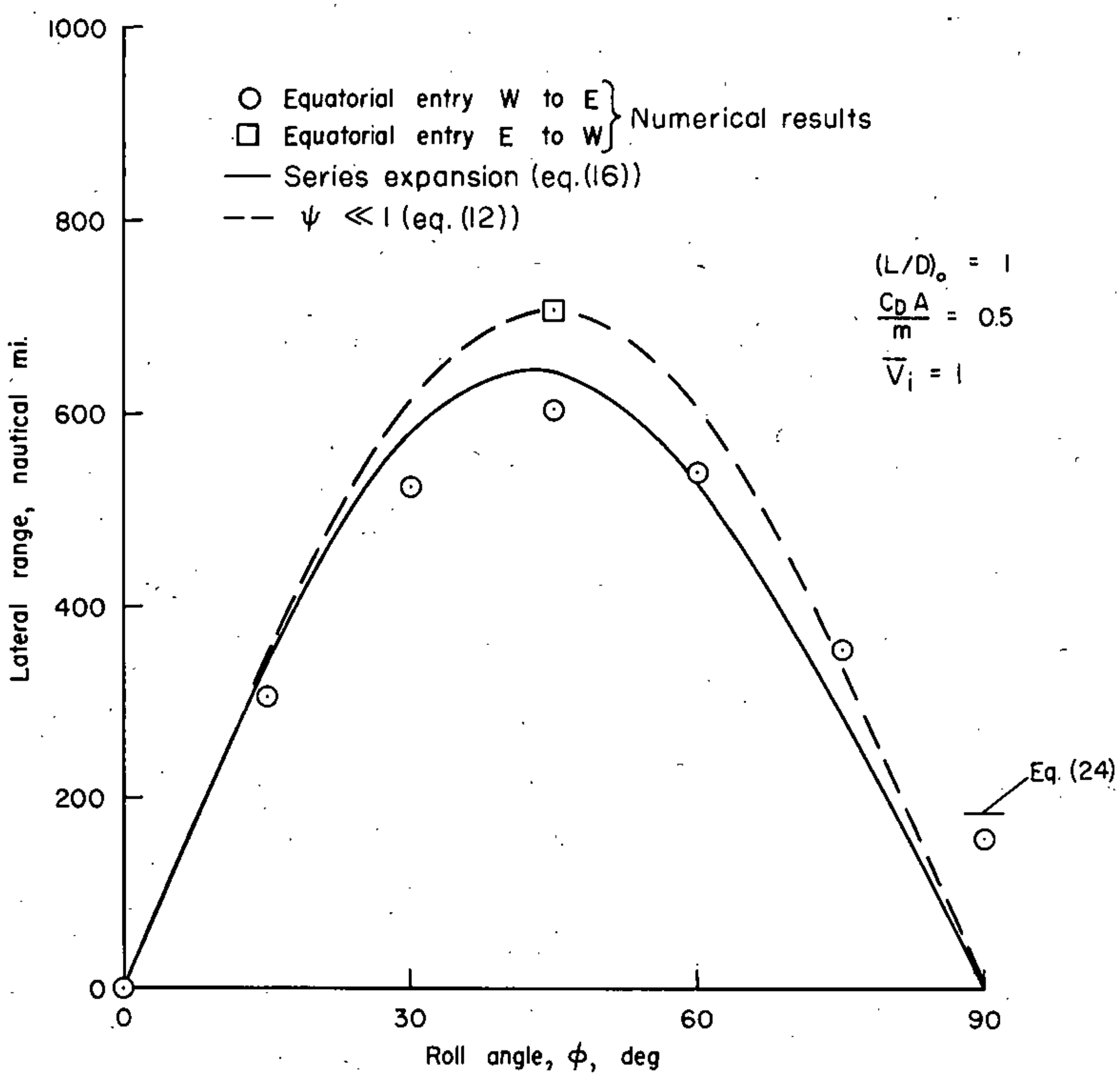

Figure 2.- Effect of roll angle.

