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WEAPONS SYSTEMS RESEARCH LABORATORY

DEFENCE RESEARCH CENTRE SALISBURY
SOUTH AUSTRALIA

TECHNICAL REPORT

WSRL-0165-TR

INITIAL RESULTS IN DEVELOPING FREE FLIGHT TESTING TECHNIQUES FOR ARTILLERY SHELLS

R.L. POPE

Approved for Public Release

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R.L. Pope

SUMMARY

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As part of a programme to develop methods for studying exterior ballistics of shells, an initial series of four shells was fired at Woomera. Two shells carried yawsondes designed and manufactured at the Ballistic Research Laboratories in the United States of America and two carried preliminary designs of a locally-developed yawsonde. Trajectory of the shells was obtained from radar tracking. Both the trajectory and the yawsonde data were analysed using parameter estimation algorithms and the results of the data analysis are reported here. Roll damping, axial force and normal force derivatives were determined for subsonic speeds up to Mach 0.8. Conclusions on the efficacy of the trials technique have been reached and these lead to recommendations for future trials.

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1. INTRODUCTION

Theory and computer programs for applying parameter estimation methods to the analysis of trajectory and yawsonde data from shell flights have been developed in a research programme into the nonlinear flight-dynamic behaviour of projectiles(ref.1). They will be used to analyse data from trials conducted in a programme of research into the exterior ballistics of shells. The overall objective of the work is to support Defence Force needs for information on shell ballistics by developing new methods for acquiring performance and aiming data, and by developing computer based methods of trajectory data analysis. Initially this research involves the development of appropriate trials techniques, instrumentation and computer programs for data processing. When these tools are available they will be used to carry out research into areas such as streamlining methods for preparing a Fire Control Model(ref.2), and studying dynamic stability and anomalous flight behaviour of shells(ref.3).

As part of the instrumentation development process and to provide data with which to test the data analysis procedure a series of four firings was conducted. Of the four shells fired, two carried yawsondes which were designed and built at the Ballistics Research Laboratory (BRL) and two carried preliminary versions of a locally-designed yawsonde. BRL have been using yawsondes to study the exterior ballistics of shells for some time and have developed a highly sophisticated design(ref.4,5). They supplied a total of five yawsondes with complete specifications for each so that experience could be gained in using them simultaneously with the development of a locally-designed yawsonde.

This report covers the analysis of the data which was gathered from the series of four firings described above. The principal objective of the analysis was to gauge the performance of the computer programs when faced with handling real data. Trajectory data was obtained from all four shells, all of good quality, and considerable experience was gained in analysis techniques. Roll rate and solar aspect angle data was obtained from both BRL yawsondes and provided sufficient material for useful testing of the programs for analysis of angular motion. Useful conclusions were arrived at both with regard to the applicability of the data analysis methods and the design of future trials. Data was received from both locally-produced sondes, but the noise level was higher than that in the data received from the BRL sondes. Since the principal objective of the data analysis was to test the performance of the computer programs on real data it was deemed sufficiently useful to process the data from the BRL sondes only and concentrate on improving data quality rather than adapt the data analysis methods to handle the poorer quality data.

As the trials were only of a preliminary nature no special attempt was made to obtain conditions particularly suitable for the data analysis procedure. Consequently, several ways of improving the trials procedure became apparent as the data analysis progressed. These conclusions are summarised in Section 6, together with conclusions on the overall performance of the various algorithms employed in analysing the data. The trials procedure actually used is described fully in Section 2. Sections 3, 4 and 5 give details of the results obtained in analysing the different components of the data, namely, roll rate, trajectory and complementary solar aspect angle.

2. TRIAL CONDITIONS

In order to mount the trials as early as possible, the series of four firings of 105 mm shells with yawsondes was inserted into another programme of firings. Consequently, some of the trial conditions were not ideal, but these were accepted in the interests of obtaining results speedily. Thus the shells were fired with an elevation of 65^0 at charge 7, which results in a nominal velocity of 464.8 m s^{-1} and a Mach number at the muzzle of 1.37. The gun used to launch the shells was situated 500 m in front of the radar which was to be used to obtain the shell trajectory. The initial direction of the radar was obtained from the geometry shown in figure 1. It was such that the shell trajectory entered the lower edge of the conical radar beam at A, was tangent to the upper edge at B and passed out from the lower edge at C. This arrangement of gun and radar was designed to allow the radar optimum conditions to acquire and track the shell to apogee, which was one of the principal objectives of the series of trials into which the yawsonde trials were inserted. Estimates of sun position for the day of the trial showed that the sun would be within the range covered by the yawsondes for the whole of the flight provided that incidence remained below 5^0 and the shells were fired before 12 noon local time. However, the trial conditions, particularly the elevation, were far from ideal for a variety of reasons which will emerge at a later stage in discussion of analysis of the different components of the data.

The meteorological conditions for the trial were obtained from a single balloon released before the series of trials. The balloon data was augmented by readings of surface conditions for each trial. Table 1 gives an amalgam of all data which was used to represent meteorological conditions in the data analysis. Data was not available for heights above 3 km due to extensive cloud cover at this height. Since the apogee of the shell was about 5.5 km the meteorological data had to be extrapolated to that height. This was done with the help of the ICAO standard atmosphere. However, owing to this extrapolation some doubts about certain of the data analysis results could not be resolved.

Since the yawsonde measures solar aspect angle, it is necessary to know the position of the sun, if we are to make a complete analysis of the yawsonde data. Clearly, in order to determine sun position we must know the time of the trial. The timing for each trial is referred to the instrument timing datum (ITD) and Table 2 gives values of ITD in Greenwich Mean Time for each trial. These were used to calculate the azimuth and elevation of the sun in Woomera range axes and the results are given in Table 3.

The sketches in figure 2 show how the yawsonde functions. Essentially, the yawsonde consists of two slits which are respectively at angles γ_1 and γ_2 to the longitudinal axis of the shell and are separated circumferentially by an angle, β. An analytic relationship may be derived(ref.1) between the complementary solar aspect angle, σ_N, and the ratio of the times, τ, the difference between pulses from different slits and, T, between pulses from the same slit. The pulses are obtained from light sensitive cells arranged beneath the slits when the sun shines into the slits. The geometry of the slits is arranged so that the field of view of the slit is as near planar as possible.

For an idealised yawsonde the theoretical calibration curve takes the form

$$\tan \sigma_N = -\sin(2\pi x+\beta) \ / \ [\tan^2\gamma_1 + \tan^2\gamma_2 - 2\tan\gamma_1\tan\gamma_2\cos(2\pi x+\beta)]^{\frac{1}{2}}$$

where $x = \tau/T$. However, practically realisable yawsondes may not fit this form of the calibration curve sufficiently accurately, and BRL have chosen to present their calibration data in the form of a fifth degree polynomial,

$$\sigma_N = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5$$

where $x = \tau/T$. The polynomials for both BRL yawsondes which were supplied

TABLE 1. METEOROLOGICAL DATA

Height (metres above mean sea level)	Range wind (m/s)	Cross wind (m/s)	Pressure (kPa)	Temperature (K)
150	0.5	-1.4	99.2	323
250	0.9	-3.1	98.9	322
500	0.0	-3.5	96.3	320
900	1.8	-2.6	91.9	316
1400	1.7	-2.8	86.8	311
1900	1.5	-2.5	82.0	306
2650	1.9	-0.9	75.2	299

NOTE: Due to cloud at 3000 m meteorological data was somewhat limited.

TABLE 2. ITD TIMES FOR EACH TRIAL

Trial	Shell	Time (hours)	Time (min)	Time (s)
FM4/2	C05	1	17	13
FM4/3	C06	1	28	14
FM4/4	C09	1	50	27
FM4/5	C10	2	06	00

NOTE: The instrument timing datum (ITD) time for each trial is referred to the Greenwich meridian.

TABLE 3. SUN POSITION

Trial	Time (seconds from ITD)	Elevation (degrees)	Azimuth (degrees)
FM4/2	0	52.05	101.55
	70	52.23	101.17
FM4/3	0	53.71	97.89
	70	53.88	97.48

NOTE: The sun positions given are for a latitude of 30° 56' 44.5" S and longitude of 135° 31' 53.3" E, the location of the gun. The azimuth of the sun is relative to the range centre line which has a bearing of 304° 42' 41" relative to true north rather than the line of fire which was along a line bearing 299° from true north.

with the yawsondes are given in Table 4(a) while the corresponding theoretical

TABLE 4. YAWSONDE CALIBRATION CURVES

Trial yawsonde	FM4/2 SN1035	FM4/3 SN1315
a_0	-104.2747	-112.6683
a_1	761.7909	860.2607
a_2	-4712.1906	-5088.0064
a_3	13912.1728	14531.7555
a_4	-16792.4479	-17234.8065
a_5	7080.8391	7184.5252

(a) Polynomial

Trial yawsonde (degrees)	FM4/2 SN1035	FM4/3 SN1315
γ_1	28.9919	29.1216
γ_2	-28.8118	-28.9855
β	168.9572	168.6914
r.m.s. error	0.67	0.78

(b) Theoretical curve

curves, which were obtained by least squares fitting are given in Table 4(b). Maximum discrepancy between the two types of curve was 1.1^0 and root mean square differences are given in Table 4(b). Each form has definite disadvantages. It is clear from the magnitude and the oscillatory behaviour of the coefficients in Table 4(a) that the polynomial curve has difficulty following the calibration. However, while the other curve is exact in the idealised case when the dimensions of the slits are infinitely small and the field of view is perfectly planar, it does not necessarily suit an actual physical yawsonde.

Table 5 shows physical data for each shell. Moments of inertia were measured only for the shells fitted with BRL yawsondes. No detailed data on angular behaviour was expected from the WSRL yawsondes, as they were set up to measure roll only.

Figure 3 shows the variation of Mach number along the trajectory. Ideally the rate of change of Mach number should be small but it can be seen from the figure that it was quite large because of the high launch elevation used. One particular effect of this is obvious from the figure: no results will be obtained for Mach numbers above 0.85 since little useful data is available for times less than 8 s.

TABLE 5. SHELL PHYSICAL DATA

Shell	C05	C06	C09	C10
mass (kg)	14.74	14.65	15.04	15.04
roll inertia (kg m^2)	0.0227	0.0228		
pitch inertia (kg m^2)	0.231	0.228		
body diameter (m)	0.105	0.105	0.105	0.105
cross sectional area (m^2)	0.00866	0.00866	0.00866	0.00866
centre of gravity (m fwd of base)	0.177	0.179	0.184	0.184

3. ROLL RATE DATA ANALYSIS

The roll period, T, as defined in figure 2 provides considerable data on the shell roll rate which can be used to determine the roll damping derivative for the shell. The method is described in detail in reference 1 and uses a polynomial representation in terms of Mach number of the aerodynamic roll damping derivative in the form

$$C_{l_p} = a_0 + a_1M + a_2M^2 \qquad (1)$$

The results from the parameter estimation algorithm are shown in Table 6 and figure 4, for both linear and quadratic variations of roll damping coefficient derivative with Mach number.

The first shell, C05 which carried a BRL yawsonde, provided data for only half the flight. The signal strength was low during the second half of the trajectory which made it difficult to process the data without employing more effort than seemed warranted since considerable data was already available and the motion of the shell had not exhibited any unusual aspects. Hence, the section of data analysed for shell C05 extends from 5 to 37 s from launch. From figure 3 it can be seen that this covers a Mach number range from 0.92 down to 0.39. The telemetry signal did not commence until about 5 s from launch because the receiver had to be tuned slightly to take account of a small frequency shift arising from the launch shock. In estimating roll damping moments sampling rates from 35 down to 31 points/s were used. It is clear from the results in Table 6 that there is a significant improvement in the fit to the data in progressing from the linear to the quadratic model. The root mean square deviation, σ, of the measured data from the theoretical roll rate, decreases from 1.42 to 0.25 rad. Since the resolution of the roll period is only of the order of 1 μs in 5 ms then the resolution of the roll rate is about 0.25 rad, and we can conclude that for the quadratic model the fit to the data is extremely good. Therefore, firstly the mathematical model is a very good representation of the physical process and secondly the noise level in the data is insignificant. Although the quadratic model of roll damping fits the data significantly better than the linear model, it is apparent from the results for C05, shown in figure 4, that the resulting changes in the derived roll damping coefficient derivative curve are not

TABLE 6. ROLL DAMPING MOMENT DERIVATIVE

Parameter	Shell			
	C05 linear	quadratic	C06 linear	quadratic
p_0 (rad/s)	1322.0 (0.17)	1323.0 (0.04)	1321.0 (0.08)	1322.0 (0.11)
a_0	-0.04092 (0.00020)	-0.05154 (0.00021)	-0.04342 (0.00009)	-0.05518 (0.00063)
a_1	0.02038 (0.00032)	0.05041 (0.00070)	0.02446 (0.00017)	0.06700 (0.00225)
a_2	- -	-0.02555 (0.00055)	- -	-0.03672 (0.00194)
σ (rad/s)	1.42	0.25	0.66	0.56
data points	969	951	997	994

NOTE: Figures in brackets indicate r.m.s. errors in estimated parameter values.

significant except at the limits of the Mach number range where end effects cause distortion of the curves.

The other shell, C06, which carried a BRL yawsonde, provided data over nearly all the trajectory. Only 8 s of record was missing from the beginning of the trajectory because of the necessity of tuning the receiver to allow for the frequency drift in the transmitter which occured between loading and firing the shell. The data from this trial which was used for analysis extended from 8 s to 61 s from launch and covered a Mach number range from 0.87 down to 0.40. The sampling rate available was up to 200 samples/s, but only 17 to 21 points/s were used. According to the root mean square of the residuals shown in Table 6, the quadratic model did not fit the data significantly better than the linear model. Figure 4 shows that the results agree remarkably well with the results for C05. In particular, the quadratic curves are very close except at the upper limits of the Mach number range where there are relatively few data points.

