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An Investigation of the Polarisation Dependence of Insect Radar Cross
Sections at Constant Aspect

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*In the days of old and insects bold
(Before bats were invented)
No sonar cries disturbed the skies
Moths flew uninstrumented.*

J. D. Pye

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Abstract

A low cost system for measuring insect radar cross section (RCS) as a function of polarisation orientation when viewed at constant vertical aspect is presented.

A low power continuous wave system (frequency 9.4 GHz) was developed which illuminated a target vertically and measured the power reflected back as the target was rotated in the horizontal plane. Data was collected by a microcomputer and stored on floppy disk for later analysis. A standard target was measured before each insect target and software used this data to calibrate the system for each insect target measurement.

A 5 parameter mathematical model, based on the scattering matrix, is described. Software was developed to calculate the parameters from collected data using a least squares procedure.

Measurements from 54 specimens representing 18 species of commonly available insect are reported. Average RCS's were similar to the RCS of water spheres of equivalent mass. For small insects, the maximum and minimum RCS occurred when the electric vector (E-vector) was parallel and perpendicular to the body axis respectively. As insect size increased, a subsidiary maximum developed when the E-vector was perpendicular to the body axis, becoming dominant for the largest insects measured. The shapes of the RCS pattern were approximately 'mirror' symmetric, except for the RCS curves from *S. gregaria*, the largest insects measured, which were asymmetrical and sensitive to the position of the large rear legs.

It was found that the ratio of maximum RCS to minimum RCS bore no simple relationship to the ratio of body length to abdomen width of the insect, even when adjusted for mass and was not a useful measure of target shape.

The implications of this data are discussed and suggestions for further work are presented.

List Of Symbols

a_1, a_2, a_3	RCS model coefficients
$a_{11}, a_{12}, a_{21}, a_{22}$	intermediate coefficients of model
a_{21}', a_{22}'	alternative RCS model coefficients
a_n, b_n	coefficients in expansion of sphere scattered field
A_r	average residual
B	cubic B-spline curve
C	radar constant
C	cosine curve
c_0, c_1	cosine curve coefficients
c_{11}, c_{12}	alternative cosine curve coefficients
d_i, d_{ij}	raw data point
D	diameter of antenna
E_i, E_r	electric field strength
f	general function
f_{sk}	fractional standard deviation
γ	orientation of electric vector transmitted by antenna
h	normalised effective length
i	general integer subscript
j	general integer subscript
k	general integer subscript
l	general integer subscript
l_t	characteristic length of target
l_{ij}	simultaneous equation matrix element
L	simultaneous equation matrix
L_r	average log residual
m	number of simultaneous equations
m_i	mean of a set of points
n	number of points
n	number of independent unknowns
n_r	number of revolutions
P	power
q, q_k	averaged data point
q_{STk}	Averaged standard target data point
Q	Givens reduction matrix
R	target range
R	upper triangular Givens reduction matrix
R_f	Range to antenna far field region
s_k	standard deviation of a set of points

S	scattering matrix
S	singular value matrix
S^+	inverse singular value matrix
S_d	differential RCS
S_D	alternative differential RCS
S_D'	mass corrected differential RCS
S_{xx}	approximation to σ_{xx}
S_{yy}	approximation to σ_{yy}
t_1	B-spline knot value
U, V	singular value decomposition matrices
x_i, y_i	general values
$\mathbf{x}$	vector of simultaneous equation unknowns
$\mathbf{y}$	vector of simultaneous equation right hand sides
α, α'	scattering matrix cross polarisation phase facto
α	dimensionless sphere diameter
β	scattering matrix phase factor
β_c	critical value of phase factor
δ	phase angle between components of electric vector transmitted by antenna
λ	Wavelength
σ	radar cross section
σ_S	radar cross section of sphere
σ_{STk}	calibrated standard target data point
σ_{Tk}	calibrated target data point
σ_{TW}	RCS of thin wire
σ_{TWm}	maximum RCS of thin wire
σ_{xx}, σ_{yy}	scattering matrix element magnitudes
σ_{xy}, σ_{yx}	scattering matrix cross polarisation element magnitudes
θ_0'	angle of polarisation in hardware coordinate
θ_1	parameter of theoretical model in natural coordinates
θ_1'	parameter of theoretical model in hardware coordinates
θ_2	parameter of theoretical model in natural coordinates
θ_2'	parameter of theoretical model in hardware coordinates
Φ	orientation angle in natural coordinate
Φ	general orientation angle
φ'	orientation angle in hardware coordinate

Chapter 1

General Introduction

Radar is a powerful tool for the remote detection of objects in the atmosphere and has been used for many years to observe airborne insects. Many pest insect species migrate large distances, often at night and at heights of about 100m, causing further outbreaks a long way from the primary source. Radar, one of the few tools available to study such movements, is contributing to the development of safe and effective techniques for preventing these damaging infestations. Most studies have measured only the position of insect targets. Recently, more of the information contained in the returned signal has begun to be exploited. However, the characteristics of the signals returned by individual insects have not been well studied. More research into the variation of insect *radar cross section* (RCS) with, for example, polarisation is required to enable the data obtained from vertically pointing radars with rotating dipole antennas (now frequently used by radar entomologists) to be correctly interpreted. This thesis describes the development of a low-cost system for measuring the polarisation dependence of the RCS of individual insects at constant vertical aspect and presents some results of measurements made using it.

This chapter is a general introduction to radar entomology. A brief history is given in section 1.1. The concept of the RCS is then introduced in section 1.2. Previous work on theories and measurements of insect RCS's are reviewed in sections 1.3 and 1.4. Interpretation of insect RCS data is reviewed in section 1.5. Finally, the aims of this study and layout of the thesis are described in section 1.6.

1.1 History of Radar Entomology

Radar was developed in the Second World War for monitoring aircraft, but it was found that many other atmospheric targets could also be detected. Often, unidentified point targets, called 'dot angels', were detected in apparently clear air. Although the radar detection of birds [Lack and Varley, 1945] and insects [Crawford, 1949] was first reported in the 1940's, it was not until the 1960's that it was generally accepted that these biological targets were the origin of most dot angels [Glover et al, 1966]. Radar was quickly used to track birds and the development of radar ornithology revolutionised bird migration studies [Eastwood, 1967].

The first detection of a locust swarm, by a 10cm naval radar in the Persian Gulf, was reported by Rainey [1955] after he realised that meteorological radars should be capable of observing such swarms. Although further proposals were made, studies lapsed. However, with ever mounting evidence that insects were regularly detected by radar systems [e.g. Hajovsky et al, 1966], interest was rekindled. Observations of locust swarms in India by a meteorological radar [Ramana Murty et al, 1964; Mazumdar et al, 1965] mark the beginning of entomological research using radar.

A trial study in Niger to observe the flight of desert locusts (*Shistocerca gregaria* Forsk.) using a modified 3.2cm ground based marine radar, proved successful [Roffey, 1969; Schaefer, 1969] and further investigations have followed. Reports include observations of grasshoppers in Mali [Riley and Reynolds, 1979], mosquitoes in New Jersey, USA [Frost and Downing, 1978], Australian plague locusts (*Chortoicetes terminifera*) in Australia [Drake and Farrow, 1983], spruce budworm moth (*Choristoneura fumiferana*) in Canada [Greenbank et al, 1980], the African armyworm moth (*Spodoptera exempta*) in Kenya [Riley et al, 1983], aphids in Britain [Bent, 1984], honey bees (*Apis mellifera*) in America [Loper et al, 1987] and planthoppers (*Nilaparvata lugens*) in the Philippines [Riley et al, 1987].

