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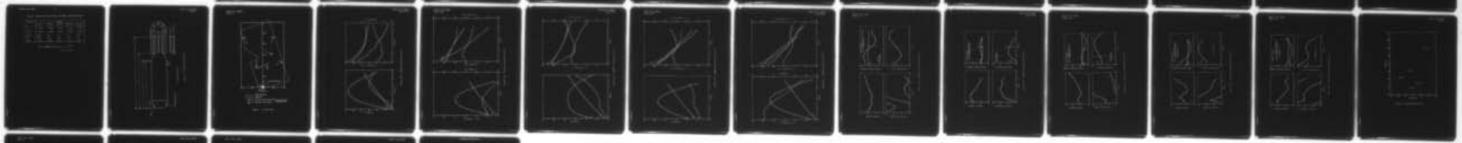

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R.L. POPE

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USE OF PRECISION TRAJECTORIES TO DETERMINE MISSILE FLIGHT BEHAVIOUR .

⑩ R. L. Pope

⑭ WRE-TN-1704(WR/D)

S U M M A R Y

The trajectories of five S-curve bomblets have been determined very accurately, on a small gas gun range. The coning behaviour and the trimmed incidence and normal force have been derived from the trajectory data. The general aerodynamic scattering performance is compared with the performance predicted using wind tunnel measurements, and the results are found to be quite consistent with wind tunnel data apart from one rather interesting discrepancy. The bomblets did not trim at the incidence value expected. This has eventually been attributed to small differences in the tail assembly between the models used in flight tests and those used in wind tunnel tests. The results have been verified by additional wind tunnel tests. The information derived from the trials demonstrates the value of simple instrumentation in assessing flight performance of missiles. A great deal of information on S-curve bomblet behaviour has been obtained with relatively little effort, mainly becaus of the accuracy of the data.

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Box 2151, G.P.O., Adelaide, South Australia, 5001.

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1. INTRODUCTION

A method for determining the trajectory of S-curve bomblets, so called because of the characteristic S-shaped aerodynamic restoring moment curve, was introduced in reference 1. The bomblets are fired from a gas gun and the image of a flashing light carried in the nose of the bomblet is recorded by three ballistic cameras. The trajectory obtained from the camera records is highly accurate so that much more information can be extracted from the trajectory measurements than is usually possible. Details of the trials technique are given in Section 2.

The S-curve bomblet has been specially designed to trim at non-zero incidence so that it will achieve maximum dispersion from a simple particle trajectory. The principal factors affecting the potential dispersion of the bomblet are the variations in magnitude and direction of the normal force during flight. These are determined by the variations in magnitude and direction of the incidence vector. The orientation in space of the incidence plane, which is the plane containing the velocity vector and the longitudinal axis of the bomblet, is particularly important because it shows the direction of the incidence and hence the normal force. If this plane rotates quickly, then irrespective of the magnitude of the normal force the resultant dispersion is low, whereas, if the plane rotates slowly or is stationary the dispersion will be high provided that the magnitude of the normal force is appreciable. The rotation of the incidence plane is called coning because the apparent motion of the bomblet describes a conical surface. Hence the aspects of bomblet flight behaviour which are most important are the normal force at trim because a large normal force provides potential for large dispersion, and the coning behaviour because a low coning rate allows that potential to be realised.

The results of five trials are presented below. Only trajectory measurements were made in all trials and the principal requirement of the data analysis was to extract results on coning behaviour and trim conditions from the data. Details of the methods used are given in Section 3. The only additional information used is the wind tunnel measurement of axial force, and even there consistency checks are possible. The results of the analysis are discussed in Section 4 with particular emphasis on consistency with static wind tunnel measurements. In particular, an interesting discrepancy arose between the wind tunnel tests used to design the bomblet trim conditions(ref.2) and the measured flight conditions, which we were able to resolve.

Finally in Section 5 there are comments and conclusions on the effectiveness of the experiments as a tool for studying S-curve bomblets.

2. TRIALS DESCRIPTION

The bomblet shape used in this trial is shown in figure 1. The bomblet is a typical S-curve shape with a bluff nose and sub-calibre fins behind a boat tail sufficiently steep to ensure separation. The nose is perspex and contains an ordinary camera flash tube, which flashes during flight at about 15 Hz. These flashes are recorded by three ballistic cameras, and are later converted into trajectory using images from reference light markers at four specified positions, according to the method described in reference 3. The positions of gas guns, reference lights and ballistic cameras are shown relative to the range grid in figure 2.

All the trials used bomblets which were as nearly as possible identical. The bomblet physical properties are given in Table 1. In particular it is worth noting that the centre of gravity was set at 2 calibres from the nose, within 1%, and from reference to wind tunnel tests this should give a trimmed incidence of 20.5^{o} and a normal force coefficient at trim of 1.225.

The bomblets were all fired from the gas gun in a similar way. The bomblets were set in wooden sabots at zero incidence and were fired from the gas gun at a nominal speed of 107 m/s with an elevation of 25°. However, the initial velocity did vary between 104 and 118 m/s over the series of trials owing to some difficulty in adjusting pressure in the gas gun. Fortunately this did not affect the validity of any of the experimental results.

The bomblets were all manufactured with nominally zero misalignments. Fin measurements showed that all fins were aligned with an average error of 0.02° and this was not considered to be significant in terms of roll rate, coning rate or changes in trimmed incidence.

3. METHOD OF ANALYSIS

The first step in the data analysis was to derive velocity and acceleration of the bomblets in range axes, where OX is downrange, OY is to the right and OZ is vertically downwards. The simple central difference relation

$$\dot{x}_m = \frac{1}{2}(x_{m+1} - x_{m-1})/\delta$$

is used to get velocity from displacement and acceleration from velocity, where δ is the time interval between data points. The errors arising from using this differencing procedure to represent derivatives are generally at least an order of magnitude less than the errors arising from noise in the data. Since the trajectory data is subject to a very low root mean square noise level the velocities and accelerations obtained are quite accurate. Table 2 gives estimates of r.m.s. errors for derived data for each of the bomblets. It can be seen from this that under good conditions the r.m.s. noise in the acceleration may have an amplitude as low as 0.5 ms^{-2}.

The acceleration components are then converted from range coordinates to velocity coordinates, using the Euler angles of yaw and pitch, ψ and θ respectively. These angles are defined by

$$\tan\psi = \dot{y}/\dot{x} \qquad -\pi < \psi < \pi$$

$$\tan\theta = -\dot{z}/(\dot{x}^2 + \dot{y}^2)^{\frac{1}{2}} \qquad -\pi/2 < \theta < \pi/2$$

Hence the velocity coordinates have an OX axis in the direction of the velocity vector, an OY axis horizontal and to the right and the OZ axis completing an orthogonal right handed set of axes. The acceleration components in these axes are,

$$\dot{u} = \ddot{x}\cos\theta\cos\psi + \ddot{y}\cos\theta\sin\psi - (\ddot{z} - g)\sin\theta$$

$$\dot{v} = -\ddot{x}\sin\psi + \ddot{y}\cos\psi$$

$$\dot{w} = \ddot{x}\sin\theta\cos\psi + \ddot{y}\sin\theta\sin\psi + (\ddot{z} - g)\cos\theta$$

The spatial orientation of the lateral aerodynamic force is given by the angle ϕ in the relation

$$\tan\phi = \dot{v} / (-\dot{w})$$

The angle, ϕ, defines the spatial orientation of the plane containing the velocity of the bomblet and the resultant lateral aerodynamic force acting on the bomblet. The angle is zero if the plane is vertical and the force is upwards and is measured positive clockwise from the rear. Wind tunnel measurements(ref.2) indicate that for moderate roll rates up to some tens of Hz, the total aerodynamic side forces will be less than 5% of normal force at trim which means that the difference between the plane of the total lateral aerodynamic force and the incidence plane will be less than 3°. In fact, with the small fin cants on this current set of bomblets, the difference will be much less than 1°. Therefore in all future discussion we will assume that ϕ is the coning angle, defining the spatial orientation of the incidence plane. The concurrent assumption that total lateral aerodynamic force is the same as the normal force introduces quite negligible errors, because of the sum of squares relationship which applies to the sum of vector components.

The coning angle, ϕ, provides a record of how the direction of the aerodynamic dispersive force varies with time. The other important factor is the magnitude of that force. The aerodynamic coefficients for lift and drag are defined by the equations

$$C_L = -m\,(\dot{v}^2 + \dot{w}^2)^{\frac{1}{2}} \,/\, \frac{1}{2}\rho\, V^2 S,$$

$$C_D = m\dot{u} \,/\, \frac{1}{2}\rho\, V^2 S$$

The lift and drag are the forces which are respectively normal to and parallel to the velocity vector. If the incidence is known, again assuming that side forces are negligible, then these can be converted to normal and axial forces relative to the bomblet axis. Alternatively, if the axial force is known the normal force and incidence can be derived. The latter approach results in a much better conditioned problem because axial force is insensitive to incidence variations in the ranges covered in these experiments and the resultant values of normal force are not particularly sensitive to the values of the axial force which are used. Then normal force and incidence are given by

$$C_Z = (C_L{}^2 - C_D{}^2 - C_X{}^2)^{\frac{1}{2}},$$

$$\alpha = \tan^{-1}(C_Z/C_X) - \tan^{-1}(C_L/C_D)$$

These results can be checked for consistency with wind tunnel measurements by comparison with the variation of normal force against incidence.