The most obvious aspect of figure 4 is the discrepancy between results at either end of the Mach number range. This is mainly due to end effects and they are particularly aggravated for higher Mach numbers by the limited amount of data in that area. This highlights a very disappointing aspect of the results. Although the Mach number of the shell at the muzzle of the gun was 1.37, insufficient data is available above Mach 0.8 for accurate determination of aerodynamic coefficients and no data at all was recorded for Mach numbers above 0.92. A variety of factors contributed to this lack of data and they will be discussed in some detail later, together with suggestions for improving the data collection for higher Mach numbers.

4. TRAJECTORY ANALYSIS

The computer programs described in reference 1 for analysing trajectory and yawsonde data from shells were set up to analyse roll rate data and trajectory data in the same program. As was foreshadowed the two functions have now been separated. Thus the sequence of events in analysis of data from a given trial begins with analysis of roll data using raw trajectory data supplied from the radar. The roll damping coefficient derivative and the initial roll rate obtained are input to the trajectory analysis program. When the analysis of trajectory data is complete the smoothed trajectory output from the mathematical model is recorded for use in analysis of the pitching and yawing motion recorded by the yawsonde. Output from trajectory or yawsonde data analysis steps can be fed back to previous steps and the process repeated if it seems likely that such a procedure will improve accuracy and consistency of the results. Such a course is generally not warranted when the shell is well behaved but may be useful occasionally if the shell has exhibited anomalous or "rogue" behaviour.

In analysing the trajectory data the variation of both axial force coefficient and normal force coefficient derivative with Mach number is represented by functions of the form,

$$C_x,\ C_{z\alpha} \;=\; (1+s)A(r) + (1-s)B(r) \qquad (2)$$

where

$$r = (M^2-K^2)\,/\,(M^2+K^2),$$

$$s = r\,/\,[(1-L^2)r^2+L^2]^{1/2},$$

$$A(r) = a_0+a_1r+a_2r^2,$$

$$B(r) = b_0+b_1r+b_2r^2.$$

This form of Mach number variation which is referred to as model A to distinguish it from other forms which are introduced below, was first developed in reference 6 and details of its properties can be found there or in reference 1. The more important properties for the purposes of the present discussion are that

(i) K represents the value of Mach number which is the centre of the rapid variation in coefficients which occurs transonically,

(ii) L is the width or range of Mach number spanning that variation, and

(iii) s is close to -1 for subsonic flow and close to +1 for supersonic flow so that

(iv) A(r) represents supersonic behaviour and B(r) represents subsonic behaviour.

The results of fitting these representations of the aerodynamic forces to the trajectory data from all four shells are given in Table 7 and a typical matching of trajectory data for C05 is given in figure 5. The limited Mach number range for which data was available proved to be a severe problem in analysing the trajectory data. Since no data was available either for transonic or for supersonic Mach numbers, the parameters associated with this Mach number range, K, L and all coefficients of the polynomial, A(r), could not be estimated. If any of these were allowed to vary the algorithm simply became unstable. Consequently, values had to be estimated for them and they were then held constant throughout the data analysis. The parameter values involved can be distinguished in Table 7 by the fact that no r.m.s. errors are stated for them.

It is important to consider the accuracy with which the mathematical model simulates the measured data values when trying to gauge the reliability of the values which have been derived for the aerodynamic forces. Figure 5 shows typical results for the theoretical values derived for each of the three components defining the shell trajectory together with the difference between measured and simulated values for every third data point. The results shown are for shell, C05, but results for the other three shells exhibit very similar characteristics. Figure 5 shows that the mathematical model reproduces both range and deviation components of the missile motion faithfully. The oscillatory behaviour of the residuals at specific points on the trajectory occurs because the radar tracking becomes uncertain and the radar tends to hunt a little. However, the residuals of the vertical component of shell position, which are plotted in figure 5(c) show an approximately parabolic variation over the trajectory in addition to the usual, intermittent oscillatory characteristics. It seems likely from this result which was consistently and accurately repeated in analysis of the other three shells, that the mathematical model does not adequately represent the motion of the shell. The discrepancy is equivalent to a vertical acceleration of approximately $0.04\ m\ s^{-2}$ acting throughout the shell trajectory. This inadequacy in the mathematical model will be discussed further below, both with regard to an alternative representation of aerodynamic forces and with regard to the analysis of the yawsonde data, but it is not likely to affect significantly the values derived for the aerodynamic force coefficients since the range component of shell position has been reproduced accurately.

Figure 6 shows that the results for both axial force coefficient and normal force coefficient derivative are consistent for all four shells as one would expect from the values indicated for parameters in Table 7. The average departure from a mean curve is less than two per cent for the axial force and less than five per cent in the case of the normal force. Only the axial force coefficient for C10 and the normal force coefficient derivative for C05 show somewhat different characteristics from the results for the error bands defined by the rms error values over most of the Mach number range from 0.4 to 0.85.

Further investigation of the parametric representation of the aerodynamic forces was undertaken both because of the limited Mach number range and because of the apparent anomaly in the mathematical model representation of the vertical acceleration. Since there was no need for the force curve to represent the transonic and supersonic behaviour of the aerodynamic forces a much simpler and more flexible representation of the subsonic parts of the force curve was possible. In addition the high elevation of the gun at launch meant that there was a large variation in vertical velocity component of the shell over the trajectory so that any inadequacy in drag representation might possibly lead to inaccuracies in estimating the vertical component of the acceleration.

The alternative parametric representation chosen for the aerodynamic force coefficients was of the form

$$C_x,\ C_{z\alpha} = f(M) = \begin{cases} C_o & M \leq M_o \\ a_o + a_1(M-M_o) + a_2(M-M_o)^2 + a_3(M-M_o)^3 & M \geq M_o \end{cases} \qquad (3)$$

TABLE 7. PARAMETER VALUES FROM TRAJECTORY ANALYSIS - MODEL A

Shell Parameter	C05	C06	C09	C10
x_o(m)	686.7	654.7	670.6	665.1
	(0.21)	(0.21)	(0.19)	(0.20)
y_o(m)	275.1	279.4	277.8	282.6
	(0.24)	(0.26)	(0.22)	(0.25)
z_o(m)	-2446.9	-2399.1	-2417.5	-2414.1
	(0.16)	(0.18)	(0.15)	(0.17)
$\dot{x}_o$(m s^{-1})	151.07	152.01	151.88	152.23
	(0.027)	(0.032)	0.026)	(0.031)
$\dot{y}_o$(m s^{-1})	-14.19	-14.40	-14.28	-13.56
	(0.046)	(0.050)	(0.043)	(0.048)
$\dot{z}_o$(m s^{-1})	-255.18	-260.13	-257.13	-259.98
	(0.040)	(0.050)	(0.039)	(0.047)
C_x K	0.977	0.977	0.977	0.977
	-	-	-	-
L	0.0563	0.0563	0.0563	0.0563
	-	-	-	-
a_o	-0.229	-0.229	-0.229	-0.229
	-	-	-	-
a_1	0.126	0.126	0.126	0.126
	-	-	-	-
b_o	-0.0474	-0.0459	-0.0476	-0.0418
	(0.00036)	(0.00040)	(0.00034)	(0.00038)
b_1	0.0452	0.0468	0.0464	0.0596
	(0.00070)	(0.00076)	(0.00066)	(0.00074)
$C_{z\alpha}$ K	0.964	0.964	0.964	0.964
	-	-	-	-
L	0.0344	0.0344	0.034	0.0344
	-	-	-	-
a_o	-0.940	-0.940	-0.940	-0.940
	-	-	-	-
a_1	-0.730	-0.730	-0.730	-0.730
	-	-	-	-
b_o	-0.576	-0.715	-0.721	-0.714
	(0.037)	(0.038)	(0.034)	(0.037)
b_1	0.550	0.346	0.362	0.424
	(0.059)	(0.060)	(0.054)	(0.059)
σ(m)	3.33	3.41	3.01	3.22
data points	2279	2278	2279	2275

NOTE: figures in brackets beneath each parameter value are estimated r.m.s. errors in that value. Where no r.m.s. error is given the value was obtained from another source and was not allowed to vary in the parameter estimation process.

Values for the first two coefficients in the polynomial are derived from conditions of continuity of both the function and its first derivative at $M=M_o$. The values are

$$a_o = C_o \text{ and } a_1 = 0.$$

To provide additional flexibility for the parameter estimation algorithm, provision was made in the modified program to allow the algorithm to vary the gravitational acceleration constant.

Some investigation was required before the most appropriate form of this model could be chosen. The more interesting results from this investigation are summarised in figure 7. In order to use the model defined by equation (3) effectively we must first test various aspects of it. Among the questions which must be answered are, what is the best choice of M_o, whether the gravitational acceleration constant, g, should be allowed to vary and what degree of polynomial provides the best fit to the data. Several runs were made with different values of M_o, with g varying or fixed and with different degrees of polynomial. The majority of these runs used the data for shell C05, including the results plotted in figure 7 but some spot checks were made using the data for other shells. It was found that for $M_o \geq 0.4$ the fit to the data was not as good as for $M_o < 0.4$. However, for $M_o < 0.4$ not only did the fit to the data not vary significantly with M_o, but neither did the values of axial and normal force which were derived change significantly with M_o. Hence a value of $M_o = 0.3$ was chosen and used to obtain the results which are plotted for comparison with those from model A in figure 7, although in the final version of model B, $M_o = 0.0$ was used.

Although the gravitational acceleration is known quite accurately for the Woomera range, we have already discussed the results from model A which indicated that there was some deficiency in the model with regard to the vertical component of acceleration. Therefore it was decided to investigate the effects of allowing g to vary as part of a modified model. Consider now the difference between results for g fixed at 9.7937 m s^{-2} and results for values of g determined by the parameter estimation algorithm. The r.m.s. of the residuals is reduced substantially when g is allowed to vary and the resulting estimate of axial force agrees much more closely with that derived with model A particularly for higher Mach numbers. It should be borne in mind in undertaking these comparisons that the higher Mach number region of the model A results is constrained by the behaviour of the curves in the transonic and supersonic regions. These parts of the curves had to be obtained from wind tunnel and ballistic range data because of the complete lack of trajectory data for Mach numbers in this range. Therefore results from model A may be considered more reliable at Mach numbers between 0.7 and 0.85 where trajectory data is less concentrated. A result which added support to the idea of allowing the parameter estimation algorithm to determine g, was that otherwise the algorithm would not converge for polynomials of degree more than 2. Generally, comparison of the results for normal force do not support the conclusions derived from the axial force results, however, the accuracy of the results is much lower and the trends are therefore not as significant.

The final choice between quadratic and cubic representations of aerodynamic force coefficients is unclear. The cubic form provides a slightly better fit to the data but the improvement is barely significant. It is clear from figure 7 that the improvement is due to better representation of the data for lower Mach numbers where there is a higher concentration of data at the expense of data for Mach numbers higher than 0.65 where the data is less dense. An overall improvement of the fit results because out of a nominal 1800 data points used in the analysis only 280 were in the range from 0.65 to 0.85. In order to avoid a choice, results have been presented for all four shells for both quadratic and cubic forms. The quadratic form is termed model B and the cubic form is called model C. Both models allow g to vary and use M_o=0.

The results for model B are presented in figure 8 and Table 8. The shaded areas in figure 8 show the range covered by the three most consistent out of the four curves obtained with model A. The agreement between results from model A and those from model B is quite good, both for axial and for normal force, although the results begin to diverge quite rapidly at the higher end of the Mach number range where the data is relatively sparse. The most startling aspect of this result is that the two different models use quite different values of g. Model A uses the measured value of 9.7937 $m\ s^{-2}$ whereas model B determines the best fit value, which averages 9.7222 $m\ s^{-2}$ with a variation of ±0.003 $m\ s^{-2}$. This suggests that the functional form of equation (2) contributes significantly to the robust qualities of the parameter estimation algorithm for model A, since significant changes occurred in the estimated axial force coefficient with model B when the g was fixed at its measured value. Results for normal force are consistent, but diverge significantly from results for model A at higher Mach numbers, an effect which probably arises from the low density of data in that region. However, trends in these results are less significant than for axial force trends because of the greater relative uncertainty in the parameter values.

The results for model C are presented in Table 9 and figure 9. The values obtained for g do not differ significantly from those obtained with model B. The only significant difference from the results for model B is the large deviation for both axial and normal force for Mach numbers above 0.65 together with a compensating slight improvement below 0.6 where the majority of the data points are found. This effect has already been noted.

The most puzzling aspect of a comparison between the results from model A and the results from models B and C is the change in g. This result indicates that a vast improvement in fitting the mathematical model to the observed data can be achieved by subtracting a constant upwards acceleration of 0.072 ± 0.003 $m\ s^{-2}$ from the measured value of the gravitational acceleration constant. There are several possible causes for this, but among the most likely are

(1) errors in the meteorological data, which as has already been discussed is not very reliable, or

(2) a deficiency in using the four degree of freedom model(ref.1) to simulate the motion of the shell, an effect which is particularly likely considering the high elevation of the gun.

The problem may lie with any one of these or other mechanisms, or it may be a combination of several different ones. More trials will be needed to reach a firm conclusion.

The overall consistency of the results from each trial shows that if problems with mathematical modelling of the shell trajectory can be overcome and accuracy requirements for subsidiary trials data such as meteorological data can be met then the trajectory data supplied by the Adour radars at Woomera

TABLE 8. PARAMETER VALUES FROM TRAJECTORY ANALYSIS - MODEL B

Shell Parameter	C05	C06	C09	C10
x_o(m)	684.5 (0.12)	654.5 (0.12)	669.7 (0.10)	665.4 (0.13)
y_o(m)	274.9 (0.13)	277.9 (0.13)	277.0 (0.12)	281.8 (0.14)
z_o(m)	-2458.1 (0.14)	-2413.6 (0.14)	-2429.9 (0.12)	-2428.7 (0.15)
$\dot{x}_o$(m s^{-1})	151.75 (0.039)	151.77 (0.039)	151.87 (0.035)	151.72 (0.042)
$\dot{y}_o$(m s^{-1})	-14.10 (0.032)	-13.96 (0.032)	-14.05 (0.029)	-13.31 (0.034)
$\dot{z}_o$(m s^{-1})	-254.21 (0.055)	-257.80 (0.054)	-255.25 (0.048)	-257.33 (0.058)
C_x a_o	-0.1671 (0.00043)	-0.1741 (0.00041)	-0.1771 (0.00039)	-0.1899 (0.00046)
a_2	0.0618 (0.0016)	0.0967 (0.0015)	0.0931 (0.0015)	0.1335 (0.0017)
M_o	0.0 -	0.0 -	0.0 -	0.0 -
$C_{z\alpha}$ a_o	-2.194 (0.017)	-2.224 (0.016)	-2.188 (0.015)	-2.273 (0.018)
a_2	1.642 (0.086)	1.750 (0.079)	1.387 (0.076)	1.481 (0.090)
M_o	0.0 -	0.0 -	0.0 -	0.0 -
g	9.7191 (0.00045)	9.7211 (0.00046)	9.7254 (0.00040)	9.7235 (0.00050)
σ	1.188	1.198	1.061	1.315
data points	1791	1792	1797	1795

will be sufficiently accurate to obtain good estimates of drag and normal force. It appears that simulations with r.m.s. residuals of less than a metre will be possible.