Advances have been made in the equipment used for these studies, although cost is a heavy constraint. Early studies used surplus military or meteorological radars working at X- or S-band [Riley, 1979a]. Most observations are now made using X-band marine radars. To increase the range, (which, although much greater than other techniques, is still shorter than many insect flights [Riley 1979a]) airborne radars have been used [Greenbank et al, 1980; Hobbs and Wolf, in preparation]. Vertically pointing linearly polarised radars with rotating polarisation planes have been used to obtain information on the orientation of insects and, using a nutating beam, the absolute RCS of a target in the radar beam has been measured [Bent, 1984]. Infra-red optical systems have also been developed to improve observations at low levels where radar is ineffective because ground echoes obscure targets [Schaefer and Bent, 1984; Schaefer et al, 1985; Riley et al, 1983].

Present radars are limited in the range at which small insects can be reliably detected and it is difficult to identify targets. Shorter wavelength (Q-band) radars are being used to improve the detectability of small insects [Riley et al, 1987]. More sophisticated processing of the returned signal may improve target recognition

although it must be remembered that many of the features that differentiate between different species are very small and will be invisible at radar wavelengths. Perhaps it will not be possible to accurately identify an unknown target, instead just assigning it to a broad class.

Ground based radars can provide detailed observations of insect movements within a 50km radius of the radar. Airborne radar systems that are complementary to ground based systems are being further developed to allow insect movements over large distances to be observed and studied. This technique has great potential as it allows the entire migration of insects to be observed, from emergence site to the final destination perhaps hundreds of kilometres away. The targets could be identified on the ground at the emergence site or destination.

1.2 Radar Cross Section

The power, P , returned from a point target to a radar is given by

$$P = C \sigma / R^4$$

where C is a constant dependent on the radar (and the atmosphere between the radar and the target), R is the distance of the target from the radar and σ is the RCS of the target. The RCS is dependent on the shape, substance and aspect of the target and also on the wavelength (λ) and polarisation of the transmitted radiation. It is a measure of the ‘size’ of the target as seen by the radar. The dependence of the RCS on the characteristic target size, l_t , is divided into three regions:

$l_t \ll \lambda$, the Rayleigh region – the RCS is approximately proportional to $(\text{volume})^2 / \lambda^4$;

$l_t \gg \lambda$, the optical region – the RCS is proportional to the geometric cross section but is also strongly dependent on target geometry;

$l_t \sim \lambda$, the interference or Mie region – the RCS varies in a complex way due to interference between signals reflected from different parts of the target.

Most radars used in radar entomology have a wavelength of 3.2cm (X-band) as they are cheap and readily available. This means that the RCS’s of small insect targets (such as aphids) are in the high end of the Rayleigh region and those of the larger insects (such as locusts) are in the low end of the interference region. Shorter wavelengths are absorbed by the atmosphere (except for specific wavelengths that are not strongly attenuated). Longer wavelengths reduce the target RCS. Both effects

shorten the range at which the targets are detectable thus preventing useful work. Because scattering is usually in or near the interference region, the RCS's of insects are complex. They vary greatly with aspect in a complex manner but in general are larger when the insect is viewed broadside than when it is viewed head- or tail-on. With linearly polarised radiation, RCS's vary smoothly with orientation (i.e. as the plane of polarisation is rotated about the line of sight without changing the target aspect) and are generally larger when the E-vector is polarised parallel to the long body axis. (These polarisations are denoted by *parallel* and *perpendicular* polarisation respectively. The names are ambiguous when viewing a target head- or tail-on and in this case, polarisation with the E-vector in the horizontal (vertical) plane will be denoted by *horizontal* (*vertical*) polarisation. These are the usual polarisation designations but are ambiguous when the target is viewed vertically as was done for the work described in this thesis. When neither set of names is ambiguous, parallel (perpendicular) polarisation is equivalent to horizontal (vertical) polarisation.)

1.3 Theoretical Determination of Insect RCS's

Because of the complexity of insect RCS's, they are not amenable to simple theoretical treatments. However, if a homogeneous, simple geometric shape is taken as a model, some theoretical results are available.

The simplest model is a sphere, for which the scattering theory is well understood [see Stratton, 1941]. The RCS of a water sphere is a surprisingly good estimate of the mean RCS of an insect of equivalent mass but gives no indication of the variation with aspect and plane of polarisation, since the RCS of a sphere is independent of these parameters.

Another possible model is a prolate spheroid. Again, the theory becomes very difficult and no general, analytical theory has been found. A theory by Stevenson [1953] gives values for spheroids in the Rayleigh region. Schaefer [1968] developed a theory for the RCS's of birds based upon a prolate spheroid. This theory demonstrated the main features of bird echoes and would probably have been applicable to insect RCS's but no mathematical details were ever published.

Several numerical models have been developed for spheroids and are reviewed by Holt [1982]. These models are often applied to water spheroids to predict the RCS's of hydrometeors for radar meteorology. As such, most results published are for

oblate spheroids, but a few are for prolate spheroids [e.g. Antar et al, 1987]. These models can probably give an indication of the RCS's of insects, but no comparisons have yet been published. The models are rather complex and, although it may be possible to implement them upon powerful microcomputers, trained mathematicians are required to operate the models and interpret the results.

1.4 Experimental Measurements of Insect RCS's

The majority of published measurements are of RCS averaged over time and/or aspect. A graph of all published RCS magnitudes was given by Riley [1985]. RCS's of insects range from approximately 10cm^2 for locusts [Hajovsky et al, 1966; Schaefer, 1976] down to 10^{-5}cm^2 for aphids [Riley, 1985]. Many measurements of the RCS's of dot angels have been published, many of which were probably insects. A complete bibliography of insect RCS measurements up to 1978 is given by Greneker and Corbin [1978].

Observations of individual, free-flying insects released from aircraft, were made by Glover et al [1966], using the powerful JAFNA multi-wavelength radar facility at NASA Wallops Flight Center, Wallops Island, Virginia, as part of a series of experiments to determine the origin of dot angels. It indicated that the cross-section varied between the inverse 2.7 and 1.8 power of the wavelength between wavelengths of 3.2cm and 10cm and as the inverse fourth power between wavelengths of 10.7cm and 71.5cm. The insects were not detectable at 71.5cm. The latter wavelength dependence agrees well with that expected for Rayleigh scattering from targets much smaller than the wavelength. The specimens were tracked, usually for several minutes, during which large fluctuations in the cross-section were observed. Random variations were thought to be due to changes in viewing angle and periodic modulations were thought to be due to changes in the wing position as the insect flew, although this interpretation has been questioned [Riley, 1979a].

Riley [1973] published some plots of the RCS against aspect of locusts and an armyworm moth (reproduced in Figure 1.1). Viewing horizontally and using horizontal polarisation he found that the largest cross-section was obtained when viewed from the side but, for some insects, it was only slightly larger than that obtained from head-on. The cross-section varied considerably, with deep nulls when viewed from some angles.

Similar polar plots for several insect species of various sizes, viewed horizontally, were presented by Schaefer [1976]. Most results were for horizontal polarisation but some were for vertical polarisation. Results indicated that in the Rayleigh region, RCS's were similar to prolate spheroids of similar dimensions, but in the interference region the RCS became very sensitive to aspect and body distortion. Polar diagrams for vertical polarisation were simpler than corresponding ones for horizontal polarisation and showed a generally smaller RCS.

Riley [1985] described some measurements of the variation of the RCS's of insects with the orientation of the polarisation plane when viewed from below at constant aspect. For the smallest insects, a maximum occurred for parallel polarisation and a minimum for perpendicular polarisation. However, for larger insects subsidiary maxima occurred for perpendicular polarisation. The largest insects had a maximum for perpendicular polarisation and a minimum for parallel polarisation.

The RCS's of insect are little understood. The few results available suggest the occurrence of complex interference phenomena. Only a few individuals of a few different insect species have been measured in the laboratory and so valid comparisons within and between species cannot be made. Although the general size of the RCS from a given target can be estimated, it is not known how the RCS depends on the body shape or if it varies significantly when the body is distorted, although it has been suggest that such a mechanism may account for the wing beat frequencies that sometimes present in returned signals [Schaefer, 1976]. Although some work has been done on the polarisation dependence of insect RCS's, this subject is poorly understood. Much research remains to be done in this field.