The root mean square noise levels for some of the derived quantities are presented in Table 2 for each of the five rounds. It is clear that even for poor data such as was obtained with SFL 10 all the quantities except incidence and normal force are well determined. Even normal force is accurate to about 5% r.m.s. error when the data is good. This is much more accurate than trim incidence estimates which contain about 15% r.m.s. errors. However, since we can expect the bomblets to trim steadily after some initial disturbance, averaging over the total flight record will produce average values, $\bar{\alpha}$ and $\bar{C}_Z$, where the r.m.s. errors are quite small. As far as can be judged from the experimental data this averaging technique should give realistic answers. The validity of the average is discussed further in the next section.

4. RESULTS

The flight results have been presented in two sets of figures, figure 3 and figure 4 parts (a) to (e) in each case. The associated r.m.s. noise levels and mean values are presented in Tables 2 and 3 respectively. In addition the impact points are shown in figure 5. Figure 3 shows position and velocity histories for each bomblet. This figure shows the results of the action of the dispersive forces, and some interesting points arise. For example, in figure 3(c), the SFL 9 trajectory shows a very flat and maintained apogee which is matched by a sudden slowing of the rate of decrease of the OZ velocity component at 2 s, indicating that the bomblet maintained a gliding position for an appreciable length of time. This matches well with the fact that SFL 9 flew to the greatest range.

The most important results of the trials are presented in figure 4, which shows the flight behaviour of each bomblet. In particular flight histories are given for deviation of velocity direction, ψ, coning angle, ϕ, incidence, α, and normal force coefficient C_Z. The angles ψ and ϕ are plotted from unfiltered data, but unfortunately the noise levels on incidence and normal force estimates are too high to provide useful plots. Hence the records for α and C_Z have been smoothed by fitting polynomials, using linear regression to determine the most applicable degree of polynomial. The curves so obtained were then plotted. The validity of the variations shown for these quantities in figure 4 is questionable because all the variations are negligible compared with the general noise levels in the data. The incidence values which correspond to the estimated values of C_Z, according to wind tunnel measurements shown in figure 6, have been plotted as dashed lines in figure 4. A comparison of the two curves for each bomblet shows in every case that the incidence history derived wholly from flight data varies much more during the flight although the general trends are similar. The most probable reason for the variation is a spurious signal arising from an r.m.s. noise level which is much larger than real variations in the data over the whole flight. A more useful measure of these quantities is the mean value over the whole trajectory. This is likely to be a reasonably good estimate because the amplitude of the oscillation of the bomblet about the trim position is much less than the noise level over most of the flight and because the high pitch frequency, between 15 and 20 Hz generally, would provide an averaging effect in any case. The mean values $\bar{\alpha}$ and $\bar{C}_Z$ are marked on figure 4 by arrows. The numerical values of the estimated means are also given in Table 3, along with the standard deviations of these estimates.

Three important points arise from these results. The first concerns the axial force coefficient used in deriving incidence and normal force, the second relates to the very low coning rates and the third point is concerned with a comparison of flight results with predictions based on wind tunnel measurements. Firstly we will look at the choice of a value for axial force coefficients. In the initial analysis of the flight behaviour of these bomblets no allowance was made for base pressure effects on the axial force, resulting in $C_X=0.23$. This value produced results where the average incidence estimates were 4° or 5° above what would be predicted from the concurrently derived results for normal force coefficients using wind tunnel measurements. Subsequently, inclusion of base pressure effects produced a new estimate for the axial force coefficient of 0.32. This lowered estimates of the incidence by between 4° and 6° but decreased normal force coefficient by only 2%, which is equivalent to about 0.2° incidence. Since the total aerodynamic force is composed largely of the normal force contribution, about 90% at trim conditions, it is clear from the equations in Section 3 that changes in axial force have little effect on estimates of normal force, but will change the incidence if they are large enough. Then using $C_X=0.32$, we find that the average difference over all trials between the mean incidence derived from flight trials and the incidence which according to wind tunnel measurements corresponds to the mean normal force derived from flight trials is less than 1^{o}. Thus the self consistency of the values derived for $\bar{a}$ and $\bar{C}_Z$ is supporting evidence that the value of axial force coefficient used in deriving them is approximately correct and that the averaging process used is also valid.

The second important point about the results is the very low coning rates which were observed. In half the cases the incidence vector remained substantially within the same quadrant over the majority of the trajectory. Clearly this is one requirement for efficient scattering of the bomblet. Unfortunately the manufacturing precision of these bomblets was much higher than can normally be achieved in a mass production situation. In particular, the fin alignment becomes much less accurate and that alone will increase average coning rates substantially.

Finally some comment is required on the discrepancy between the trim conditions predicted using wind tunnel measurements and those estimated from the flight behaviour of the bomblets. The centre of gravity of the bomblets was set at two calibres from the nose, with an error of less than 0.5%, hence the nominal trim conditions as given at the bottom of Table 3 are

$$a\ (\text{trim}) = 20.5 \pm 0.2,$$

$$C_Z\ (\text{trim}) = 1.23 \pm 0.02$$

The values set out in Table 3 are all consistently lower and in general suggest that the nominal trim incidence is about 2^{o} or 3^{o} lower than predicted from wind tunnel results. This is important because there is a resultant 20% reduction in normal force and hence in dispersive capability. A detailed comparison of the trial bomblets and the wind tunnel model showed only one minor discrepancy in the tail assembly. The two types of fins are shown in figure 1. The fins on the bomblets used in the trials had uniform thickness whereas the fins on the bomblet used for wind tunnel measurement tapered in thickness from about the same thickness on the leading edge to approximately half the thickness on the trailing edge, one side being aligned with the bomblet axis and the other side being at an angle of about 1.3^{o}. The wind tunnel model was set up in this way in order to obtain measurements of rolling moments. Unfortunately, this had a substantial effect on the trim position of the bomblet. Tests on a flight trials bomblet in a pitching rig in a low speed wind tunnel at 46 m/s show a trim angle of $(19^{o} \pm 0.5^{o})$. Corrections for Reynold's number showed that this would vary from $(17.8^{o} \pm 0.5^{o})$ to $(18.2^{o} \pm 0.5^{o})$ over the flight path and this agrees well with the average values in Table 3 of 17.7^{o} derived directly from the trials results and of 18^{o}, which is the equivalent trim incidence for the derived value of lift force coefficient at trim.

A quick look at centre of pressure positions shows how the trim incidence can be altered appreciably by changes in tail lift which are too small to produce an appreciable change in the total lift. If we consider the wind tunnel data at 18^{o} incidence (see figure 6), the centre of pressure is 1.865 calibres from the nose and the total lift coefficient is 1.00. If the body centre of pressure is about 1.2 calibres from the nose and the tail centre of pressure is about 4.0 calibres aft of the nose, then the components of normal force are C_Z (nose) = -0.7625 and C_Z (tail) = -0.2375. If the centre of gravity is 2.00 calibres from the nose then the bomblet will be expected to trim at 20.5^{o} incidence, but it follows from the above figures that a trim angle of only 18^{o} can be obtained if there is an increase of 28% in tail lift, which represents less than 7% increase in total normal force. The increase in normal force may be even less if some of the increase in stability is due to a backward shift in the tail centre of pressure. In fact the whole change in trim might be accounted for by a shift of about half a calibre in the tail centre of pressure. Such a shift is fairly substantial. However, the two effects combined may produce an alteration of 2.5° in trim incidence together with a corresponding change in pitching moment without noticeably affecting the variation with incidence of axial force and normal force.

5. CONCLUSION

The results of these trials show the usefulness of even minimal instrumentation on a small gas gun range. The requirements for these trials were ballistic cameras, some lights to provide a reference when reading the camera plates and a relatively simple piece of on-board instrumentation, the flashing light. The great value of the technique arises basically from the very high accuracy which is attainable. On good trials the r.m.s. noise in position measurements will be as low as 0.01 m. It follows that acceleration can be estimated relatively accurately with little effort, and the other variables including coning angle and normal force at trim can be obtained from this.

An important outcome of this series of trials is the self consistency of the results and their consistency with wind tunnel measurement. Firstly all the rounds show good agreement between trimmed incidence and the resultant normal force according to predictions from wind tunnel measurements. As emphasised in Section 4 this is basically arrived at by using a good estimate for axial force coefficient and again this is consistent with wind tunnel measurements. The only discrepancy occurred between expected and measured values of incidence and normal force, the trimmed normal force being reduced by 20% and the incidence by 2.5°. Although there is some scatter in the mean values estimated from the experimental results they are all consistently below the predicted values. The discrepancy was resolved by testing one of the bomblets constructed for the flashing light trials in a low speed wind tunnel. Trim incidence values within half a degree of values derived from flight trials were obtained after correcting for Reynolds number.

It has been a common experience in S-curve bomblet development that small differences in manufacture of free flight models have produced quite large differences in aerodynamics. In consequence of this the scattering performance of bomblets has often declined drastically for no apparent reason. In many cases the problem areas have been difficult to locate owing to lack of information on flight behaviour. The only difference between the bomblets used in the wind tunnel measurements and those used in these flight trials was in the fin section. We confidently predicted at the trials planning stage that the effects would not be appreciable. However, the trimmed lift, which is a direct measure of scattering potential was reduced by 20% of the expected value because of minor differences from the wind tunnel model. It is apparent from these results that instrumentation, particularly the flashing light, is a valuable design aid, especially for S-curve bomblets because they are so sensitive to slight changes in manufacture.

6. ACKNOWLEDGEMENT

I would like to thank Mr. R.E. Dudley for his contributions to the work reported here. He has organised and conducted all the flashing light trials and the high accuracy of the results is in large part due to his efforts.