5. SOLAR ASPECT ANGLE

The data from the yawsondes was treated as described in Section 2 of this report. After initial treatment, the data from the trial consisted of a

TABLE 9. PARAMETER VALUES FROM TRAJECTORY ANALYSIS - MODEL C

Shell Parameter	C05	C06	C09	C10
x_o(m)	683.2 (0.13)	652.9 (0.13)	667.6 (=.12)	662.8 (0.13)
y_o(m)	274.8 (0.17)	278.0 (0.17)	277.1 (0.15)	282.4 (0.17)
z_o(m)	-2459.9 (0.18)	-2410.8 (0.19)	-2426.6 (0.17)	-2423.9 (0.19)
$\dot{x}_o$(m s^{-1})	153.12 (0.086)	153.40 (0.085)	153.88 (0.079)	154.61 (0.089)
$\dot{y}_o$(m s^{-1})	-14.07 (0.080)	-14.04 (0.079)	-14.15 (0.071)	-13.79 (0.080)
$\dot{z}_o$(m s^{-1})	-256.42 (0.135)	-260.53 (0.137)	-258.50 (0.125)	-262.10 (0.143)
C_x $a_o=C_o$	-0.2216 (0.0029)	-0.2371 (0.0028)	-0.2547 (0.0026)	-0.3017 (0.0028)
a_2	0.637 (0.030)	0.751 (0.029)	0.906 (0.027)	1.290 (0.029)
a_3	-0.675 (0.036)	-0.759 (0.033)	-0.950 (0.031)	-1.339 (0.034)
M_o	0.0 -	0.0 -	0.0 -	0.0 -
$C_{z\alpha}$ $a_o=C_o$	-1.823 (0.138)	-2.058 (0.129)	-2.012 (0.121)	-2.623 (0.137)
a_2	-2.80 (1.67)	-0.23 (1.56)	-0.78 (1.47)	5.70 (1.64)
a_3	5.59 (2.1)	2.48 (1.98)	2.78 (1.87)	-5.40 (2.08)
M_o	0.0 -	0.0 -	0.0 -	0.0 -
g	9.7199 (0.00043)	9.7229 (0.00044)	9.7268 (0.00037)	9.7270 (0.00045)
σ	1.141	1.135	0.970	1.149
data points	1785	1786	1788	1789

record of the complementary solar aspect angle, σ_N. The measurements obtained

for shells C05 and C06 are shown in figure 10. Some data is missing from the beginning of each record because of the need to tune the telemetry receivers after launch to account for the drift in the transmitter frequency which occurs while the shell is in the gun. Hence useful data was only available for each shell from 8 s after launch. This gap is much longer than expected and it should be possible to decrease it substantially in future trials by more careful planning. The signal strength of the transmission for shell C05 dropped significantly during the trial so that no useful data was obtained after 30 s from launch although most of the missing data could have been recovered by more sophisticated processing techniques which are currently being developed. The transmission from C06 was much stronger, however, and data were obtained right up until impact, although only the first 55 s is shown in figure 10. The final 10 s of the flight will be discussed later in this section. This was the only part of the data from both shell flights, during which the shell oscillated with any appreciable amplitude.

Although the data in figure 10 contain oscillation components with both precessional and nutational frequencies, both are of such low amplitude that it is not possible to estimate any aerodynamic moment coefficients from the data. The simulated values for complementary solar aspect angles, which are shown in figure 10 were obtained by using trajectory and roll rate information with the parameter estimation program described in reference 1 to estimate the initial conditions for the attitude angles of the shell, setting $C_{m\alpha}=4$. Apart from some slight difficulties with the phase of the simulated results which leads to large amplitude oscillations in the residuals the simulation follows the flight measurements quite well. However, there is a discrepancy between the characteristics of the simulated and measured complementary solar aspect angles and that is shown by the fact that the average difference between the two curves starts from zero at the beginning and increases to a maximum of nearly four degrees just prior to apogee afterwards decreasing to zero as the shell approaches impact. The r.m.s. values for the residues indicate the magnitude of the discrepancy; they are 0.0517 and 0.0351 rad for shells C05 and C06 respectively. The reason for the difference between measurement and simulation is obscure, but possible causes are inaccurate meteorological data or a deficiency in the mathematical model of the dynamic behaviour of the shell which is not normally significant but is accentuated by the high elevation at launch. The discrepancies which were discussed in the previous section with reference to trajectory simulation probably arise from the same source. It is interesting to note with regard to the second possibility that similar simulated and measured yawsonde records were obtained during an investigation of high angle fire which is described in reference 7.

It was indicated previously that the majority of the yawsonde data could not be used to find aerodynamic coefficients of the shell. There were two causes for this inadequacy in the data. It arose, firstly because the precession and nutation modes of motion had very small amplitudes, generally much less than one degree, and secondly because the velocity dropped so rapidly due to the high launch elevation that velocity was quite low for much of the trajectory. Low velocities mean low dynamic pressures and low precession frequencies; for example, the precession frequency at apogee was only 1/5 of that at launch. Consequently, even when the motion has sufficient amplitude, it is difficult to obtain a length of data containing enough precession cycles and with other parameters such as Mach number reasonably constant. It is necessary to have such a section of data to obtain an accurate estimate of aerodynamic moment coefficients. One small section of the yawsonde data, although by no means ideal, had the necessary characteristics to provide a useful test for the parameter estimation algorithm. The results of the analysis are given in Table 10 and figure 11. It is clear from figure 11 that the parameter estimation algorithm produced a very good simulation of the yawsonde measurements. In fact the r.m.s. value of the residuals was 0.0061 rad, and certainly merits further discussion. The initial estimates of the value of each parameter are given as run zero in Table 10. In the first run of the algorithm, the only parameter allowed to vary was ψ_o, the initial value of azimuth angle for the shell at time t_o, which was 58 s from launch in this case. In each successive run another parameter was added to those which were allowed to vary until a total of eight was reached. The addition of any further parameters after this produced conditions such that the algorithm diverged. In fact, some of the parameters already included in Table 10 are not needed by the mathematical model to produce a good simulation of this particular data. Consider the successive values of σ, the r.m.s. value of the residuals. It does not decrease significantly after run 4. The addition of further parameters following run 4

TABLE 10. PARAMETER ESTIMATION RESULTS FOR YAWSONDE DATA FROM SHELL C06

RUN	ψ_o	ϑ_o	$C_{m\alpha}$	C_{mq}	q_o	$C_{m\alpha^3}$	$C_{np\alpha}$	r_o	σ
0	0.040	-1.110	4.0	0.0	-0.02	0.0	0.0	0.0	-
1	-0.004 (0.0021)(1)								0.022411
2	-0.004 (0.0014)	-1.089 (0.0007)							0.015563
3	-0.038 (0.0007)	-1.112 (0.0005)	4.250 (0.003)						0.006667
4	-0.028 (0.0010)	-1.111 (0.0004)	4.252 (0.003)	-35.1 (2.8)					0.006156
4A	-0.027 (0.0010)	-1.111 (0.0004)	4.252 (0.003)				-0.212 (0.017)		0.006208
5	-0.030 (0.0023)	-1.112 (0.0004)	4.252 (0.003)	-34.8 (2.8)	0.10 (0.09)				0.006154
6	-0.031 (0.0023)	-1.111 (0.0004)	4.200 (0.003)	-33.6 (2.8)	0.10 (0.09)	49.3 (31.)			0.006149
7	-0.035 (0.0046)	-1.111 (0.0006)	4.208 (0.029)	-160.0 (42.0)	0.09 (0.19)	44.0 (28.0)	0.76 (0.25)		0.006126
8	-0.035	-1.112	4.208	-160.0	0.09	44.0	0.76	-0.08	0.006128

(1) Figures in brackets indicate rms errors in estimated parameter values.

leads to one of two possible effects. Either the probable error in the parameter value is of the same order as the parameter value or there is correlation between values for two or more parameters. An example of the former are the rms errors in estimates of initial pitch and yaw rates, q_o and r_o, which are larger than the values themselves. The latter situation is exemplified by the correlated parameter pairs ($C_{m\alpha}$,$C_{m\alpha^3}$) and (C_{mq}, $C_{np\alpha}$). In

each case when the second member of each pair is added to the parameter set the value of the first member changes significantly and its r.m.s. error increases alarmingly, which generally indicates that the motion being analysed does not contain the information necessary to differentiate between the effects of the two parameters. The reasons are clear in this case. It is difficult to distinguish between $C_{m\alpha}$ and $C_{m\alpha^3}$ because incidence amplitudes are low and the nonlinear term will have little effect. On the other hand the ambiguity in differentiating C_{mq} from $C_{np\alpha}$ arises because there is no nutational component in the motion. Nutation would provide an independent estimate of a different linear combination of C_{mq} and $C_{np\alpha}$ to that obtained from precession, thus enabling the algorithm to distinguish different effects on the motion from the two different aerodynamic moments. Unfortunately we cannot distinguish absolute values for C_{mq} and $C_{np\alpha}$. It is clear from comparison of the results from runs 4, 4a and 7 that the mathematical model can simulate the motion equally well using one or the other or both. However, if a reliable estimate for one of those parameters were available from some independent source, then that parameter could be fixed at the known value and the algorithm used to estimate a value for the other. This would no doubt be the case when a comprehensive series of yawsonde trials was being analysed.

Although the data from these trials has many unsuitable characteristics from the point of view of the data analyst, the results are generally encouraging. The overall agreement between measurement and simulation which is shown in figure 10 and the excellent detailed simulation of measured data shown in figure 11 indicate that with more experience in planning yawsonde trials we can expect to obtain a lot of useful results. The particular areas of trials planning which require more attention are the launch conditions and some means of generating incidence behaviour more suitable for analysis by parameter estimation. These problems, together with similar ones arising from the results of the trajectory analysis will be discussed in some detail in the next section.

6. CONCLUSIONS AND RECOMMENDATIONS

Analysis of both yawsonde and radar data obtained from firings of four 105 mm shells has produced certain conclusions which should be used to improve planning of such trials in the future. This section summarises the conclusions which were reached during the analysis of data from radar tracking of the shells and from yawsondes carried by the shells and from these conclusions deduces particular points which should be remembered when future trials are planned.

Many of the problems encountered in data analysis were common to both sets of data, both trajectory data from the radar and solar aspect angle data from the yawsondes. In all cases little useful data was recorded before eight seconds after launch. The gap in the trajectory data was caused by the geometry of radar position and shell trajectory and requirements for optimizing radar acquisition. This time can be substantially reduced by lowering the gun elevation and accepting minimum requirements for radar acquisition. On the other hand loss of early yawsonde data arose from problems in tuning the telemetry receiver to account for drift in transmitter frequency. Experiments indicate that this time lag can be reduced to about one second by accurately measuring the rate of frequency drift and switching the transmitter on before the shell is placed in the barrel. The second problem common to both sets of data arose from the rapid deceleration of the shell immediately it left the barrel. Together with the delay in acquiring data from the shell, this caused the loss of all data for Mach numbers above 0.85 even though the Mach number at the muzzle of the gun was 1.37. Thus no data was obtained for the very important transonic region even though the shell was fired at maximum velocity. The remedy is simple; the elevation of the gun should be reduced to a minimum value consistent with shell trajectory having sufficient elevation from the radar that ground clutter does not significantly debase the quality of the tracking data. The third problem area which both sets of data have in common is the meteorological data, particularly the profile of wind velocity and direction. The only solution in this case is to restrict firings to conditions where wind velocities are low and have been adequately measured beforehand. The fourth and final difficulty which both algorithms have in common involves the adequacy of the models used in the parameter estimation both for trajectory data analysis and for yawsonde data analysis. There are systematic errors in the simulation of both sets of experimental data. There is a consistent discrepancy in the simulation of the altitude of the shell which corresponds to a vertical acceleration of approximately 0.07 $m\ s^{-2}$ and there is a discrepancy in the simulated complementary solar aspect angle which reaches a maximum value of about four degrees near apogee. The origins of these faults are not clear but the most probable cause is some inadequacy in the mathematical representation of the shell behaviour, which is allied to the poor performance of the four degree of freedom model for high angle fire combined with low dynamic pressure and consequent minimally effective aerodynamics. Two courses are open to us to counter this problem. Either we can attempt to avoid it altogether by firing at lower elevation, a solution to several other problems as well, or we can design a series of trials using high angle fire with the aim of improving modelling techniques in that area and thus obtaining increased usefulness for the four degree of freedom trajectory model.

No other difficulties were encountered in analysing the trajectory data; however, there were two aspects of the results which were particularly encouraging. First the outcome of test runs using different functional forms for the axial and normal force coefficients showed that model A, which was the form proposed in reference 1, provided a particularly robust representation of aerodynamic forces that was not nearly as sensitive to problems with model adequacy as the other functional forms which were tested. This robust behaviour is in part due to the additional a priori information on transonic and supersonic behaviour contained in these curves. However, in view of the capabilities of model A in coping better than other approaches with the peculiar discrepancies arising in vertical components of the motion we conclude that other factors contribute to its superior performance. The second result of the test runs was that the accuracy of the trajectory measurement by the Adour radar was sufficient to yield the necessary accuracy in the derived values of axial and normal force coefficients.