1.5 Interpreting RCS's

Target identification has always been a serious problem in radar studies. Normally, it is not possible to identify the target (which may be several kilometres away) directly and so other information, possibly derived from the RCS, must be used. The characteristics of insect RCS's must also be known for quantitative measurements of aerial densities [Drake, 1981; Riley, 1979b] and can be used to resolve the orientation of a flying insect [Riley, 1979a, 1979b].

The average RCS gives a measure of the characteristic length of the target although there is large scatter and it becomes multiple valued in the interference

region. However, most entomological radars currently in use cannot make an absolute measurement of RCS since it is not possible to determine where in the radar beam the target is situated. For example, a small returned signal may be due to a small insect in the beam centre, or a large insect at the edge. Nutating beam radars, such as that described by Bent [1984], do have this capability.

Insect RCS's are sometimes modulated by a wing beat frequency (WBF) as with birds. As each WBF is characteristic of an insect species, it can sometimes be used to identify the target to within a few species [Riley, 1973]. In one study, it was even possible to differentiate between sexes using the WBF [Schaefer, 1976]. However, the intraspecific variability and species overlap of the WBF frustrates positive identification unless only a few species are present and a single species is numerically dominant [Riley, 1979a].

It has been suggested that a combination of the WBF and a 'body shape factor' (the ratio of the maximum and minimum RCS) could be used for identification purposes [Riley, 1979b]. However, it was reported to be difficult and little further quantitative work has been done.

Collective orientation of flying insects (i.e. insects orientated in approximately the same direction) was discovered using radar [Schaefer, 1969, 1976; Roffey, 1972; Riley, 1975; Drake, 1983; Riley and Reynolds, 1986]. On a typical plan position indicator (PPI) collective orientation appears as an ellipsoidal pattern, normal to the direction of common orientation) i.e. a dumb-bell shaped pattern perpendicular to the direction of orientation). (This occurs because the RCS is larger when viewing insects broadside than when viewing head-on [Schaefer, 1976].) The mean direction of orientation indicates the direction in which the insects are pointing (and is often different from the actual direction of movement because of the effect of wind). Use of this pattern to determine the mean direction orientation is not, however, very accurate since it is difficult to determine the exact orientation of the indistinct ellipsoidal pattern. Furthermore, a bi-modal distribution of orientations is easily obscured within the pattern [Riley, 1979b].

A technique for measuring the orientation of individual insects was developed by Schaefer [1979] and Riley and Reynolds [1979]. It employed a vertically pointing radar with a rotating plane of polarisation and depended on the variation of the RCS with polarisation. It was assumed that the RCS was largest when the polarisation was parallel to the insect orientation. However, recent work indicates that care should be

taken when interpreting results since this may not be true of the larger insects [Riley, 1985].

Interpreting the RCS of an unknown insect target requires a deep understanding of insect RCS's. Since this understanding is largely lacking, present attempts at interpretation are limited to phenomena that are obviously linked to some physical characteristic of the insect such as its orientation or its WBF. Currently it is not possible to deduce information such as body shape from the returned RCS signal since it is not known how such factors affect the RCS. Advances in this area require significant improvements in the understanding of insect RCS's.

1.6 Aims of Study

It is clear that further experimental measurements of insect RCS's are required. However, complete radar ranges are difficult and expensive to build and operate. A limited system, capable of measuring the amplitude of the RCS's of insects in restricted, but realistic conditions would be much cheaper to implement, and the result would be relevant to many entomological radar systems currently in use or being developed.

This thesis describes the development of a low cost system to measure RCS's of insects in the size range $0.01\text{-}20\text{cm}^2$, using linearly polarised radiation with a wavelength of 3.2cm (Plate 1.1). Built using parts salvaged from old equipment for less than £3000, it was designed to measure the variation of RCS with the orientation of the plane of polarisation at vertical incidence, as insects would usually be observed with a vertically pointing radar. Measurements of several common insects are presented and the interpretation of field measurements with vertically pointing radars is discussed with reference to these results.

The thesis is presented in eight chapters and two appendices. Chapter 2 introduces the standard theory and a simple RCS model on which the system is based. (Some of the mathematical derivations are deferred to Appendix A.) The system developed is described in the following three chapters. Chapter 3 describes the hardware built for the system. Chapter 4 describes the software written to collect and process data. (Appendix A outlines the algorithms used.) Chapter 5 assesses the performance of the system. Chapter 6 briefly describes the acquisition and treatment of the insects measured using the system. Chapter 7 presents and discusses the results

and comments on the target parameter estimation from field data with reference to these results. (Appendix B presents all the data obtained in tabulated form.) Chapter 8 gives a summary of the thesis and discusses further work that could benefit the field of radar entomology. Finally, the references cited are listed.

Figure 1.1 Angular Variation of RCS for Several Insects

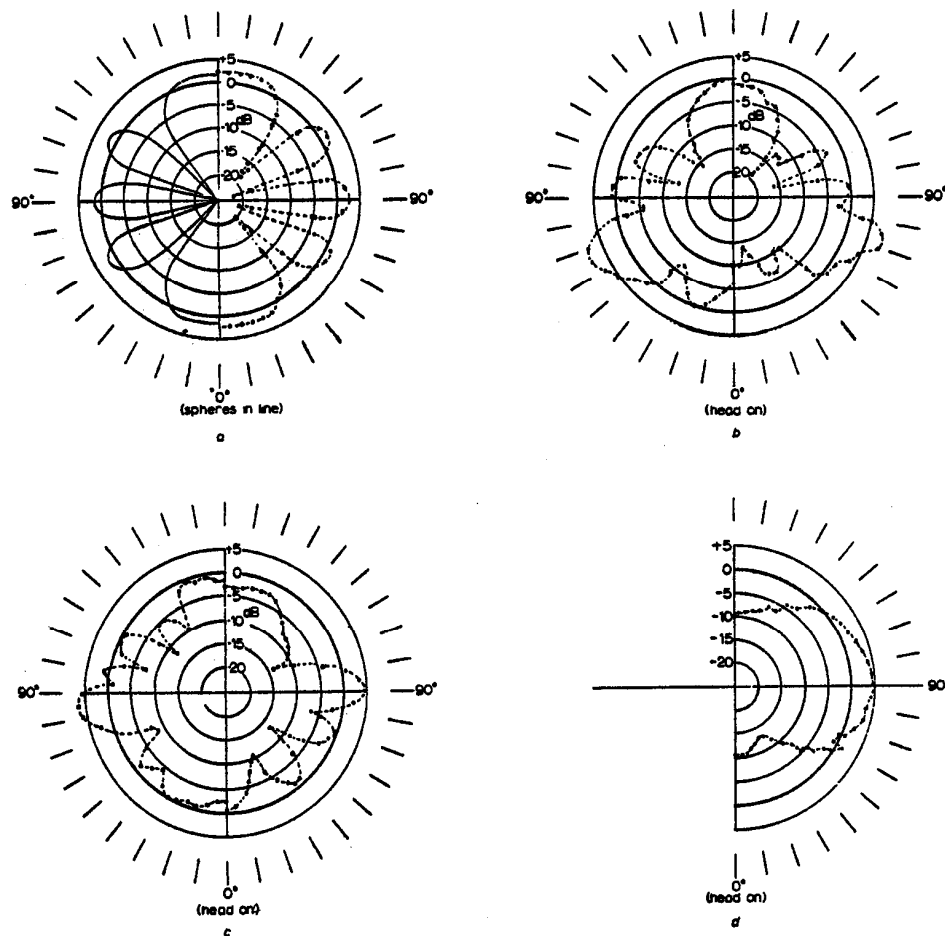
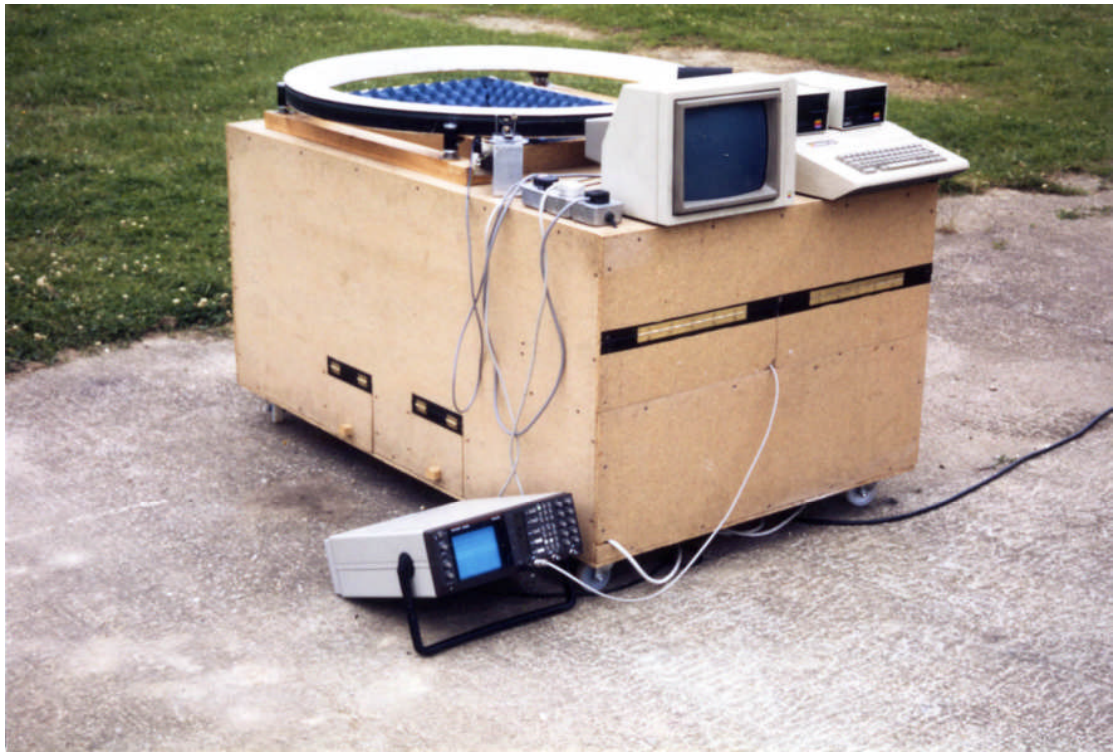