NOTATION

C_D	aerodynamic drag coefficient
C_L	aerodynamic lift coefficient
C_X	axial force coefficient
C_Z	normal force coefficient
m	bomblet mass
S	reference area
$\dot{u}$	bomblet acceleration component along velocity vector
V	bomblet speed
$\dot{v}$	bomblet acceleration component normal to velocity and in a horizontal plane
$\dot{w}$	bomblet acceleration component orthogonal to the other two
x	range
y	azimuth, positive to the right
z	altitude, positive downwards
α	incidence
δ	time interval between data points
θ	angle of pitch of velocity vector
ρ	air density
ϕ	coning angle
ψ	angle of yaw of velocity vector
superscripts	
.	single differentiation with respect to time
..	double differentiation with respect to time

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2	Robinson, M.L.	"Wind Tunnel Tests of the Static Aerodynamic Characteristics of Lifting Axisymmetric Bomb Shapes at Subsonic Speeds". WRE-TN-533 (WR&D), November 1971.
3	Roughan, J.L.	"Computation of Vehicle Position from Several Cameras". WRE-TN-558 (T), December 1971.

TABLE 1. BOMBLET PHYSICAL DATA

Mass	0.994 kg
Roll inertia	0.0000123 kg m^2
Pitch inertia	0.000168 kg m^2
Diameter (calibre)	0.05 m
Reference Area	0.00196 m^2
Centre of Gravity	2.00 calibres from nose

TABLE 2. ROOT MEAN SQUARE ERRORS IN FLIGHT DATA

Variable	Round				
	SFL 7	SFL 8	SFL 9	SFL 10	SFL 11
x(m)	0.0202	0.0206	0.0156	0.0238	0.0196
y(m)	0.0064	0.0167	0.0088	0.0156	0.0099
z(m)	0.0096	0.0153	0.0282	0.0133	0.0357
$\dot{x}$(m/s)	0.085	0.068	0.054	0.203	0.135
$\dot{y}$(m/s)	0.048	0.047	0.056	0.157	0.038
$\dot{z}$(m/s)	0.053	0.100	0.040	0.123	0.123
$\ddot{x}$(m/s^2)	0.87	0.56	0.47	1.44	1.04
$\ddot{y}$(m/s^2)	0.43	0.50	0.47	1.51	0.57
$\ddot{z}$(m/s^2)	0.48	0.50	0.45	1.30	0.38
ψ(^{o})	0.028	0.027	0.032	0.092	0.023
θ(^{o})	0.044	0.062	0.030	0.102	0.091
ϕ(^{o})	7.0	6.5	5.8	18.0	8.2
C_Z	0.096	0.063	0.064	0.194	0.115
α(^{o})	5.5	3.6	3.3	11.6	11.3

Note: These are average values over the whole flight record. The r.m.s. errors will vary along the flight path according to the position of the vehicle relative to the three ballistic cameras.

TABLE 3. MEAN VALUES OF INCIDENCE AND NORMAL FORCE COEFFICIENT

Variable	Round				
	SFL 7	SFL 8	SFL 9	SFL 10	SFL 11
$\bar{C}_Z$	-1.120	-1.029	-0.975	-0.951	-0.920
$\sigma(\bar{C}_Z)$	0.0075	0.0063	0.0057	0.0212	0.0135
$\alpha(C_Z)$	19.4	18.4	17.7	17.4	17.0
$\bar{\alpha}$	18.1	19.7	15.8	17.5	15.2
$\sigma(\bar{\alpha})$	0.43	0.36	0.29	1.26	1.33