As with the trajectory data the results of analysing the yawsonde data demonstrated the feasibility and the enormous potential of the approach for investigations into the ballistic performance of missiles and of spin stabilised shells in particular. Two particular requirements emerged which would have to be met if the full potential of the yawsonde is to be realised. First, because of the stringent requirements placed on measurement accuracy of the yawsonde, a highly accurate calibration of the yawsonde is needed. The yawsondes which were used in the trials described in this report were supplied by BRL and were accompanied by accurate calibration information obtained by the method described in reference 4. In order to use the yawsondes developed within the Weapons Systems Research Laboratory effectively, a similarly accurate calibration system must be developed. The second requirement for developing the potential of the yawsonde is a means of initiating an appropriate disturbance which will exhibit the mixture of nutational and precessional modes required by the parameter estimation algorithm to enable it to obtain the maximum amount of information about the aerodynamic moment coefficients. It was possible to extract only very limited results for aerodynamic moments from the data considered here because of the generally steady flight of the shell. Means of creating controlled initial disturbances have been developed which use either asymmetric muzzle brakes or asymmetric mass distributions(ref.8) and they partially satisfy this requirement. However, a more flexible method which could be used throughout the flight would certainly be more useful, particularly in view of the problems associated with recording data from the first few seconds of flight of the shell.

Thus the trials described in Section 2 and the subsequent analysis of the data from them have shown the potential of the yawsonde and radar measurements to provide a basis for investigating new and cheaper methods for developing a Fire Control Model and for conducting research on exterior ballistics of new shell designs. However, before the approach can achieve its full potential, further development will be needed. The conclusions from the data analysis show that the following actions will greatly improve the trials technique;

(1) keep the gun elevation low for better modelling and lower deceleration,

(2) reduce the time for the radar to acquire and track the shell,

(3) reduce the time to tune the telemetry receiver,

(4) carry out trials only when meteorological conditions are suitable and accurately measured,

(5) develop an accurate calibration procedure for the yawsonde, and

(6) develop techniques for perturbing the shell during flight.

7. ACKNOWLEDGEMENT

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NOTATION

$A(r)$, $B(r)$	polynomial functions of r
a_i, b_i	coefficients in various polynomial functions
C_{lp}	roll damping moment coefficient derivative
C_m	pitching moment coefficient
$C_{m\alpha}$	pitching moment coefficient derivative
$C_{m\alpha^3}$	nonlinear pitching moment coefficient derivative, so that $C_m=C_{m\alpha}\alpha+C_{m\alpha^3}\alpha^3$
C_{mq}	pitch damping moment coefficient derivative
$C_{np\alpha}$	magnus moment coefficient derivative
C_x	axial force coefficient
$C_{z\alpha}$	normal force coefficient derivative
g	gravitational acceleration at sea level
K	mach number at centre of transonic drag rise
L	width of transonic effects
M	mach number
$\begin{bmatrix} p \\ q \\ r \end{bmatrix}$	components of angular velocity of shell
r,s	variables in definition of aerodynamic force curves $r = (M^2-K^2)/(M^2+K^2)$ $s = r/[(1-L^2)r^2+L^2]^{1/2}$
T	roll period of shell
$\begin{bmatrix} x \\ y \\ z \end{bmatrix}$	position of shell in range axes, OX at 304° 42' 41" T, OZ vertically downwards and OY completing a right handed set.
β	circumferential angle between yawsonde slits (see figure 2)
γ_1,γ_2	angles between yawsonde slits and

	longitudinal axis of shell (see figure 2)
ϑ	elevation of shell longitudinal axis
τ	time between pulses from different slits in the yawsonde (see figure 2)
σ	r.m.s. value of the residuals of the simulated and measured data in the parameter estimation process.
σ_N	complementary solar aspect angle (see figure 2)
ψ	azimuth of shell longitudinal axis

subscripts

o	initial conditions for integration

superscript

	differentiation with respect to time

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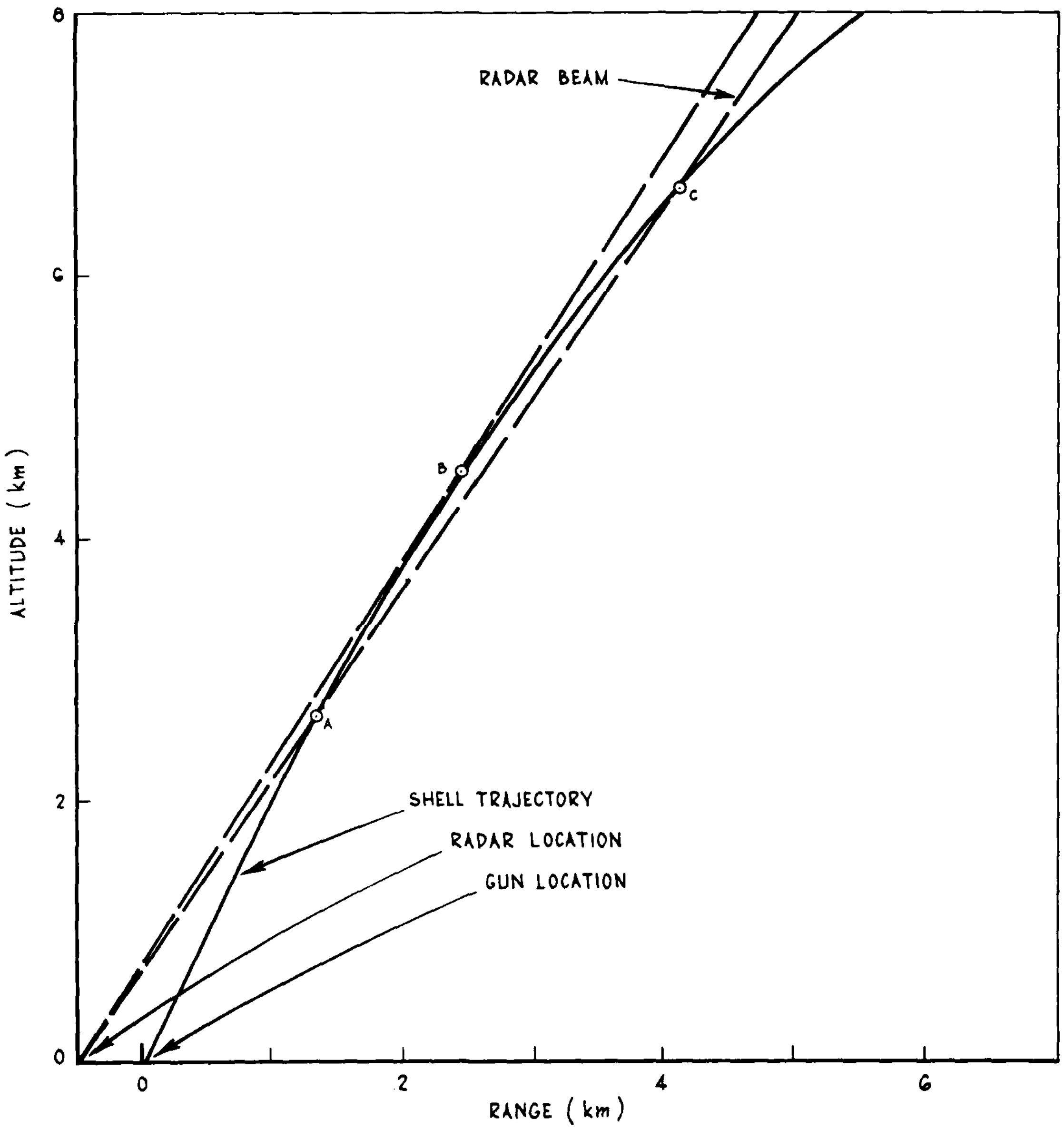
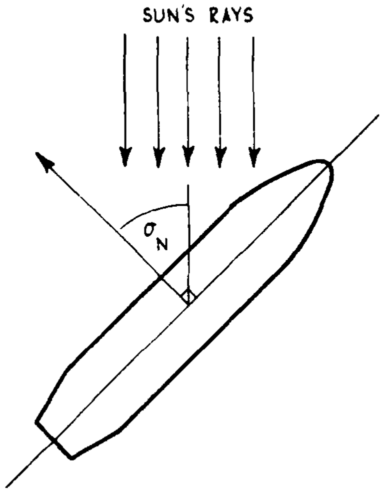
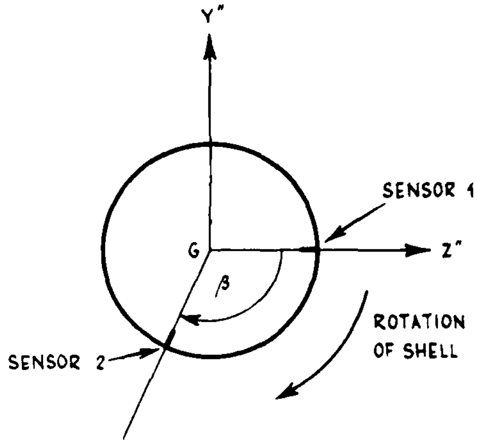


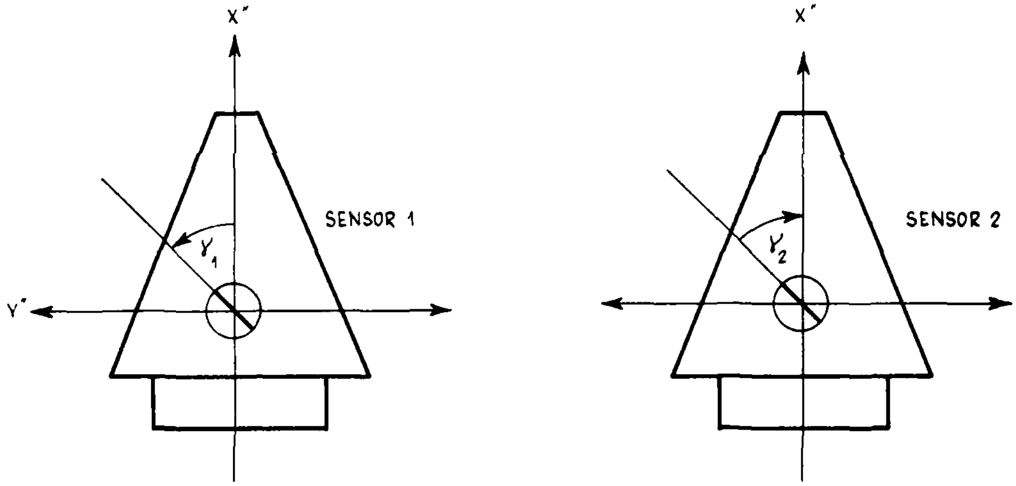
Figure 1. Schematic of radar acquisition



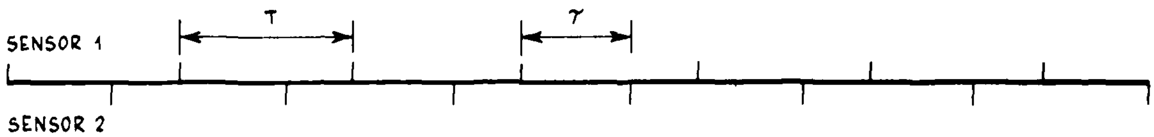
(a) Complementary solar aspect angle σ_N