Fig 1

Angular variation of radar scattering cross-sections; $\lambda = 3.18\text{cm}$; body axes and electric vector horizontal, legs in (approximately) flying positions; $0\text{ db} = 1\text{ cm}^2$

- a Two steel spheres, 0.636 cm in diameter, centres separated on a horizontal axis by 3.18cm; l.h.s., theoretical values, r.h.s., experimental value
- b Desert locust: l.h.s., male; r.h.s., female
- c African migratory locust: l.h.s., female; r.h.s., male
- d Armyworm moth: female

Plate 1.1 RCS Measuring System



Chapter 2

Theoretical Background

This chapter describes the theory behind the RCS measuring system. The definition of the radar cross-section is presented in section 2.1. The scattering matrix, a generalisation of the RCS to account for polarisation effects, is introduced in section 2.2. A model describing the variation of RCS with angle for a radar with a rotating dipole is derived from the scattering matrix in section 2.3. Finally, in section 2.4, the characteristics of this model are discussed.

2.1 Definition of RCS

The radar cross section of a target was introduced in section 1.2 as a measure of the size of the target as seen by the radar. It is defined as the ‘area intercepting that amount of power which, when scattered isotropically, produces an echo at the radar equal to that from the target’. In mathematical terms, this is:

$$\sigma = \lim_{R \rightarrow \infty} 4\pi R^2 |E_r / E_i|^2,$$

where R is the distance between the radar and the target, E_r is the reflected electric field strength at the radar and E_i is the strength of the incident field at the target [Skolnik, 1981]. (The limit is needed to ensure that the illuminating radiation is a plane wave.) The RCS is affected by size, shape and material (specified by two aspect angles and an orientation angle, as defined in Figure 2.1). The RCS is independent of the power and range of the radar, but is strongly dependent on the wavelength and polarisation.

The concept of RCS is useful for long ranges but breaks down near the radar, where the radiated field is a poor approximation of a plane wave. The minimum range, R_f , at which the RCS can be used depends upon the *effective area* of the antenna, D^2 , and is usually taken to be

$$R_f = 2 D^2 / \lambda$$

[Skolnik, 1981]. The effective area is not necessarily directly related to, but is always less than, the physical area covered by the antenna. Ranges larger than R_f are said to be in the *far-field* and ranges less than R_f are in the *near-field*. Radars almost always operate exclusively in the far-field.

In theory, the RCS could be derived using Maxwell's equations but in practice this is only possible for a few geometrically simple bodies. For example, the RCS of a sphere is given by

$$\sigma_s = (\pi a^2 / \alpha^2) \left| \sum (-1)^n (2n + 1) (a_n - b_n) \right|^2$$

where a is the drop radius and $\alpha = 2\pi a / \lambda$ [Batten, 1973]. The quantities a_n and b_n are coefficients in the expression for the scattered field. They can be expressed in terms of spherical Bessel functions and Hankel functions of the second kind with arguments α and m , the complex index of refraction of the sphere. A plot of the RCS of a perfectly conducting sphere is shown in Figure 2.3. Because of its symmetry, the RCS of a sphere is independent of the sphere's aspect and orientation with respect to the radar (although linear polarisation is assumed). Clearly, an expression for the RCS of a more elaborate body would have to include these factors and would be far more complicated.

2.2 Scattering Matrix

The RCS can be generalised to include the dependence on radar polarisation.

Consider a radar antenna transmitting a plane wave. The polarisation of the wave can be represented by the *normalised effective length*, $\mathbf{h}$, of the antenna:

$$\mathbf{h} = \begin{pmatrix} \cos \gamma \\ \sin \gamma e^{i\delta} \end{pmatrix}$$

a column vector with elements that are the normalised polarisation components of the transmitted wave. Thus, if E is the field magnitude, then $E \cos \gamma$ is the component of the wave polarised in the x-direction (see Figure 2.2), $E \sin \gamma$ is the component of the wave polarised in the y direction and δ is the phase difference between the two components making up the wave [Stutzman and Thiele, 1981]. If $\delta = 0$, $\mathbf{h}$ describes radiation linearly polarised in the γ direction. If $\delta = \pm\pi/2$ and $\gamma = 45^\circ$, $\mathbf{h}$ describes circularly polarised radiation. (By convention, positive δ denotes left- and negative δ denotes right-hand polarisation.) The normalised effective length also describes how the antenna will accept an incoming polarised wave when it is used for reception.

The RCS of the target, observed by a radar with transmitting and receiving antennae with normalised effective lengths $\mathbf{h}_t$ and $\mathbf{h}_r$ is

$$\sigma = |\mathbf{h}_r^* S \mathbf{h}_t|^2$$

where $*$ denotes complex conjugate and

$$S = e^{i\theta} \begin{pmatrix} \sqrt{\sigma_{xx}} & \sqrt{\sigma_{yx}} e^{i\alpha'} \\ \sqrt{\sigma_{xy}} e^{i\alpha} & \sqrt{\sigma_{yy}} e^{i\beta} \end{pmatrix}$$

This is the *linear scattering matrix*. Here, $\sigma_{ij} \geq 0$ is the RCS observed when the transmitting and receiving antennas are polarised in the $\mathbf{i}$ and $\mathbf{j}$ directions respectively; α, α', β and θ are phase factors. θ depends on the local position of the target; it has no effect on the RCS and this term is now dropped. The scattering matrix is symmetrical ($\sigma_{xy} = \sigma_{yx}$, $\alpha = \alpha'$) for backscattering from an arbitrary linear body or bistatic scattering from a perfect conductor [Skolnick, 1970]. This leaves five numbers to define the significant parameters of the scattering matrix, 3 amplitudes and two phases. The matrix is diagonal ($\sigma_{xy} = 0$) when the target is mirror symmetric about the x-z or y-z plane (see Appendix A.1.2). For example, a body of revolution, with the axis of revolution in the x-z or y-z plane has a diagonal scattering matrix (see Figure 2.4). If the body possesses a rotational symmetry about the z-axis, the matrix is a multiple of the unit matrix (see Appendix A.1.3). (Note that other formulations in terms of alternative polarisation vectors are possible. Another common formulation is in terms of left and right circular polarisation. These formulations are equivalent and transformations between them are easily constructed [Crispin and Siegel, 1968].)