Note: Nominal values are $\alpha = 20.5^\circ$

$C_Z = 1.23$

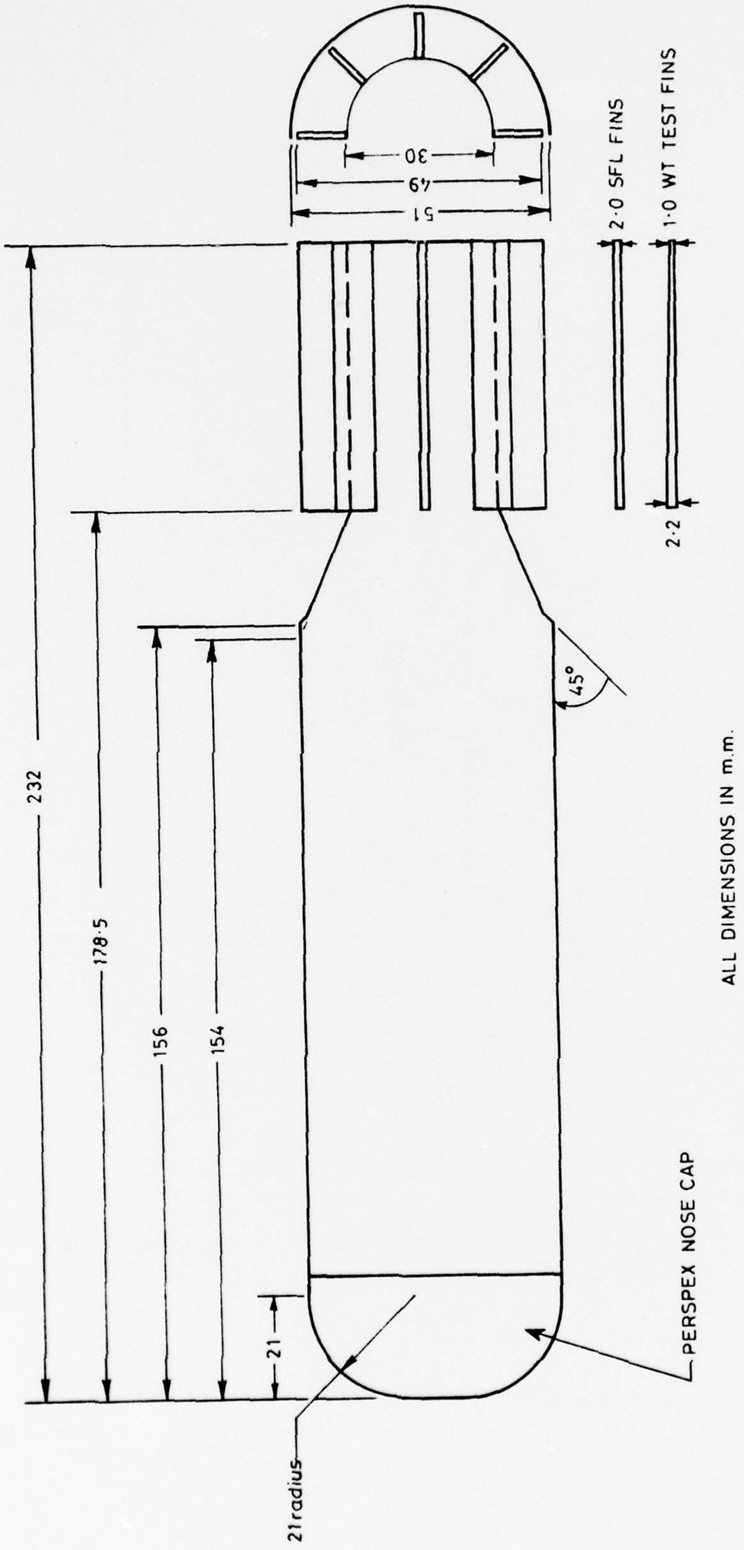

Figure 1. Bomblet configuration

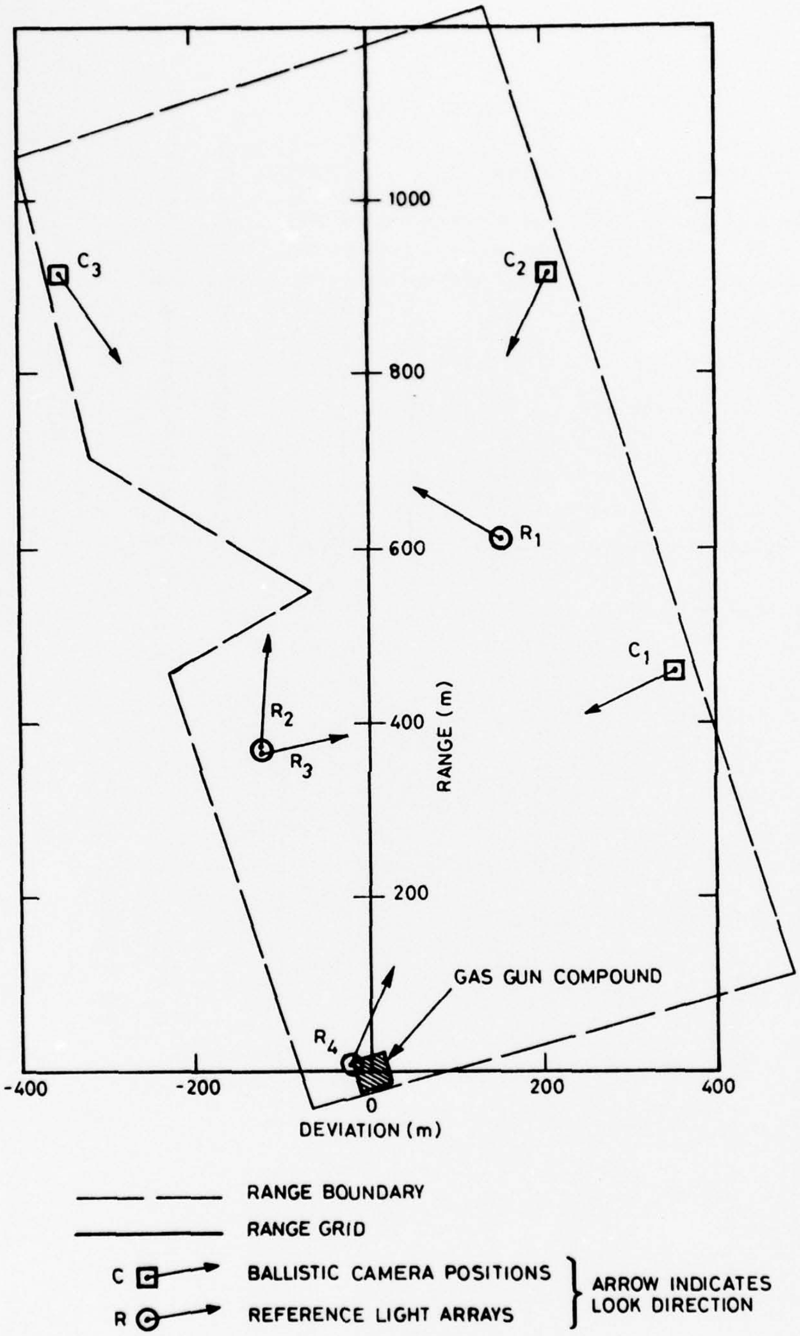

Figure 2. Gas gun range

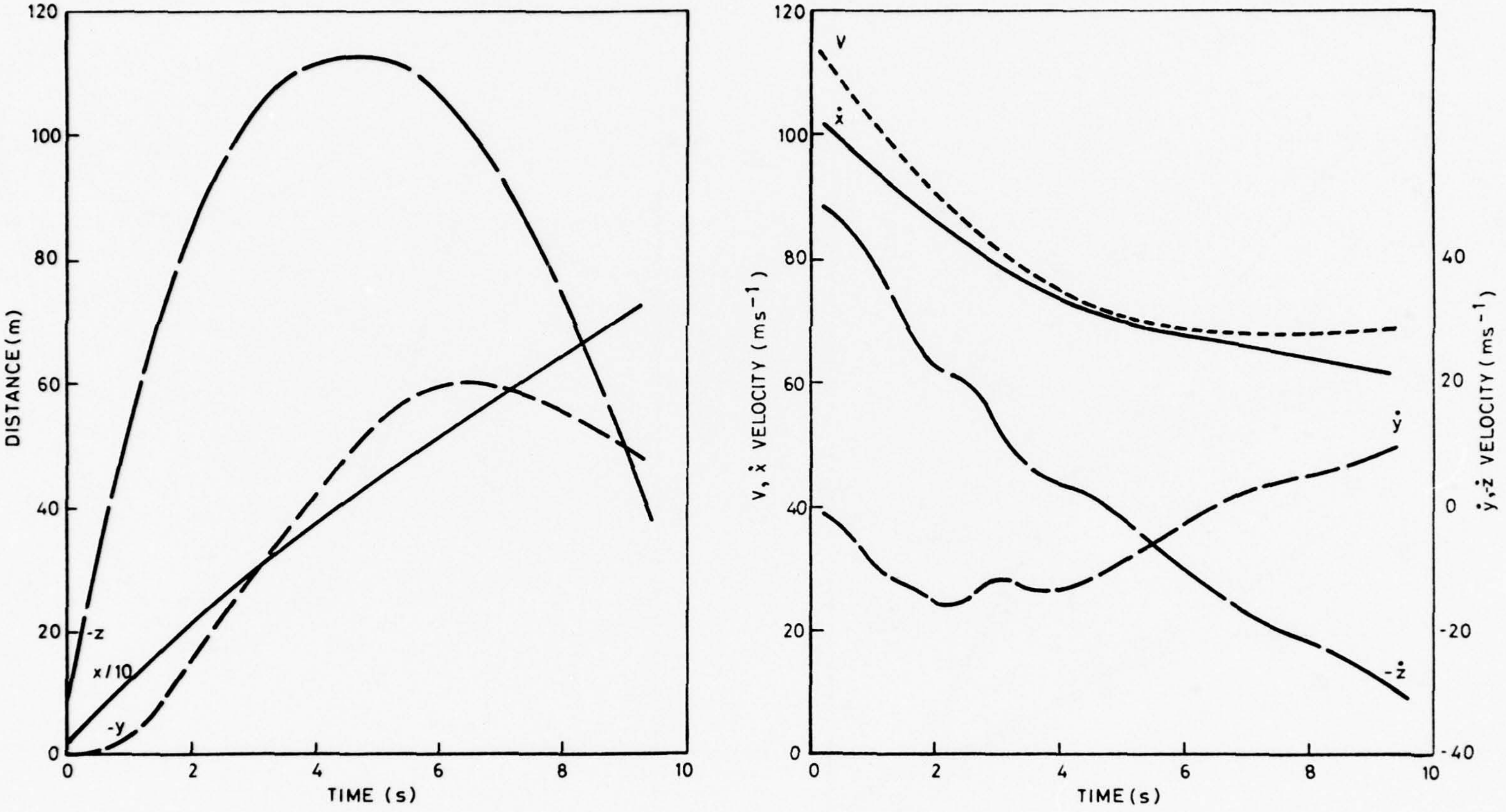

Figure 3(a). Bomblet trajectories SFL 7

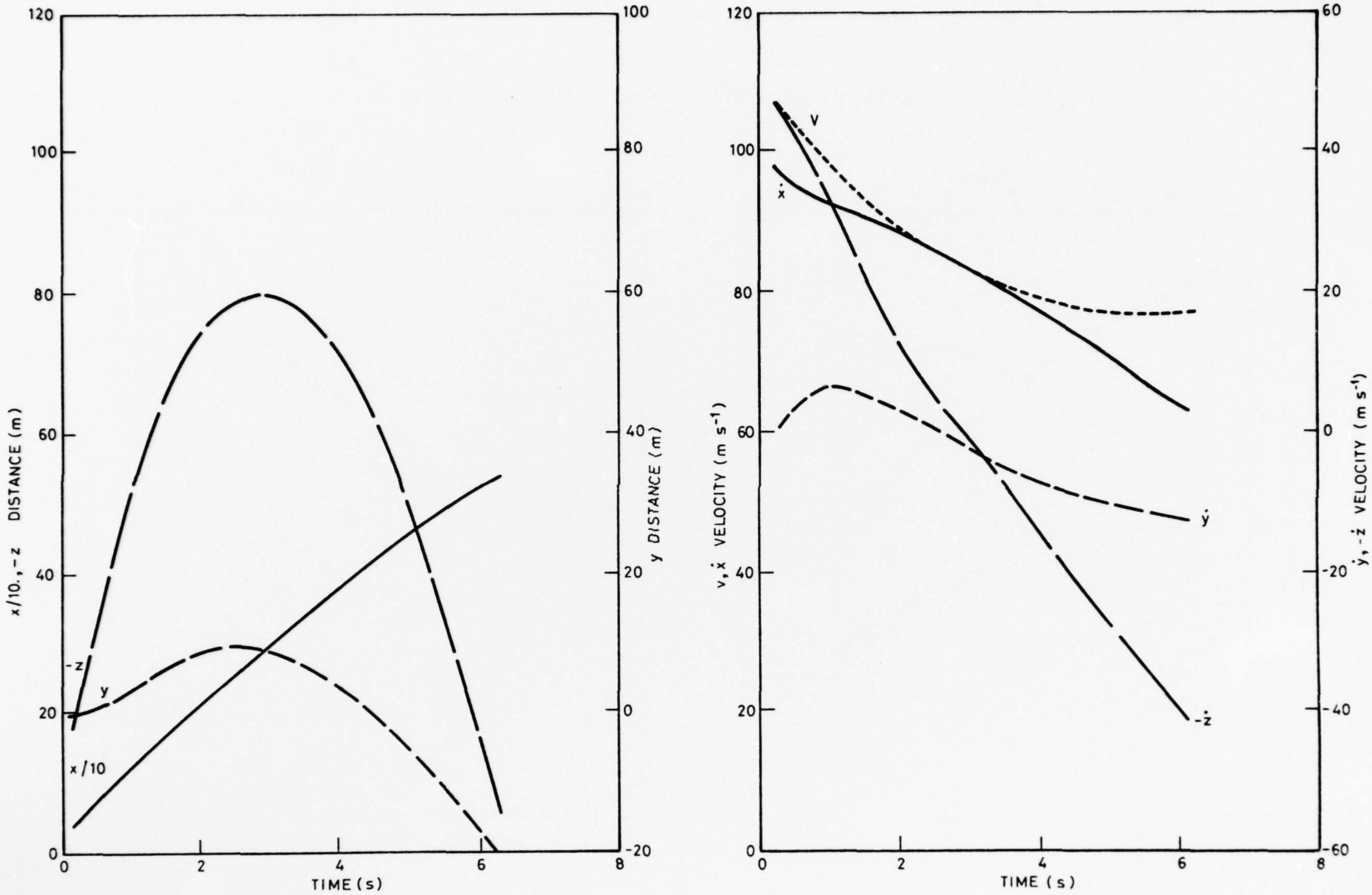

Figure 3(b). Bomblet trajectories SFL 8

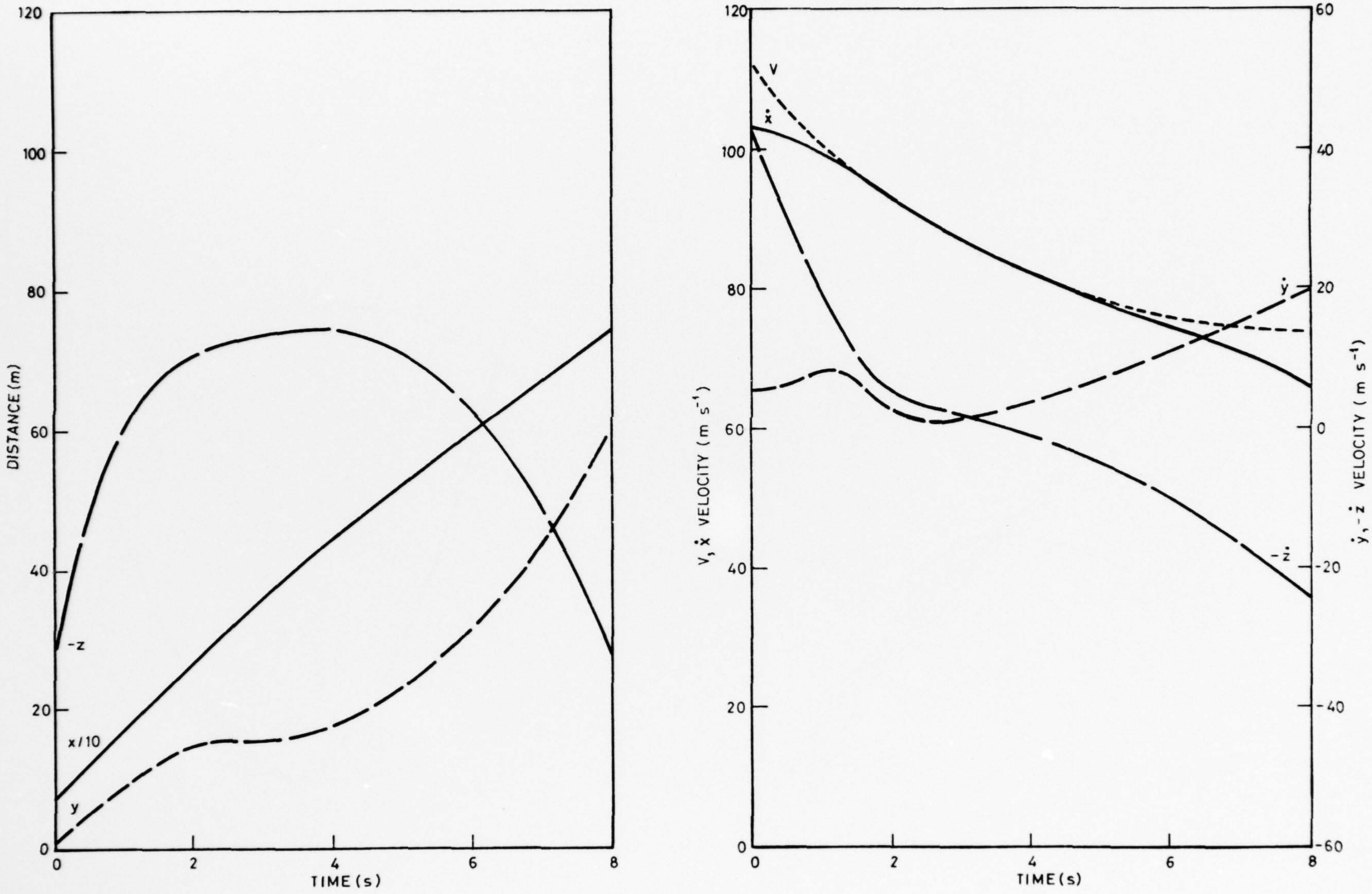

Figure 3(c). Bomblet trajectories SFL 9

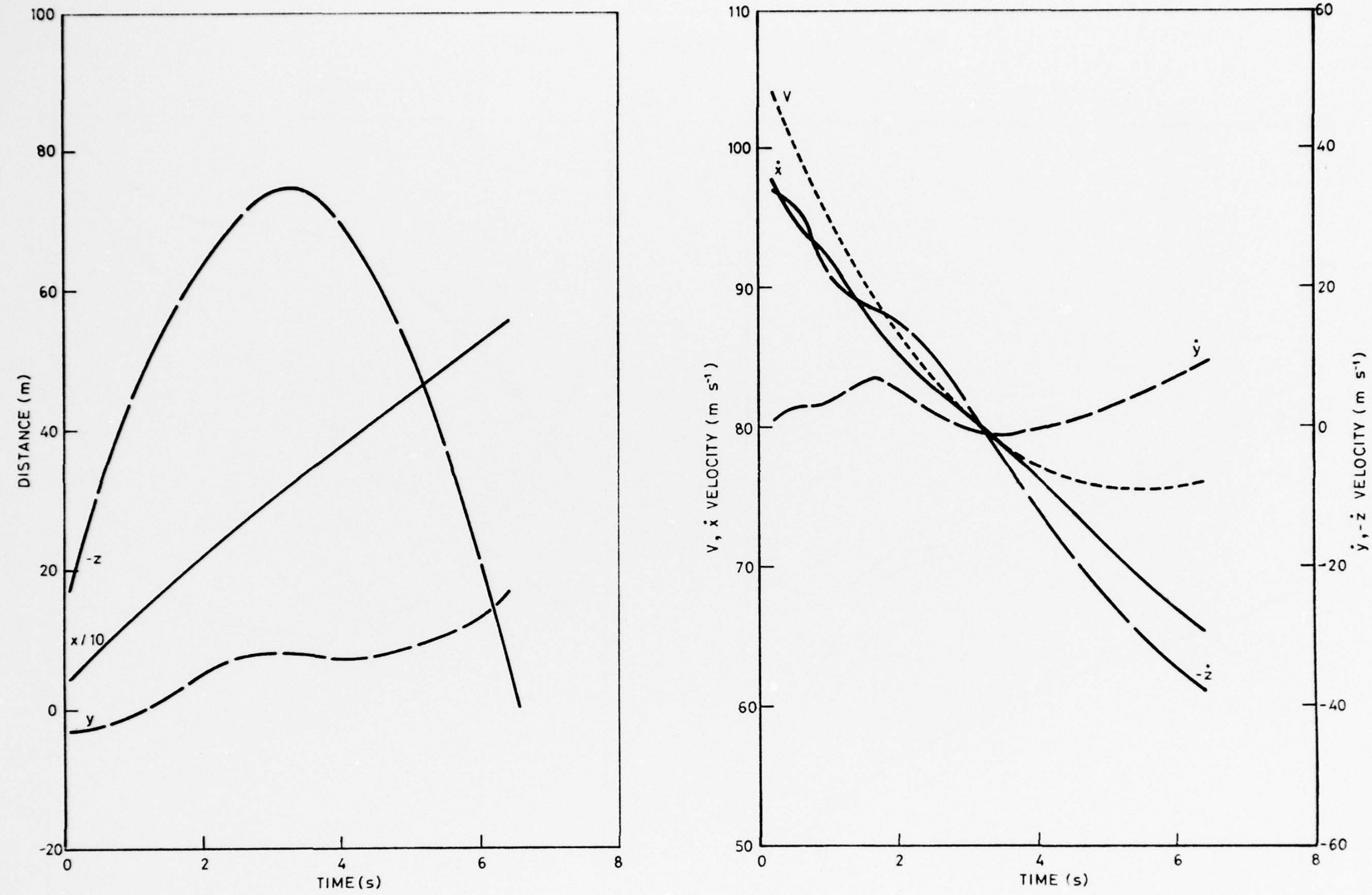