(b) Angle of rotation between slits



(c) Orientation of slits relative to the longitudinal axis of the shell



(d) Pulse train from yawsonde

Figure 2. Schematic representation of a yawsonde

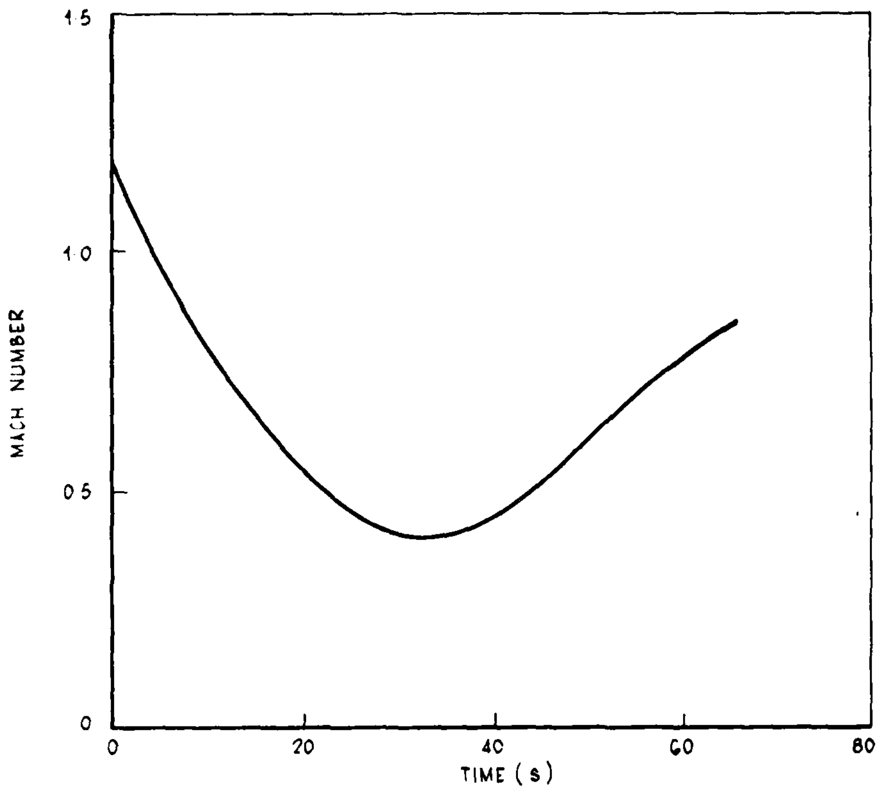


Figure 3. Flight Mach number

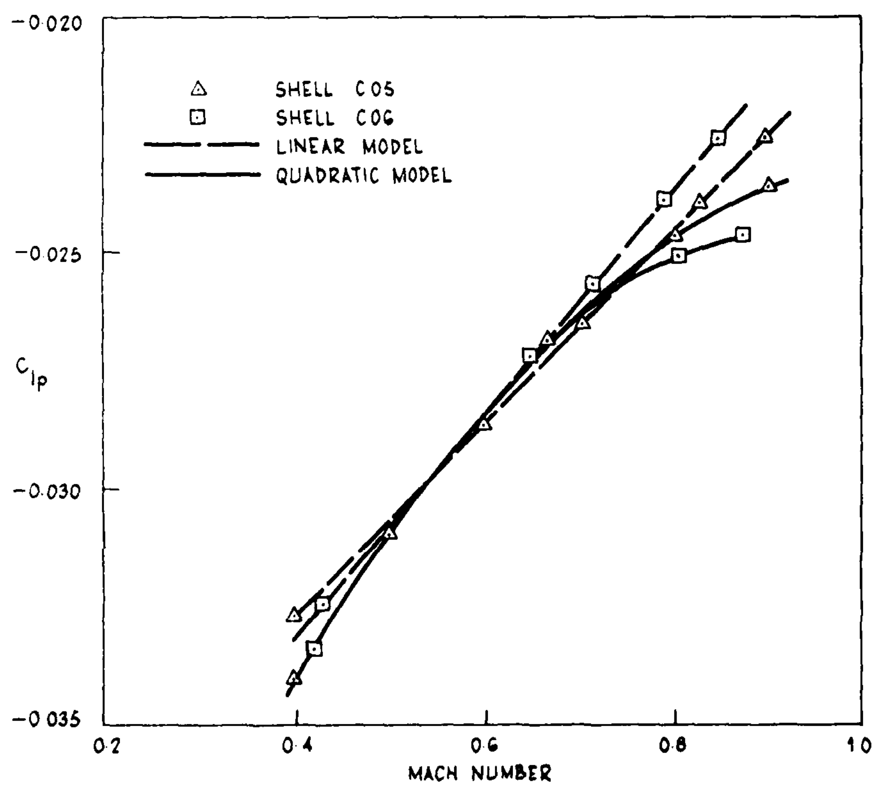
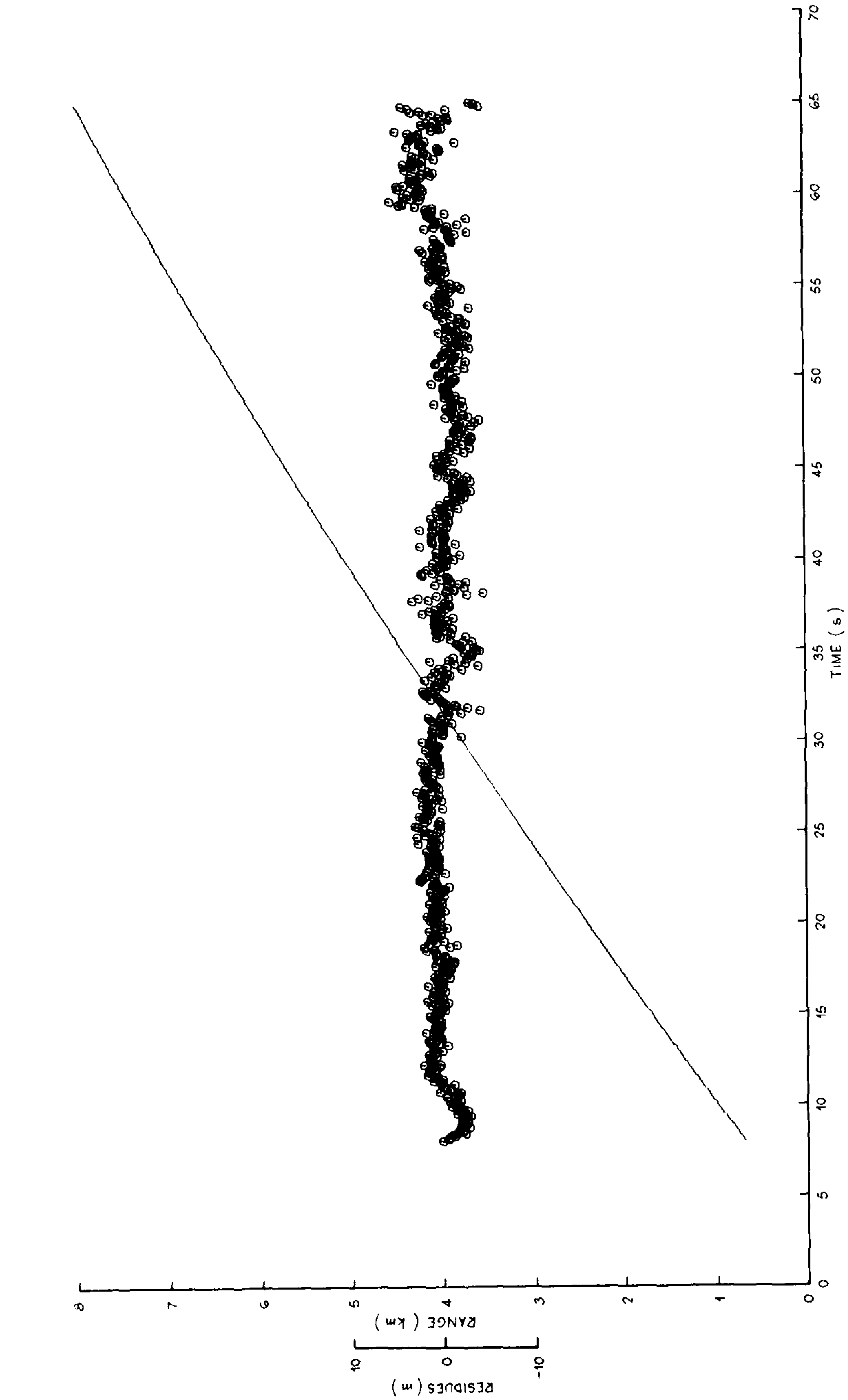
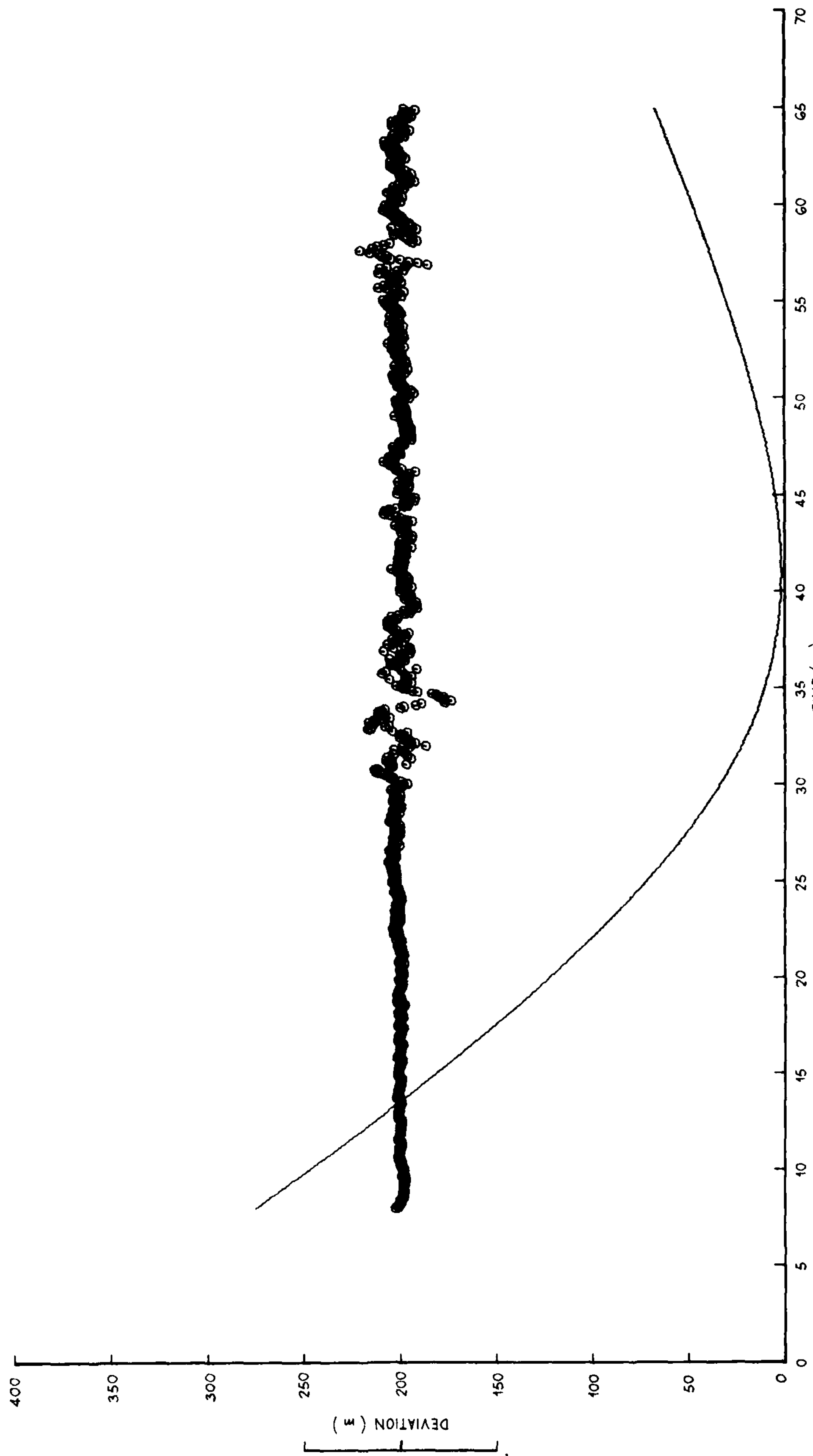