A
3
7
9

A
3
7
9

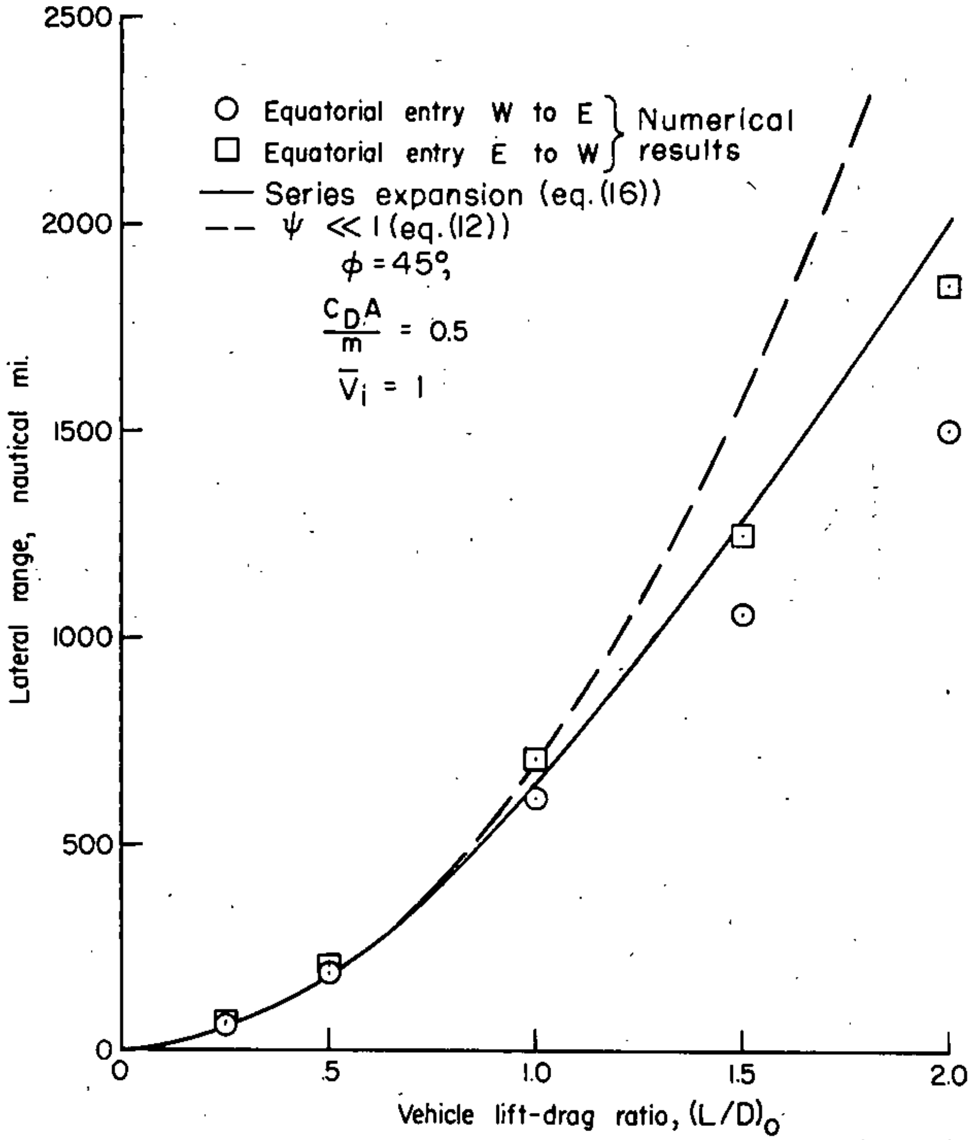

Figure 3.- Lateral range capability.