2.3 RCS Model

Consider a radar with a rotating dipole antenna (used for both transmission and reception). The radiation transmitted is linearly polarised and the orientation depends on the angular position, Φ , of the dipole (see Figure 2.5). The normalised effective length is the same for both transmission and reception and is given by

$$\mathbf{h}_t = \mathbf{h}_r = \begin{pmatrix} \cos \Phi \\ \sin \Phi \end{pmatrix}$$

This corresponds to linear polarisation with the plane of polarisation at an angle Φ . The RCS of the target, as observed by the radar, is then

$$\sigma(\Phi) = |\mathbf{h}_r^* S \mathbf{h}_t|^2$$

$$= \left| \begin{pmatrix} \cos \Phi & \sin \Phi \end{pmatrix} \begin{pmatrix} \sqrt{\sigma_{xx}} & \sqrt{\sigma_{xy}} e^{i\alpha} \\ \sqrt{\sigma_{xy}} e^{i\alpha} & \sqrt{\sigma_{yy}} e^{i\beta} \end{pmatrix} \begin{pmatrix} \cos \Phi \\ \sin \Phi \end{pmatrix} \right|^2$$

$$\begin{aligned}
&= \left| \sqrt{\sigma_{xx}} \cos^2 \Phi + \sqrt{\sigma_{yy}} e^{i\beta} \sin^2 \Phi + 2\sqrt{\sigma_{xy}} e^{i\alpha} \cos \Phi \sin \Phi \right|^2 \\
&= \sigma_{xx} \cos^4 \Phi + \sigma_{yy} \sin^4 \Phi + 4\sigma_{xy} \cos^2 \Phi \sin^2 \Phi \\
&\quad + 2\sqrt{\sigma_{xx}} \sqrt{\sigma_{yy}} \cos^2 \Phi \sin^2 \Phi \cos \beta \\
&\quad + 4\sqrt{\sigma_{xx}} \sqrt{\sigma_{xy}} \cos^3 \Phi \sin \Phi \cos \alpha \\
&\quad + 4\sqrt{\sigma_{yy}} \sqrt{\sigma_{xy}} \cos \Phi \sin^3 \Phi \cos(\alpha - \beta) \\
&= a_0 + a_{11} \cos 2\Phi + a_{12} \sin 2\Phi + a_{21} \cos 4\Phi + a_{22} \sin 4\Phi
\end{aligned}$$

where

$$\begin{aligned}
a_0 &= \frac{1}{8} (3\sigma_{xx} + 3\sigma_{yy} + 4\sigma_{xy} + 2\sqrt{\sigma_{xx}} \sqrt{\sigma_{yy}} \cos \beta), \\
a_{11} &= \frac{1}{2} (\sigma_{xx} - \sigma_{yy}), \\
a_{12} &= \sqrt{\sigma_{xy}} (\sqrt{\sigma_{xx}} \cos \alpha + \sqrt{\sigma_{yy}} \cos(\alpha - \beta)), \\
a_{21} &= \frac{1}{8} (\sigma_{xx} + \sigma_{yy} - 4\sigma_{xy} - 2\sqrt{\sigma_{xx}} \sqrt{\sigma_{yy}} \cos \beta), \\
a_{22} &= \frac{1}{2} \sqrt{\sigma_{xy}} (\sqrt{\sigma_{xx}} \cos \alpha - \sqrt{\sigma_{yy}} \cos(\alpha - \beta)).
\end{aligned}$$

This can be rewritten as

$$\sigma(\Phi) = a_0 + a_1 \cos 2(\Phi - \theta_1) + a_2 \cos 4(\Phi - \theta_2)$$

where

$$\begin{aligned}
a_1 &= \sqrt{(a_{11}^2 + a_{12}^2)}, \\
a_2 &= \sqrt{(a_{21}^2 + a_{22}^2)}, \\
\theta_1 &= \frac{1}{2} \tan^{-1} \left(\frac{a_{12}}{a_{11}} \right), \quad -90^\circ < \theta_1 \leq 90^\circ, \\
\theta_2 &= \frac{1}{4} \tan^{-1} \left(\frac{a_{22}}{a_{21}} \right), \quad -45^\circ < \theta_2 \leq 45^\circ,
\end{aligned}$$

The function $\tan^{-1}$ only returns an angle in the range -90° to $+90^\circ$. The range -180° to $+180^\circ$ is obtained using the signs of the numerator and denominator of the argument (which are effectively the sine and cosine of the required angle). Note that a_0 , a_1 and a_2 are all *non-negative*. This expression serves as a mathematical model to describe the RCS as a function of dipole orientation. The system described in this thesis

measures such a curve and, by fitting the above model to the data obtained, estimates the five independent parameters.

2.4 Characteristics of Model

The model has some interesting features. It can be seen that it is periodic in Φ with period 180° , so that

$$\sigma(\Phi) = \sigma(\Phi + 180^\circ)$$

This is because the linearly polarised radiation emitted by the radar is in the same plane when the dipole is orientated at angle Φ and angle $\Phi + 180^\circ$, so the same power is reflected back to the radar by the target at both these angles.

The model can be rewritten as

$$\sigma(\Phi) = a_0 + a_1 \cos 2(\Phi - \theta_1) + a'_{21} \cos 4(\Phi - \theta_1) + a'_{22} \sin 4(\Phi - \theta_1)$$

where

$$a'_{21} = a_2 \cos 4(\theta_2 - \theta_1)$$

$$a'_{22} = a_2 \sin 4(\theta_2 - \theta_1)$$

In this form, the model can be identified as that developed by Huynen [1965]. θ_1 is the orientation of the target that, when illuminated with radiation of the appropriate polarisation, returns the maximum power. Since it is constant for a target at a given aspect, it can be used a measure of orientation of the target.

The orientation of the coordinate axes is arbitrary. A reasonable choice for calculations is to choose the new primed coordinates such that $\theta_1' = 0^\circ$. The transformation from an arbitrary set of axes to this primed set is a simple rotation by θ_1 ; a_0 , a_1 and a_2 are unaffected. $\Phi' = \Phi - \theta_1$ and $\theta_2' = \theta_2 - \theta_1$. It can be shown that if the scattering matrix can be diagonalised by a rotation of the coordinate axes, then the required rotation is θ_1 (see Appendix A.1.4). Thus, choosing the primed coordinate axes such that θ_1' is zero ensures that the axis of rotation of a rotationally symmetric body, for example, is in the x' - z or y' - z plane, or that the plane of symmetry of a mirror symmetric body is the x' - z or y - z plane. *Further discussion will use these primed coordinate axes and the prime is now dropped.* Note that in these axes, $a_{12} = 0$ since $\theta_1 = 0$, so that

$$a_1 = a_{11} = \frac{1}{2}(\sigma_{xx} - \sigma_{yy}),$$

and

$$\sqrt{\sigma_{xx}} \cos \alpha + \sqrt{\sigma_{yy}} \cos(\alpha - \beta) = 0,$$

so that

$$a_{22} = \frac{1}{2} \sqrt{\sigma_{xy}} \sqrt{\sigma_{xx}} \cos \alpha = -\frac{1}{2} \sqrt{\sigma_{xy}} \sqrt{\sigma_{yy}} \cos(\alpha - \beta).$$