Figure 4. Roll damping coefficient derivative



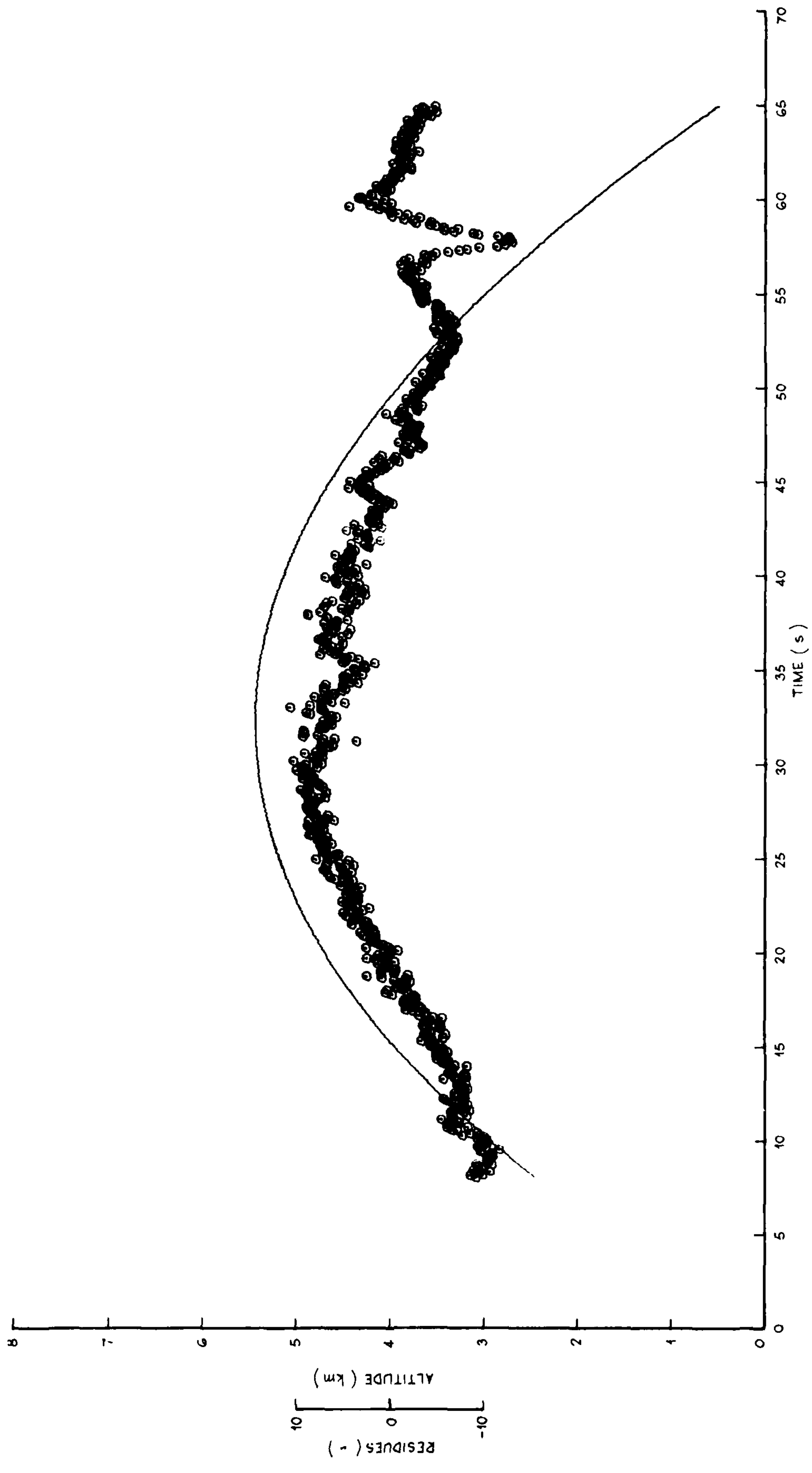
(a) Range

Figure 5. Goodness of fit for shell trajectory data for C05



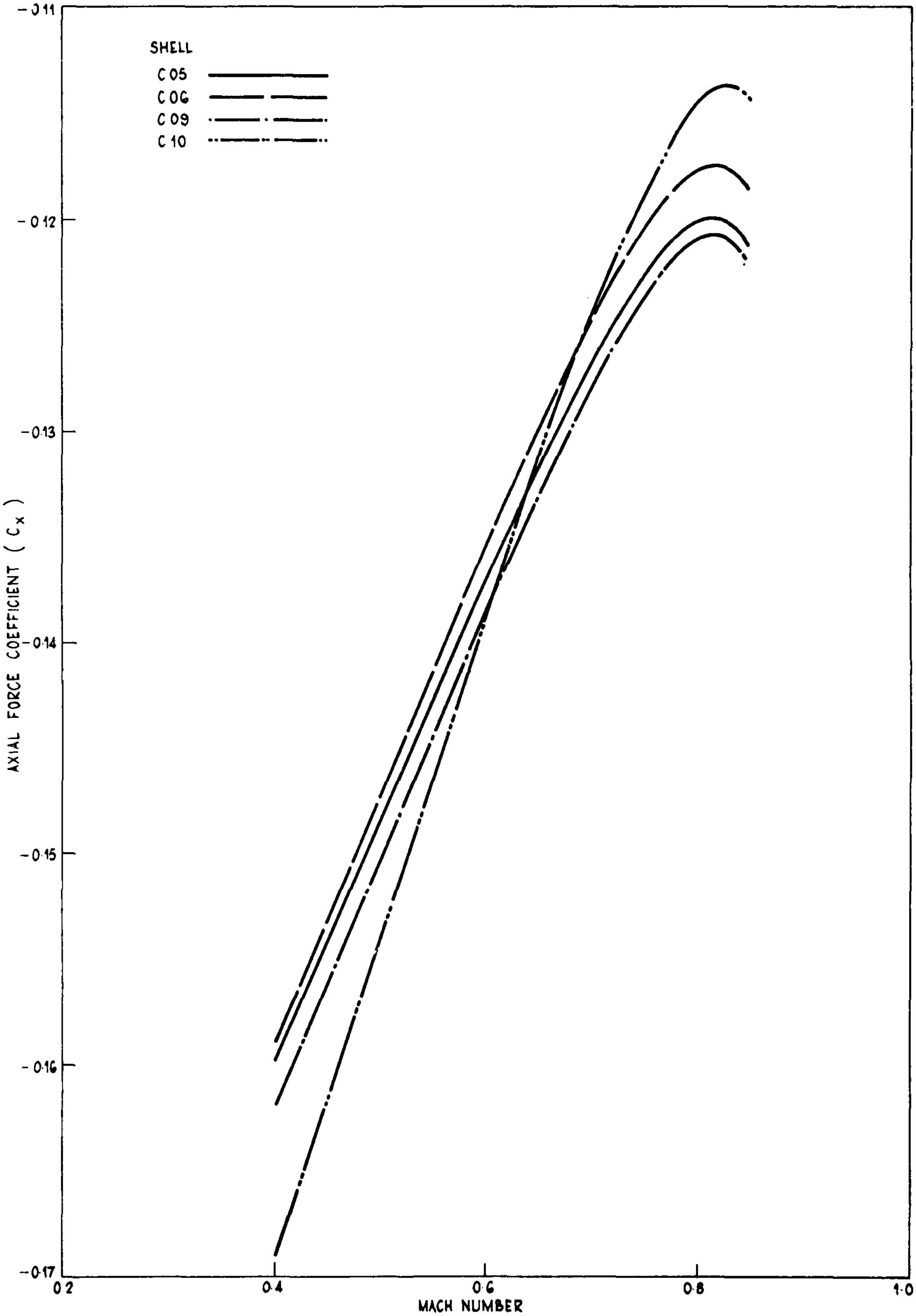
(b) Deviation

Figure 5(Contd.). Goodness of fit for shell trajectory data for C05



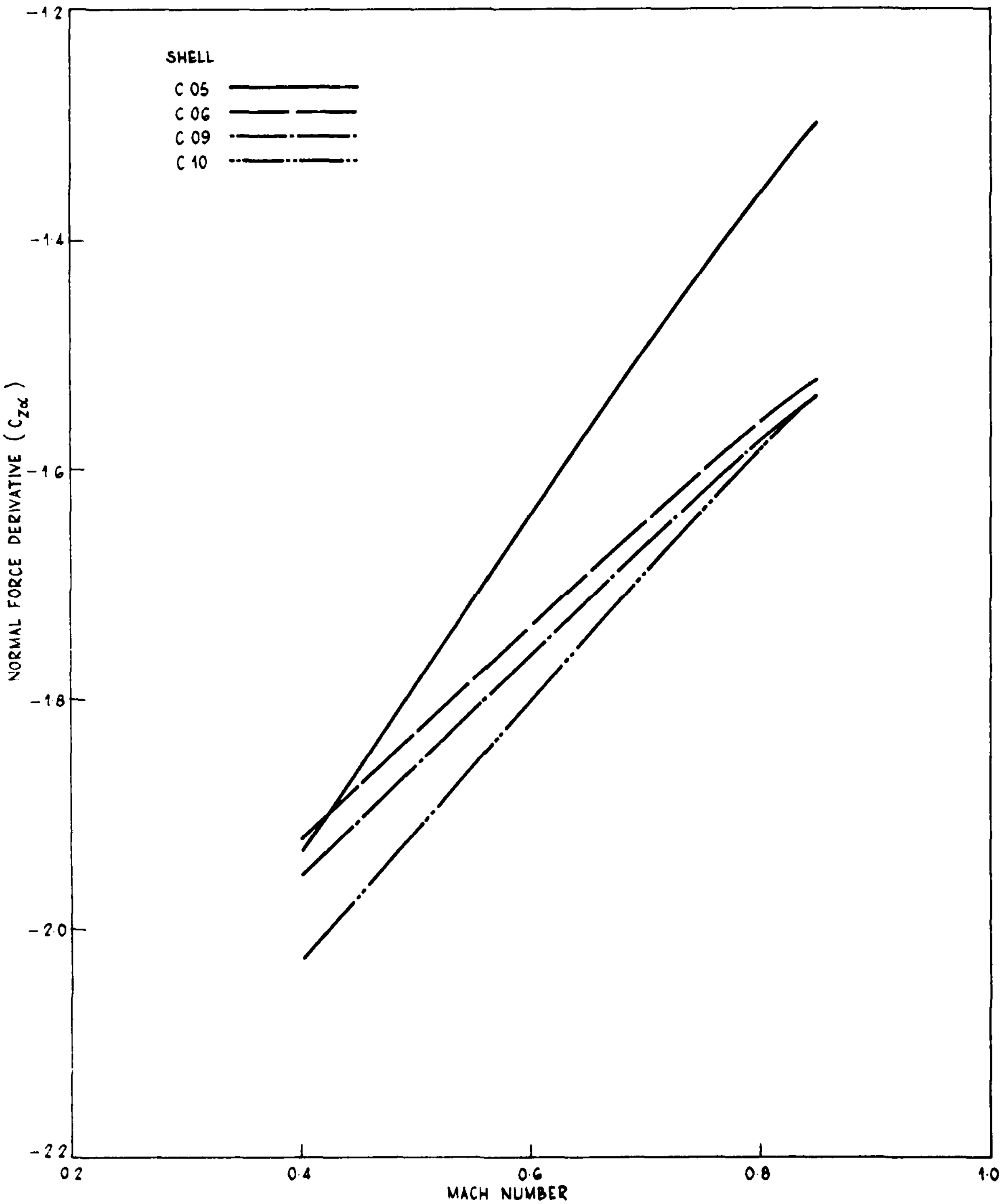
(c) Altitude

Figure 5(Contd.). Goodness of fit for shell trajectory data for C05



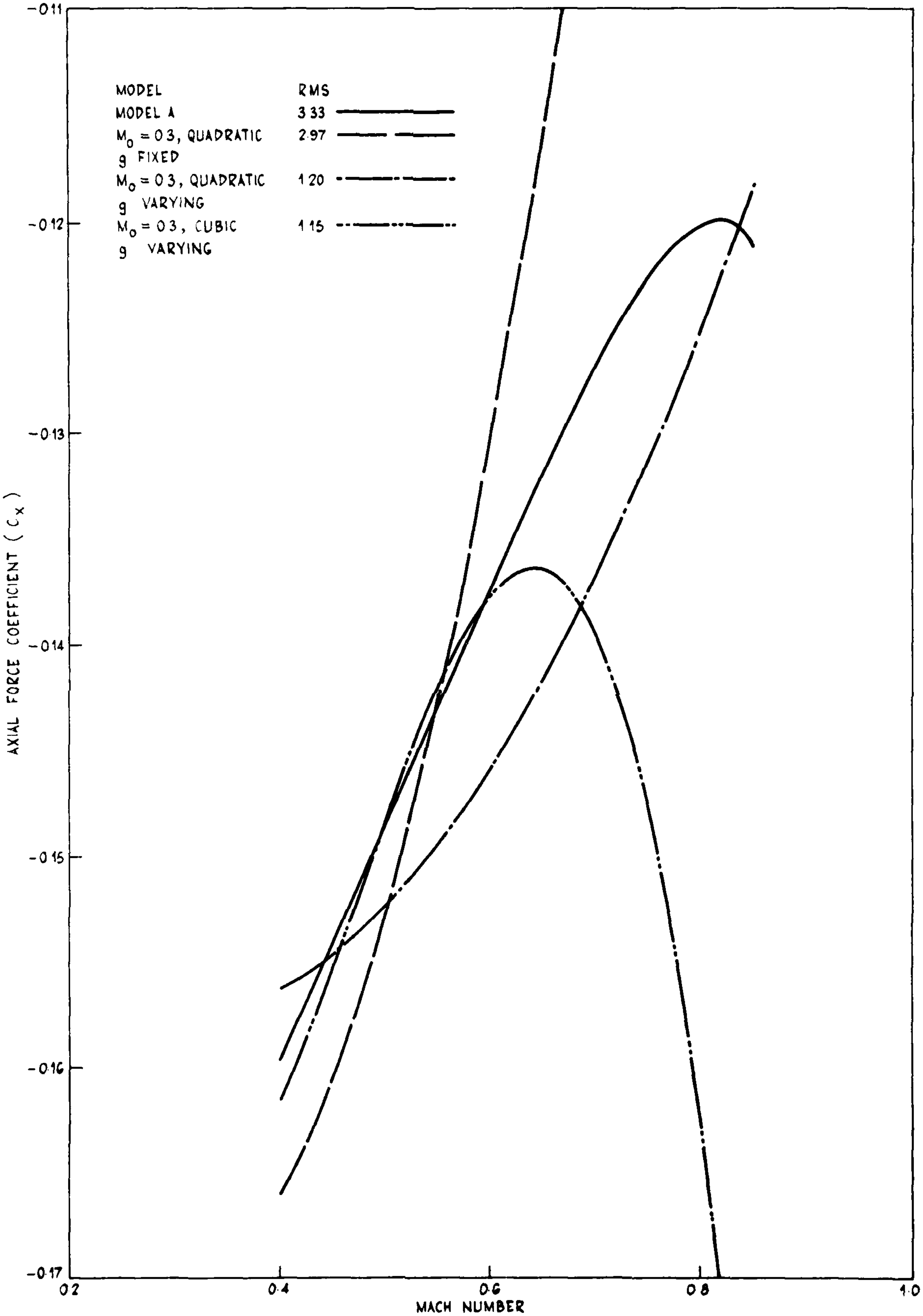
(a) Axial force

Figure 6. Force estimates from trajectory analysis (model A)



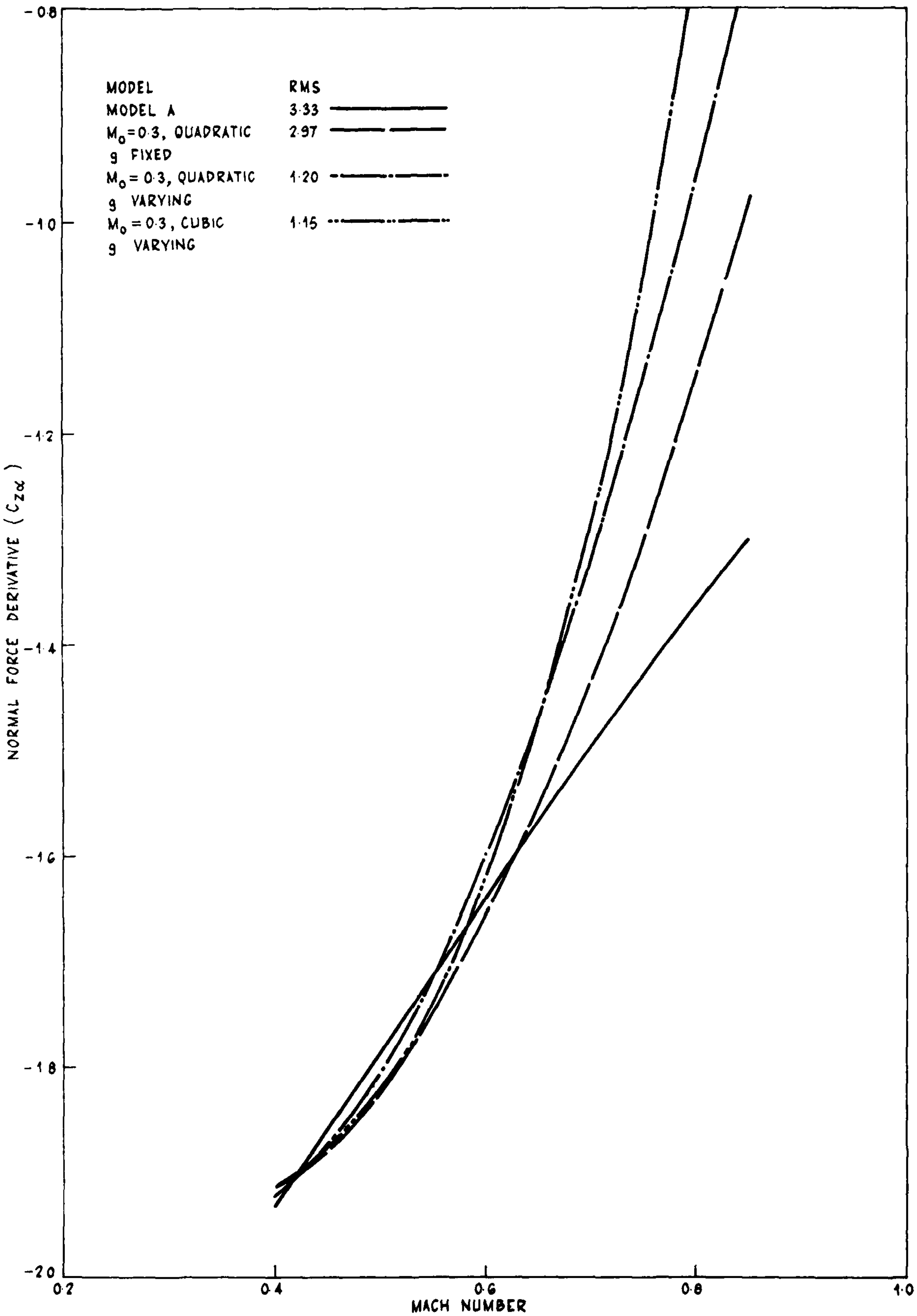
(b) Normal force

Figure 6(Contd.). Force estimates from trajectory analysis (model A)