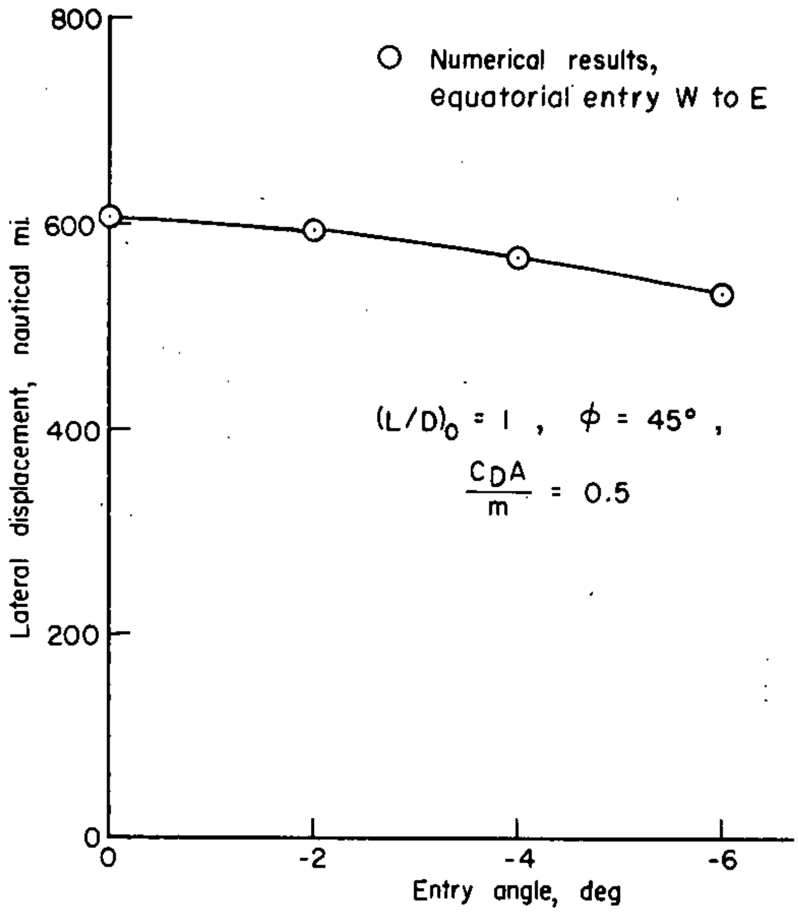

Figure 4.- Effect of entry angle.

A
3
7
9

A
3
7
9

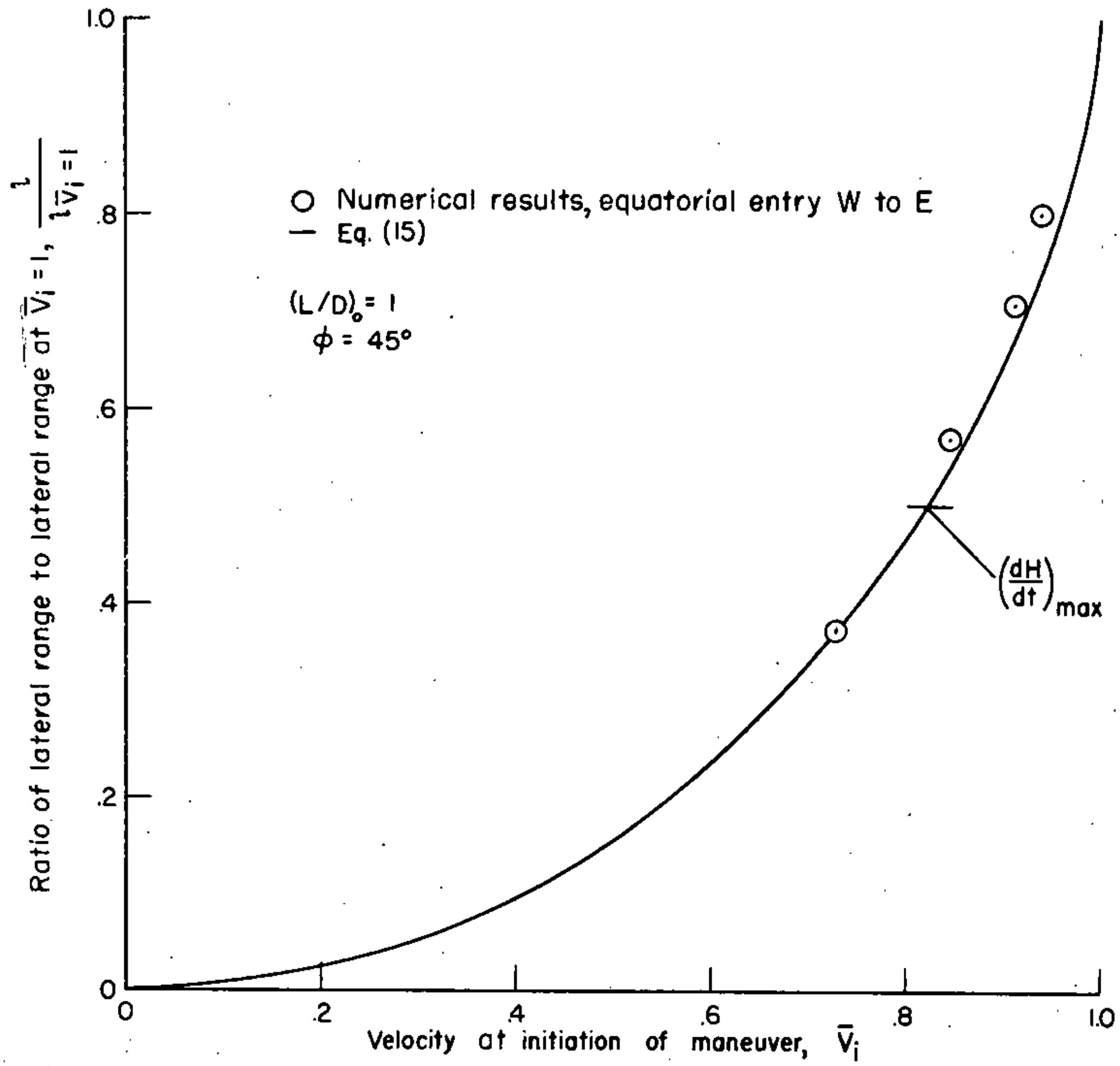

Figure 5.- Effect of velocity at initiation of maneuver on lateral range.