The magnitudes of the diagonal scattering matrix elements can easily be obtained from the model:

$$\sigma(0^\circ) = a_0 + a_1 + a_2 \cos 4\theta_2 = \sigma_{xx}$$

$$\sigma(90^\circ) = a_0 - a_1 + a_2 \cos 4\theta_2 = \sigma_{yy}$$

(Choosing the axes such that θ_1 is zero ensures that $\sigma_{xx} \geq \sigma_{yy}$ since a_0 , a_1 and a_2 are all non-negative.) Unfortunately, it is not possible to obtain all the scattering matrix parameters from the model as there are usually two different sets of scattering matrix elements that lead to the same model parameters [Huynen, 1965]. However, if $\sigma_{xy} = 0$, then

$$a_0 = \frac{1}{8} (3\sigma_{xx} + 3\sigma_{yy} + 2\sqrt{\sigma_{xx}} \sqrt{\sigma_{yy}} \cos \beta),$$

$$a_1 = \frac{1}{2} (\sigma_{xx} - \sigma_{yy}),$$

$$a_2 = \frac{1}{8} (\sigma_{xx} + \sigma_{yy} - 2\sqrt{\sigma_{xx}} \sqrt{\sigma_{yy}} \cos \beta),$$

$$(\theta_1 = 0^\circ,$$

$$\theta_2 = 0^\circ)$$

so that

$$\sigma_{xx} = a_0 + a_1 + a_2,$$

$$\sigma_{yy} = a_0 - a_1 + a_2$$

$$\beta = \cos^{-1} \left(\frac{a_0 - 3a_2}{\sqrt{a_0^2 - a_1^2 + a_2^2 + 2a_0a_2}} \right)$$

If $\theta_2 = 0^\circ$, $a_{22} = 0$ and the model has ‘mirror’ symmetry:

$$\sigma(\Phi) = \sigma(-\Phi).$$

The angle θ_2 is zero when either one of the following conditions is satisfied:

- 1) $\sigma_{xy} = 0$ so that the scattering matrix is diagonal (if, for example, the target is rotationally symmetric);

or 2) $\cos \alpha = 0$ or $\cos (\alpha - \beta) = 0$ so that the phase difference between the cross-polarised component and either the x or y components is 90° .

Note that if θ_2 is zero, no information about σ_{xy} can be obtained from the model (unless other information about the target is known such as the fact that it is mirror symmetric). Since $\cos \alpha$ is small for values of α near 90° , this suggests that the model can be insensitive to the value of σ_{xy} .

The shape of the curve depends on the parameters. When θ_2 is zero, the value of

$$\sigma(\Phi) = a_0 + a_1 \cos 2\Phi + a_2 \cos 4\Phi$$

is at a maximum or minimum when

$$\begin{aligned} \frac{d\sigma}{d\Phi} &= 0 \\ &= -2a_1 \sin 2\Phi - 4a_2 \sin 4\Phi \\ &= -2a_1 \sin 2\Phi - 4a_2 (2 \sin 2\Phi \cos 2\Phi) \\ &= -2 \sin 2\Phi - 4a_2 (a_1 + 4a_2 \cos 2\Phi) \end{aligned}$$

This is when $\Phi = 0^\circ$, $\Phi = 90^\circ$ (i.e. $\sin 2\Phi = 0$) or when

$$\cos 2\Phi = \frac{-a_1}{4a_2}.$$

This only has a solution when

$$\left| \frac{a_1}{4a_2} \right| \leq 1,$$

which is equivalent to

$$\cos \beta \leq \frac{\sqrt{\sigma_{yy}}}{\sqrt{\sigma_{xx}}}.$$

(Recall that $\sigma_{xx} \geq \sigma_{yy} \geq 0$.) There are therefore two general curve shapes, depending on the phase difference between the x and y components:

1) $\cos \beta \geq \frac{\sqrt{\sigma_{yy}}}{\sqrt{\sigma_{xx}}}$ ($a_1 \geq 4a_2$): the curve has a maximum at 0° and a single minimum at 90° (Figure 2.6a);

and 2) $\cos \beta < \frac{\sqrt{\sigma_{yy}}}{\sqrt{\sigma_{xx}}}$ ($a_1 < 4a_2$): the curve has a maximum at 0° , a subsidiary maximum at 90° and minima between (Figure 2.6b).

In general, θ_2 is not zero and $\sigma(\Phi)$ is not ‘mirror’ symmetric, the degree of asymmetry depending on σ_{xy} and the phase α . The value of σ is at a maximum or minimum when

$$\begin{aligned}\frac{d\sigma}{d\Phi} &= 0 \\ &= -2a_1 \sin 2\Phi - 4a_2 \sin 4(\Phi - \theta_2)\end{aligned}$$

which is when

$$a_1 \sin 2\Phi = 2a_2 \sin 4(\Phi - \theta_2)$$

and is not easily solved analytically. The equation is not satisfied for $\Phi = 0^\circ$ or $\Phi = 90^\circ$ (unless $\theta_2 = 0^\circ, 45^\circ, 90^\circ$). The two curve shapes described above are modified so that the primary maximum is displaced from $\Phi = 0^\circ$ and the curve is not ‘mirror’ symmetric. It is difficult to derive the condition that determines if a curve has a secondary maximum or not. However, if it does, then the secondary maximum is displaced from $\Phi = 90^\circ$, the minima are not of equal depth and are not symmetrically placed about $\Phi = 90^\circ$. If the curve does not have a secondary maximum, then the only minimum is displaced from $\Phi = 90^\circ$.

Two examples of asymmetric curves are given in Figure 2.7. Each curve was formed by creating an arbitrary scattering matrix and then rotating the coordinate axes so that θ_1 became zero. For Figure 2.7a, before the rotation, $\sigma_{xx} = 8$, $\sigma_{yy} = 4$, $\sigma_{xy} = 1$, $\alpha = 45^\circ$, $\beta = 90^\circ$, so that $\theta_1 = 29.8^\circ$. For Figure 2.7b, $\sigma_{xx} = 8$, $\sigma_{yy} = 1$, $\sigma_{xy} = 1$, $\alpha = 20^\circ$, $\beta = 0^\circ$, so that $\theta_1 = 22.9^\circ$. The latter curve is nearly symmetrical despite the fact that $\sigma_{xy} > 0$ and neither $\cos \alpha$ nor $\cos(\alpha - \beta)$ are near zero in the final, rotated coordinate axes. This also suggests that the model can be insensitive to the value of σ_{xy} . The model therefore suggest that the RCS curve obtained from a linearly polarised radar with a rotating plane of polarisation will be insensitive to the cross-polarised component of the target scattering matrix and therefore may not be able to differentiate between targets that mainly differ in this parameter.