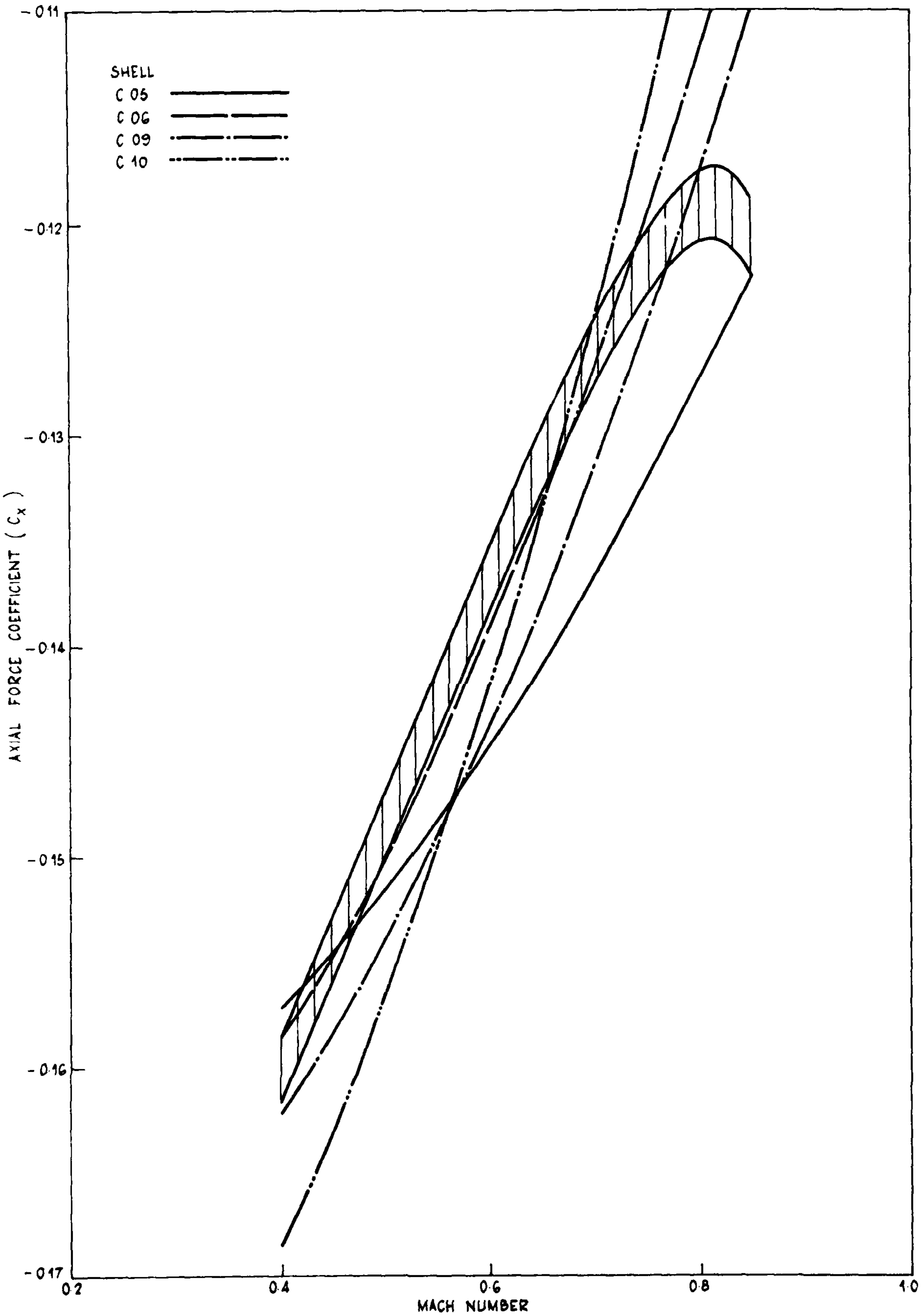
(a) Axial force

Figure 7. Comparison of results for different models



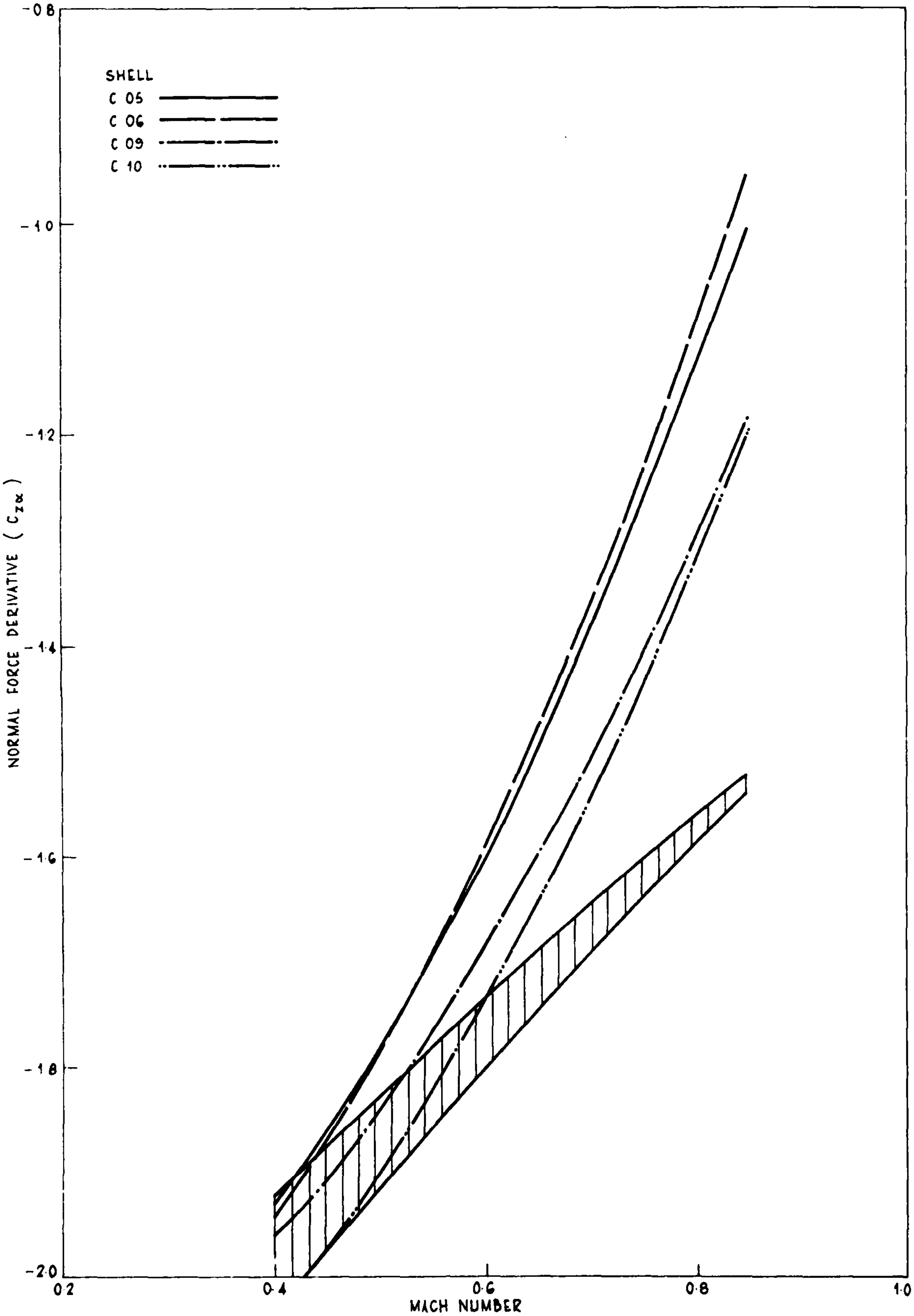
(b) Normal force

Figure 7(Contd.). Comparison of results for different models



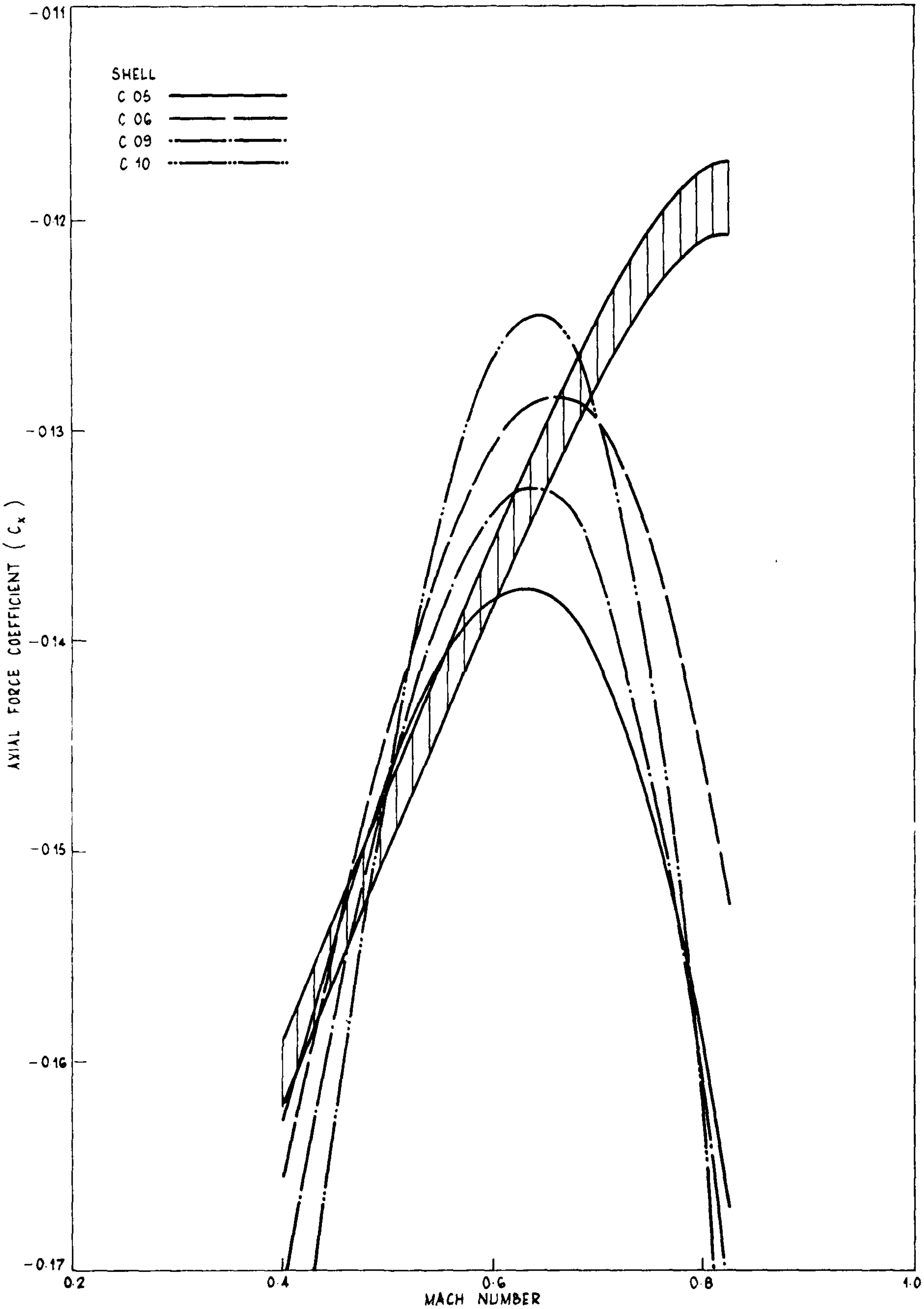
(a) Axial force

Figure 8. Force estimates from trajectory analysis (model B)