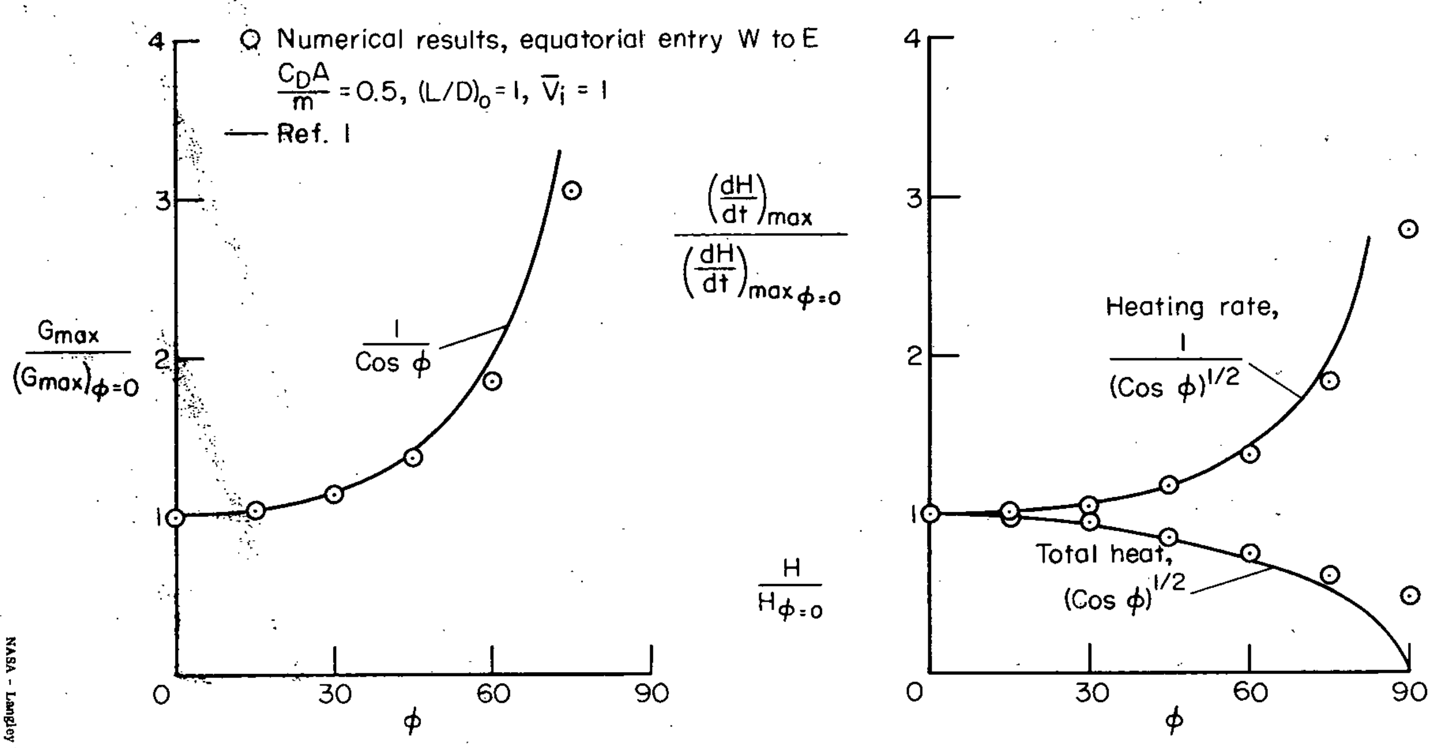

Figure 6.- Effect of roll angle on maximum deceleration and heating.

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The method presented is applicable for small entry angles and results obtained with the method are compared with results from numerical integration of the complete equations of motion. The method is found useful for studying maneuvers of vehicles with aerodynamic lift-drag ratios up to about 1.5. It is found that bank angles of about 45° are sufficient to utilize the near maximum lateral-range potential of a vehicle without overly penalizing entry heating effects.

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