Figure 3(d). Bomblet trajectories SFL 10

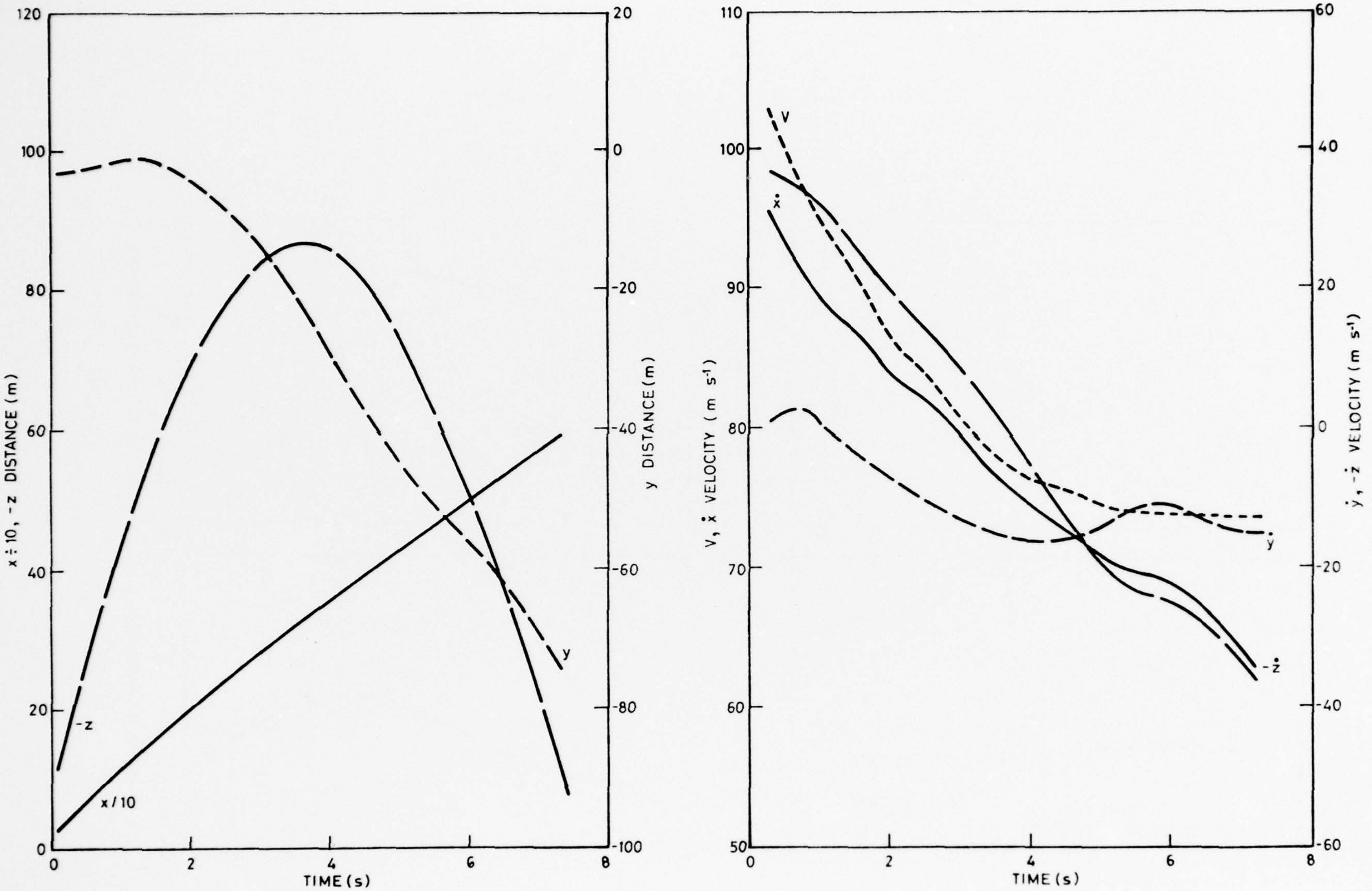

Figure 3(e). Bomblet trajectories SFL 11

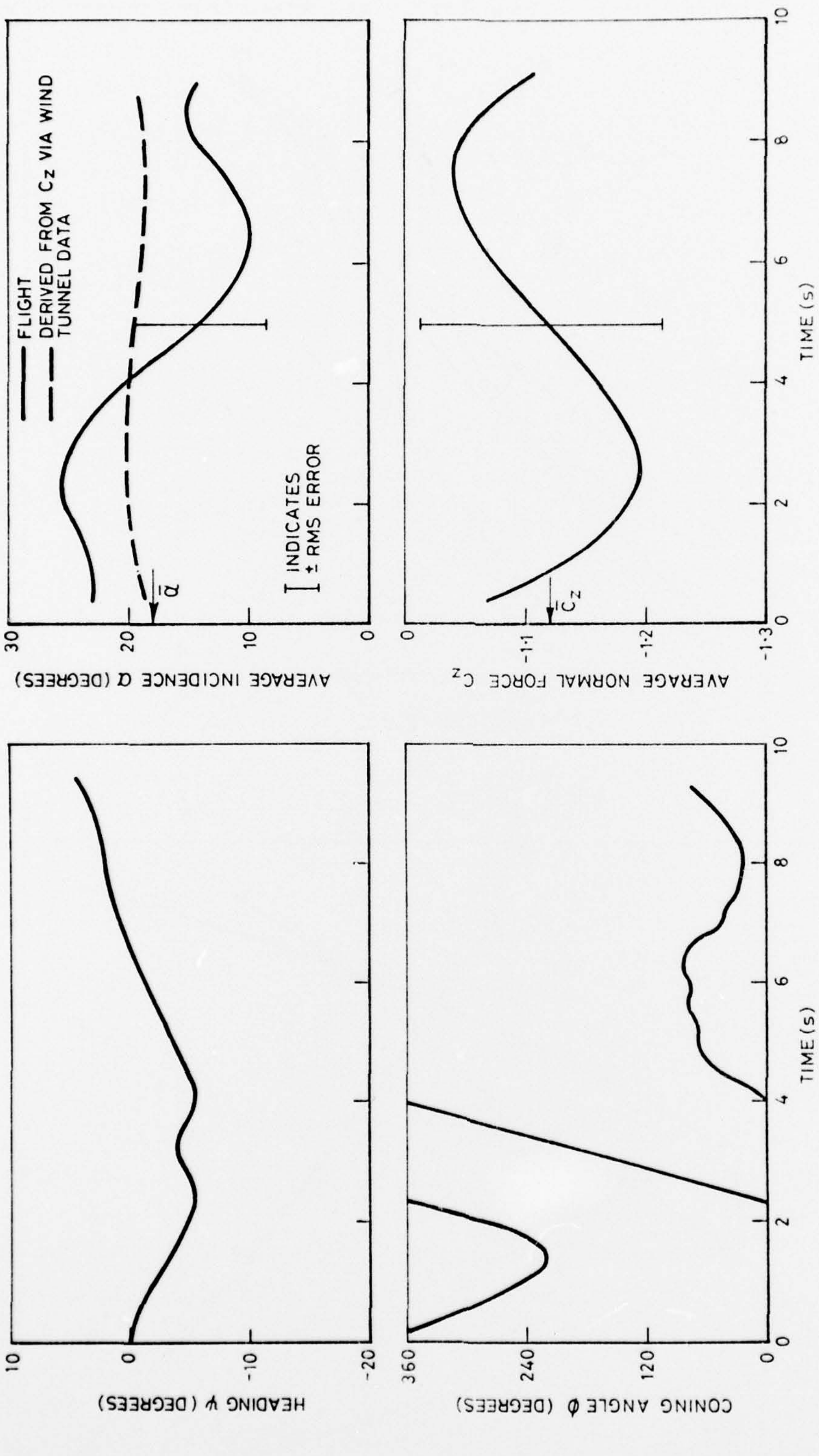

Figure 4(a). Bomblet flight behaviour SFL 7

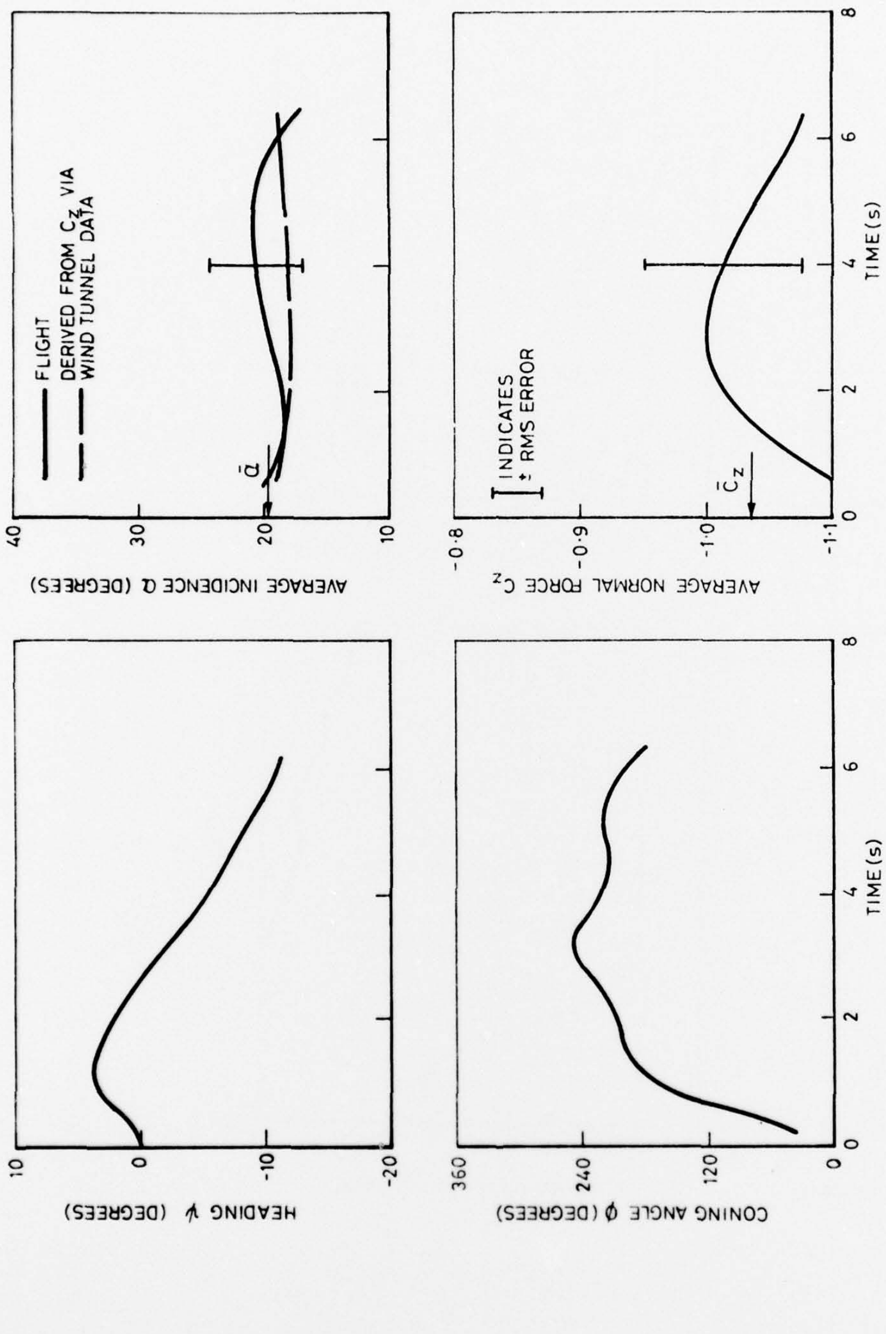

Figure 4(b). Bomblet flight behaviour SFL 8

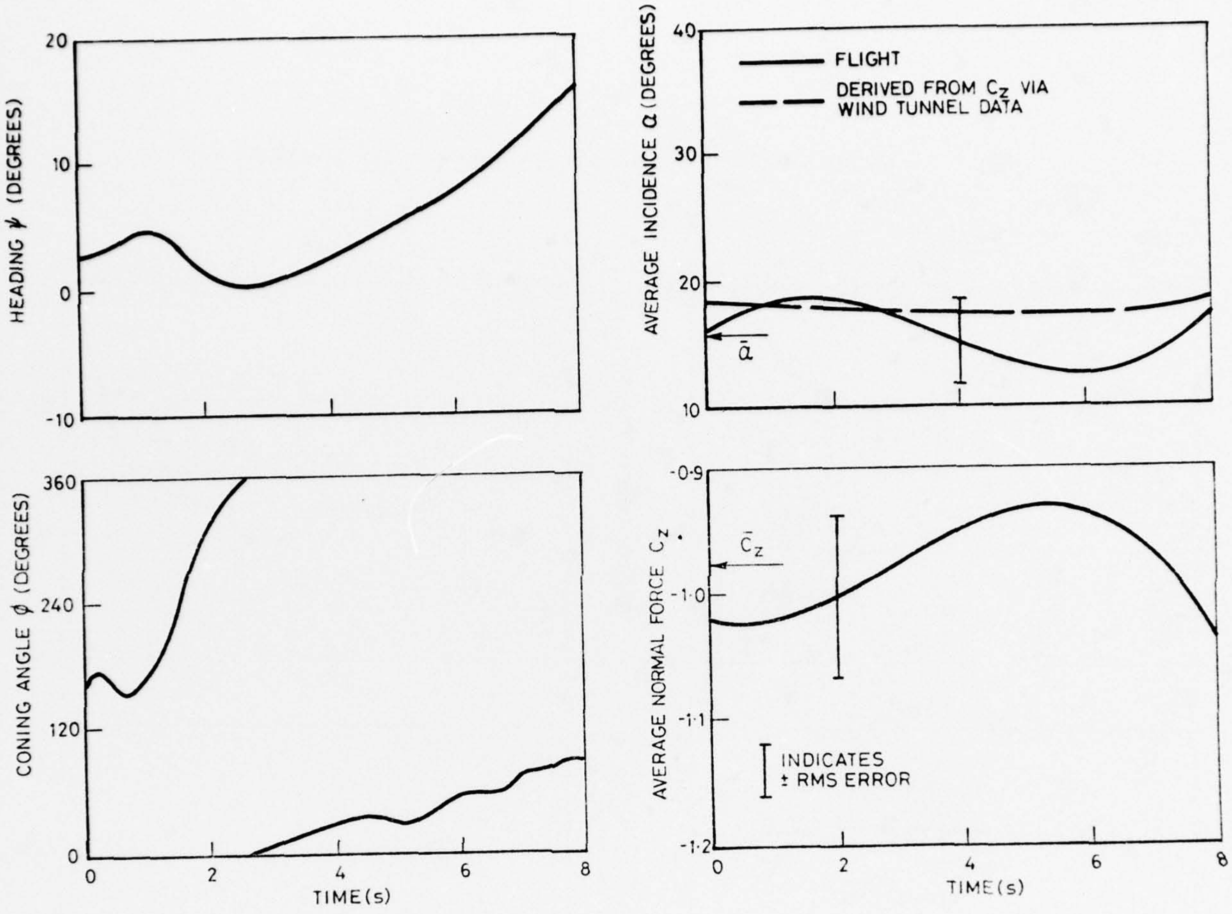

Figure 4(c). Bomblet flight behaviour SFL 9

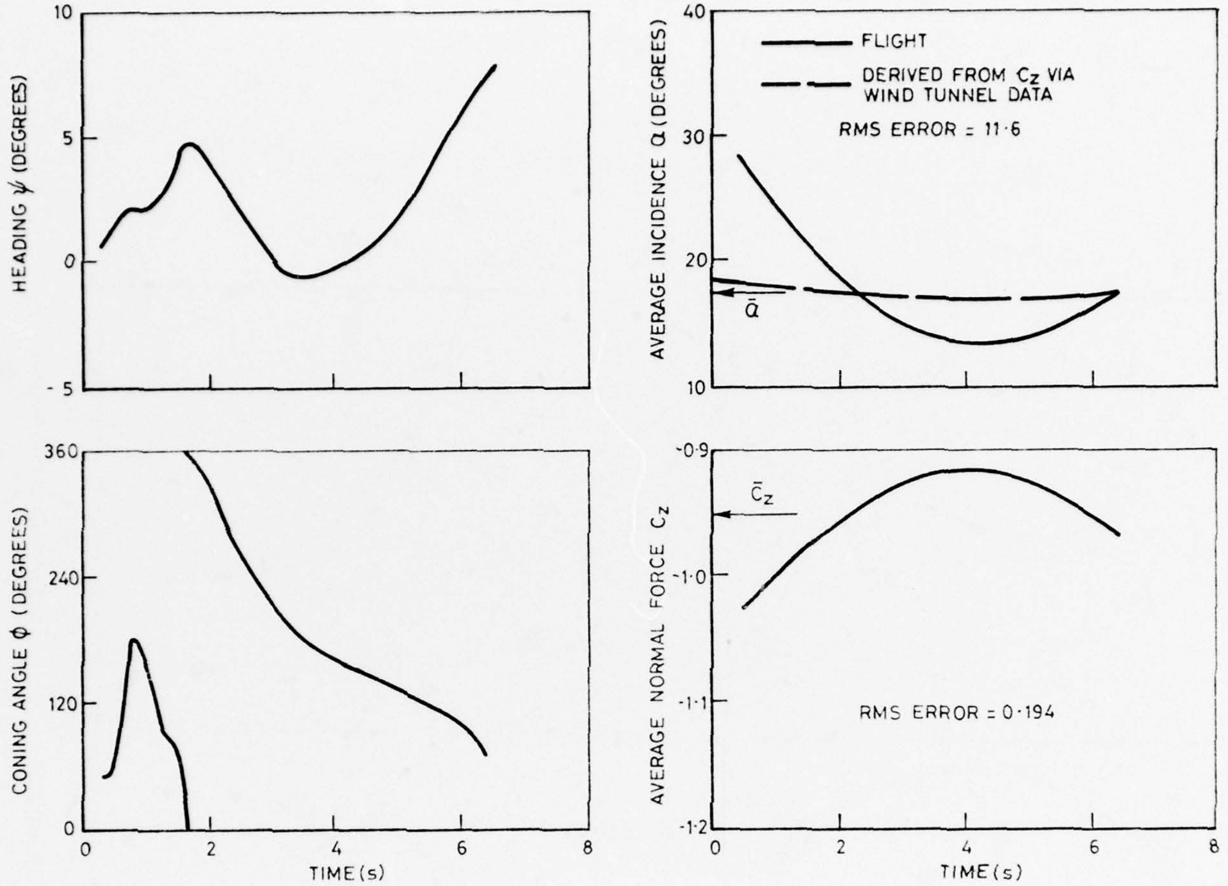

Figure 4(d). Bomblet flight behaviour SFL 10