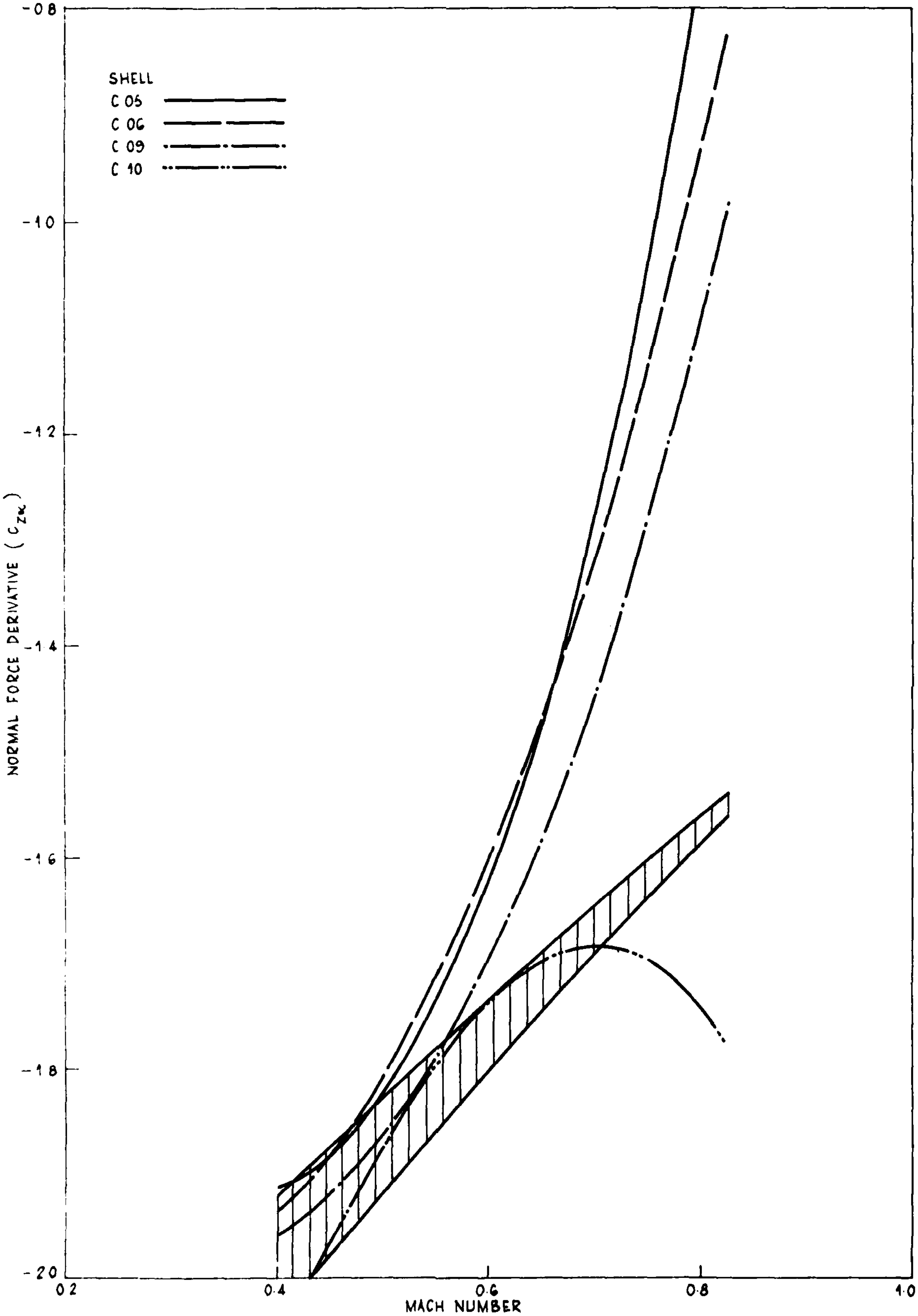
(b) Normal force

Figure 8(Contd.). Force estimates from trajectory analysis (model B)



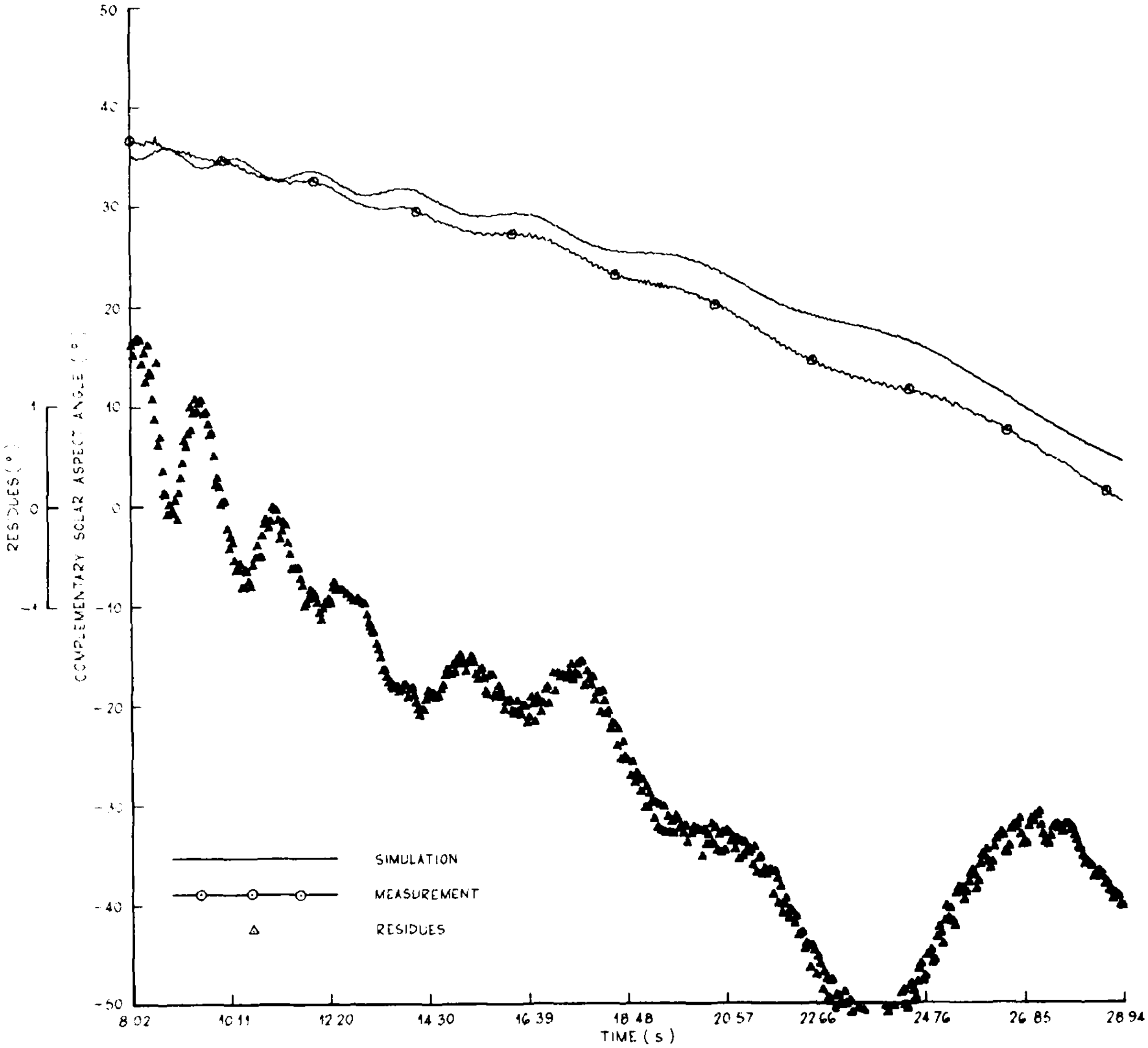
(a) Axial force

Figure 9. Force estimates from trajectory analysis (model C)



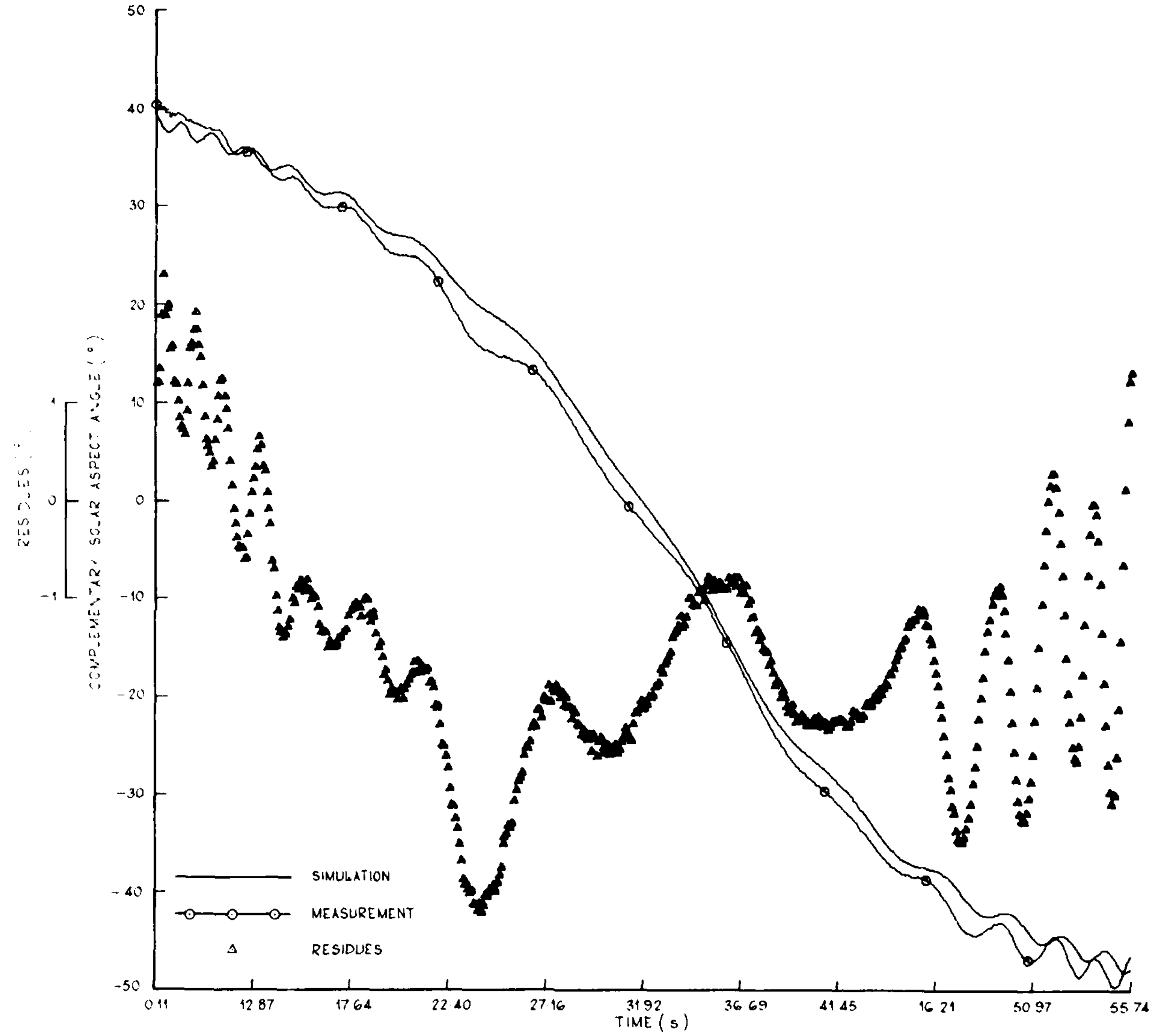
(b) Normal force

Figure 9(Contd.). Force estimates from trajectory analysis (model C)



(a) Shell C05

Figure 10. Goodness of fit of yawsonde data



(b) Shell C06

Figure 10(Contd.). Goodness of fit for shell yawsonde data

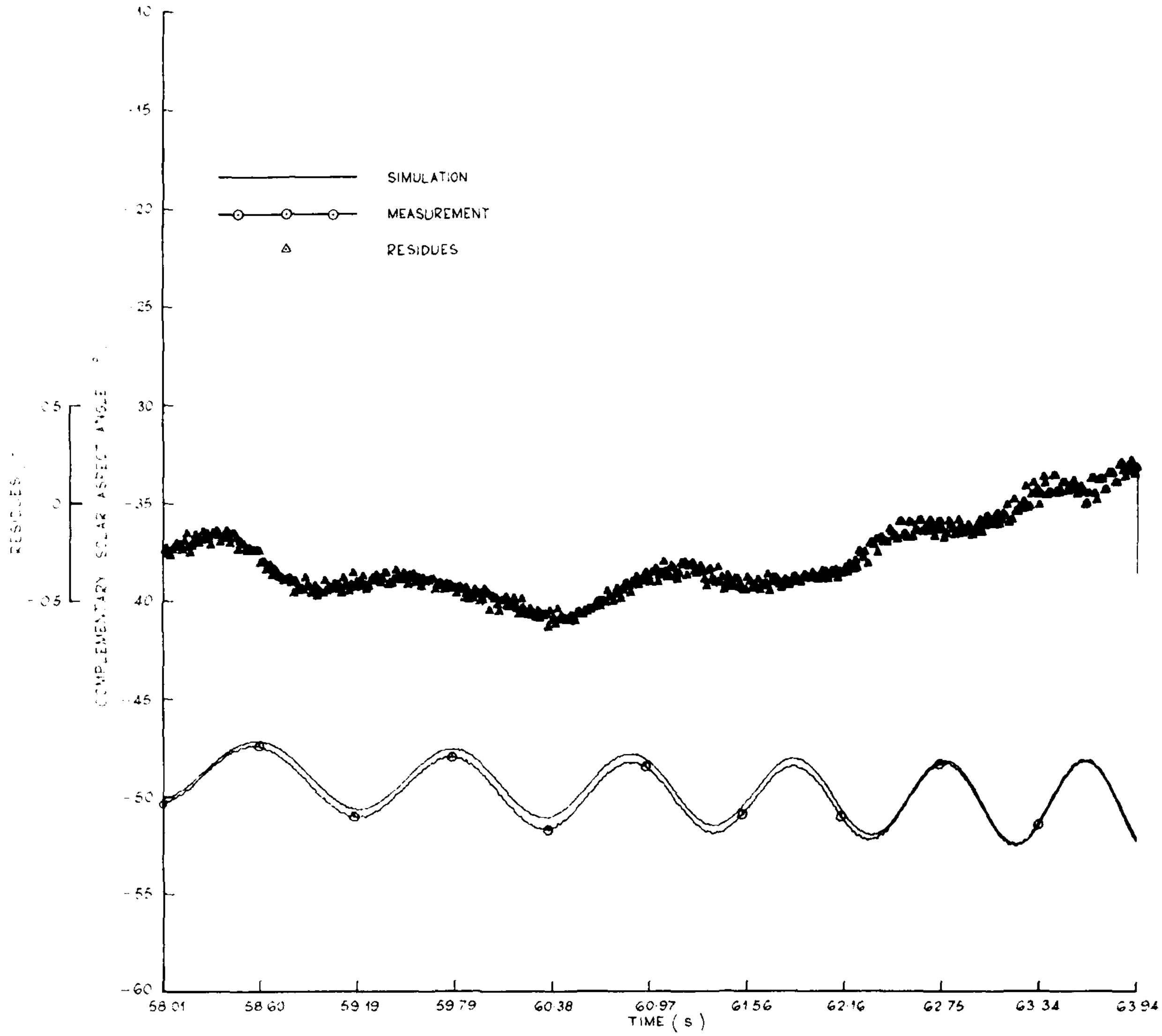


Figure 11. Simulation for yawsonde data from C06

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