Figure 2.1 Target Aspect Direction and Orientation Angle

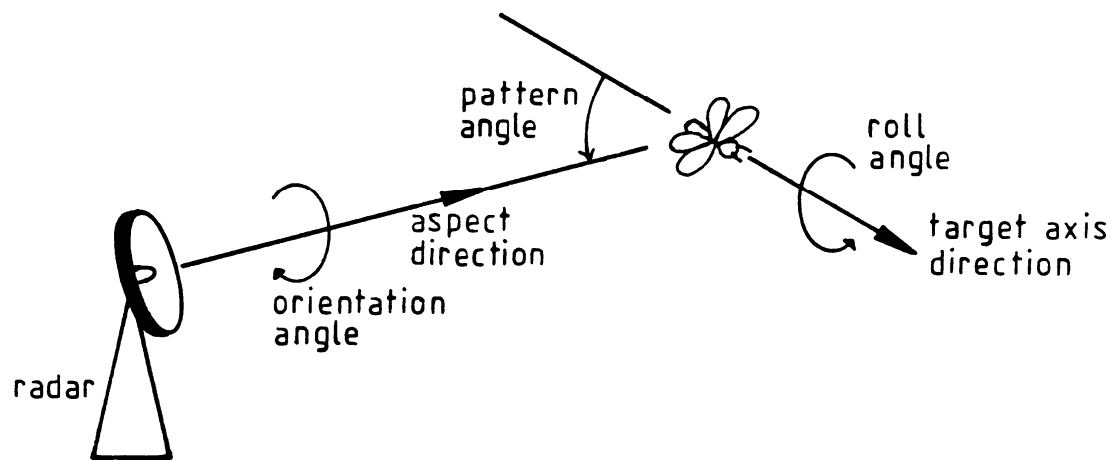
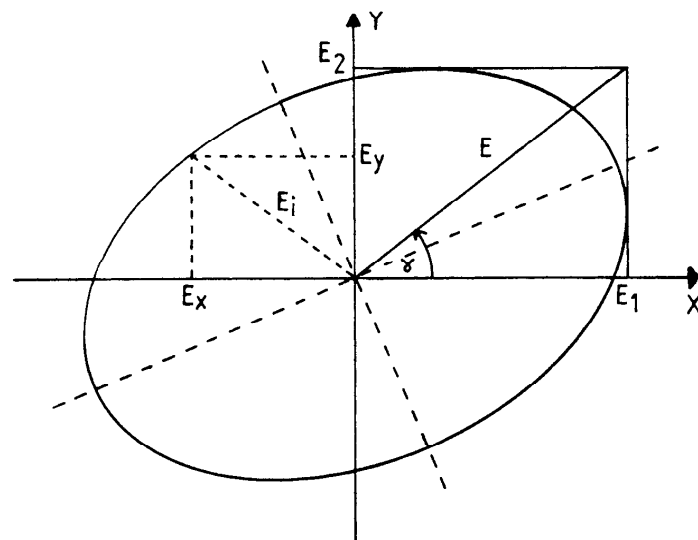


Figure 2.2 General Polarisation Ellipse

The tip of the instantaneous electric field vector E_i traces out the ellipse.



Wave propagation is in the +Z-direction out of the page.

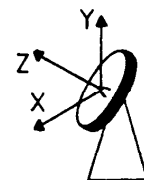


Figure 2.3 RCS of Perfectly Conducting Sphere

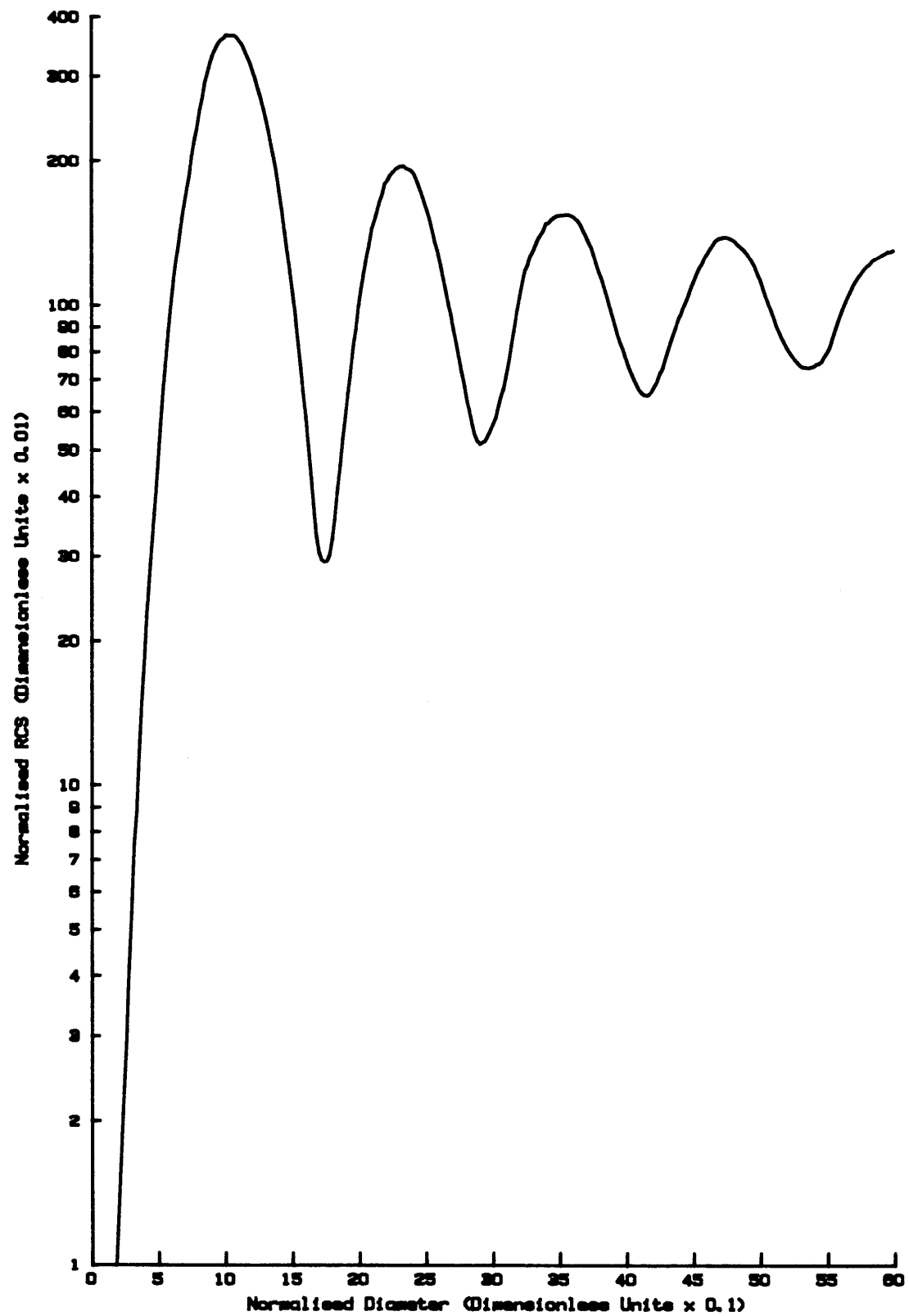
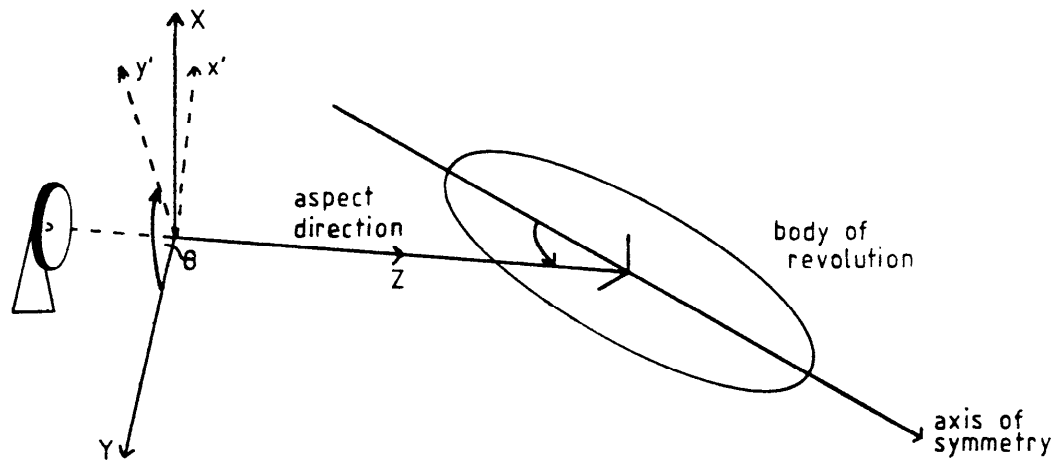
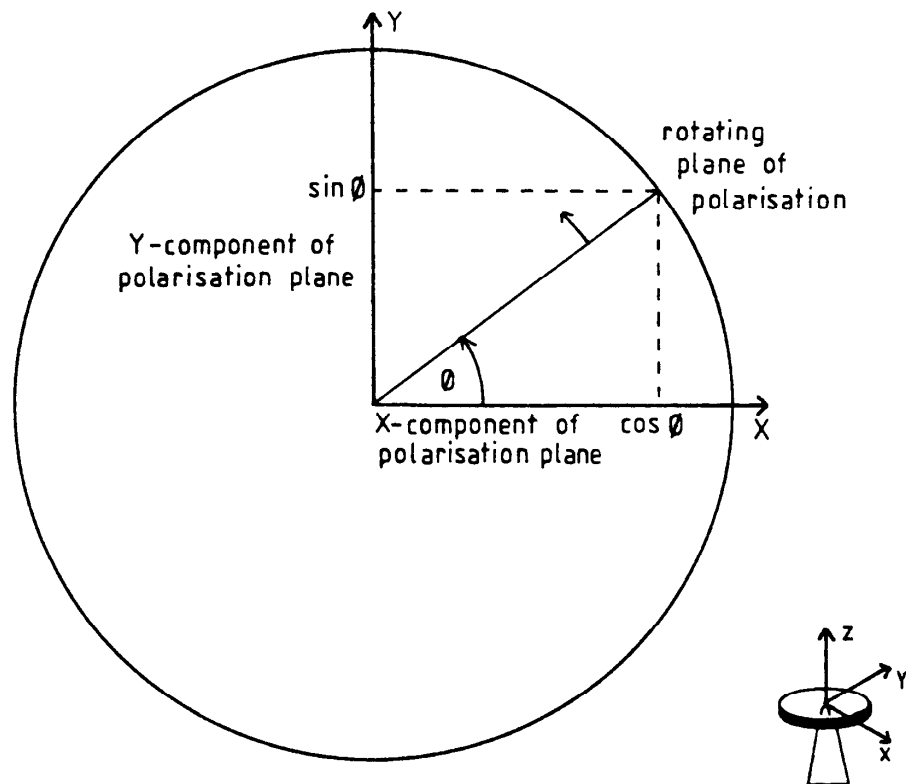