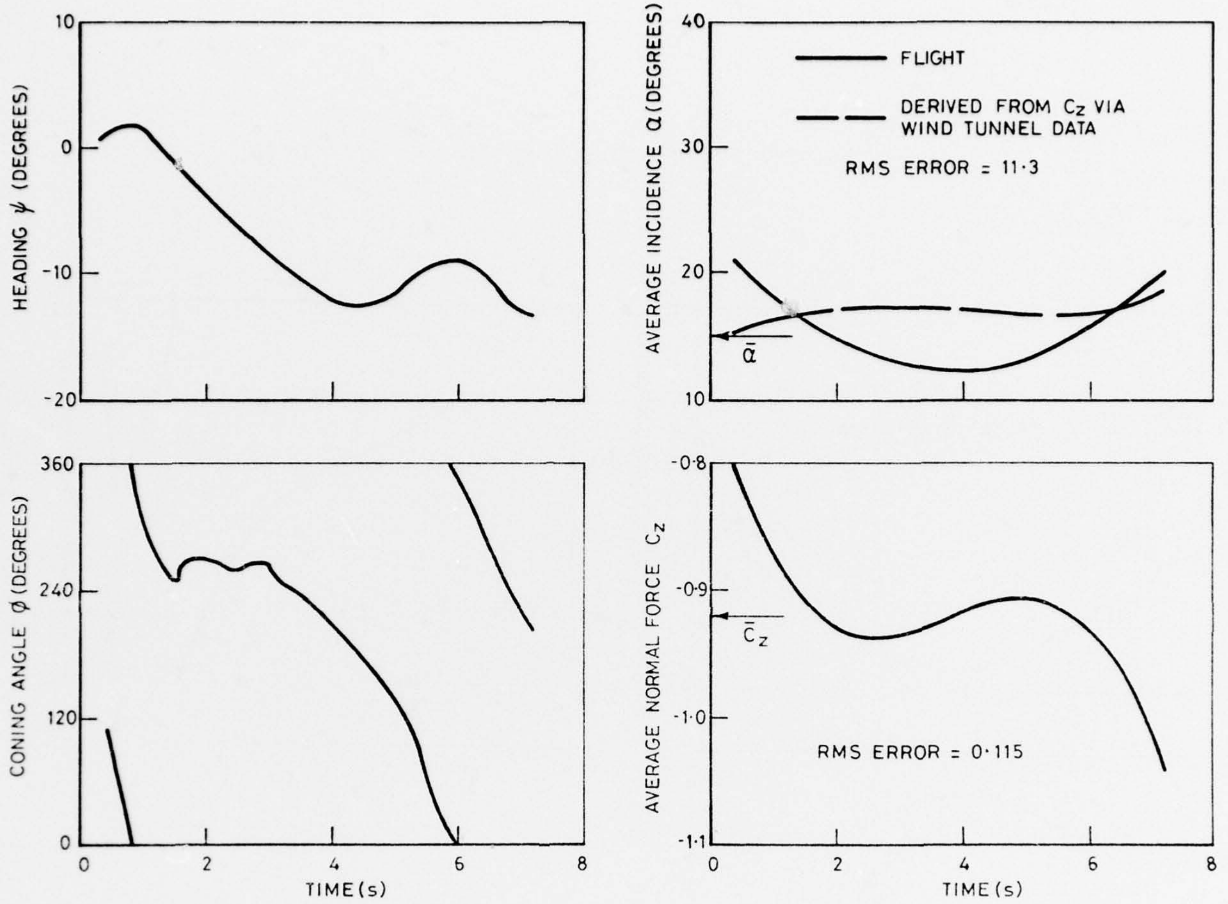

Figure 4(e). Bomblet flight behaviour SFL 11

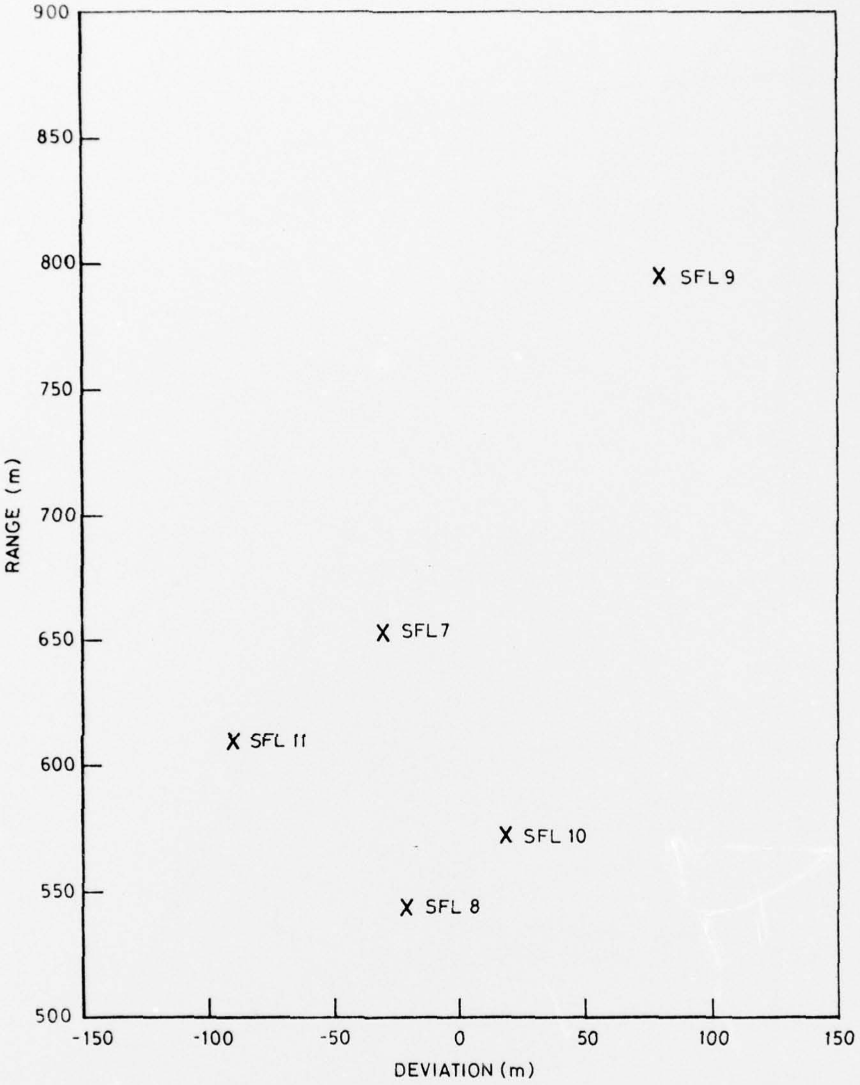

Figure 5. Bomblet impact points

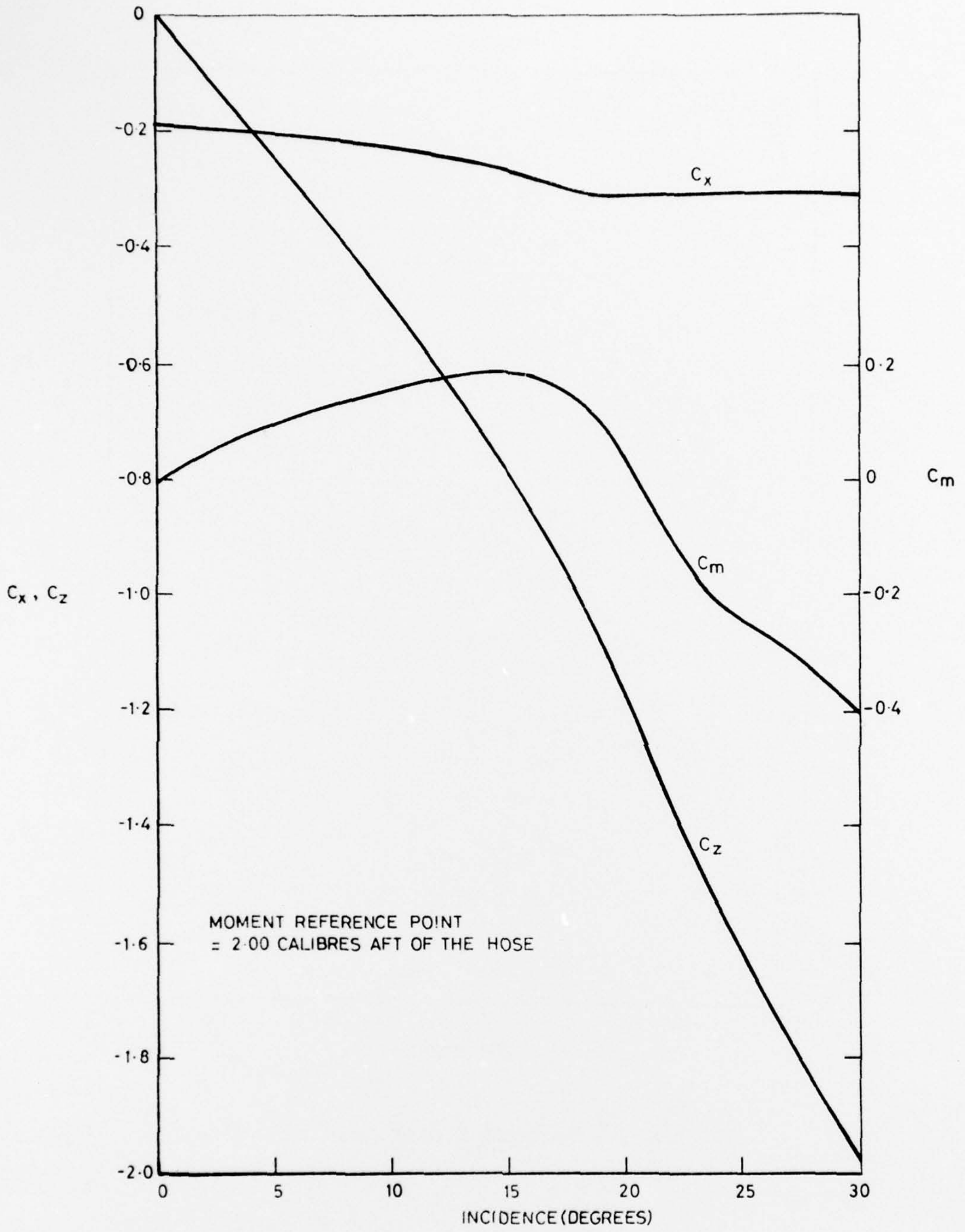

Figure 6. Typical wind tunnel measurements

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7. Summary

The trajectories of five S-curve bomblets have been determined very accurately, on a small gas gun range. The coning behaviour and the trimmed incidence and normal force have been derived from the trajectory data. The general aerodynamic scattering performance is compared with the performance predicted using wind tunnel measurements, and the results are found to be quite consistent with wind tunnel data apart from one rather interesting discrepancy. The bomblets did not trim at the incidence value expected. This has eventually been attributed to small differences in the tail assembly between the models used in flight tests and those used in wind tunnel tests. The results have been verified by additional wind tunnel tests. The information derived from the trials demonstrates the value of simple instrumentation in assessing flight performance of missiles. A great deal of information on S-curve bomblet behaviour has been obtained with relatively little effort, mainly because of the accuracy of the data.

8. Descriptors
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Scattering
Aerodynamic characteristics
Scattering

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