Figure 2.4 Coordinate Axes for Scattering Matrix to be Diagonal



Radar observing in $+Z$ direction.
 Axis of symmetry in $Y-Z$ plane.
 $X-Y$ axes rotated about Z axis by θ to become $x'-y'$ axes.
 Scattering matrix is diagonal in $X-Y$ coordinate system but not in $x'-y'$ system.

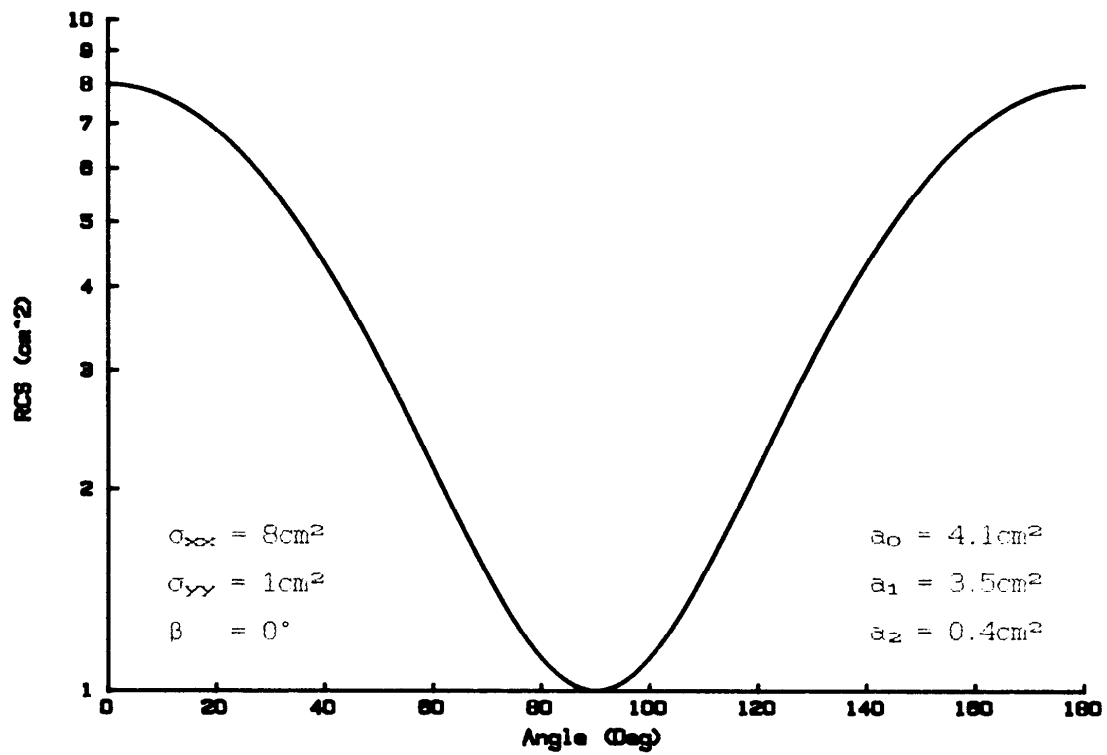
Figure 2.5 Plane of Polarisation from a Rotating Dipole Antenna



Wave propagating in $+Z$ -direction, out of page.

Figure 2.6 Two Possible Symmetric Curve Shapes

a) Curve with single maximum



b) Curve with dual maxima

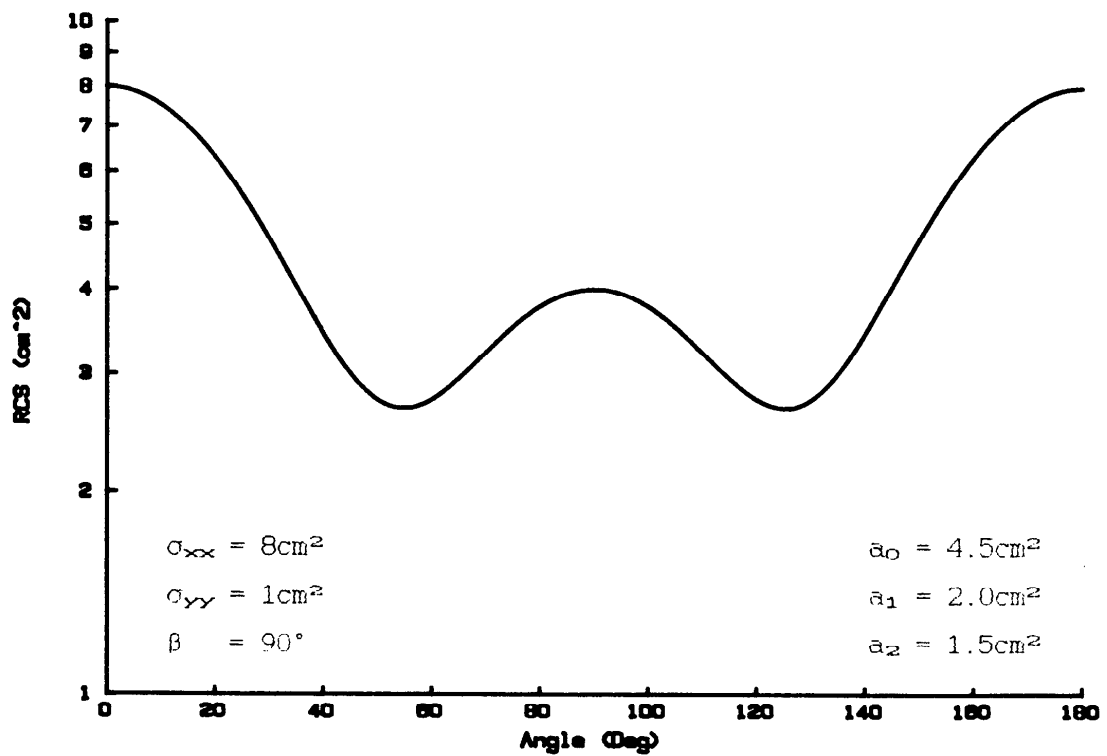
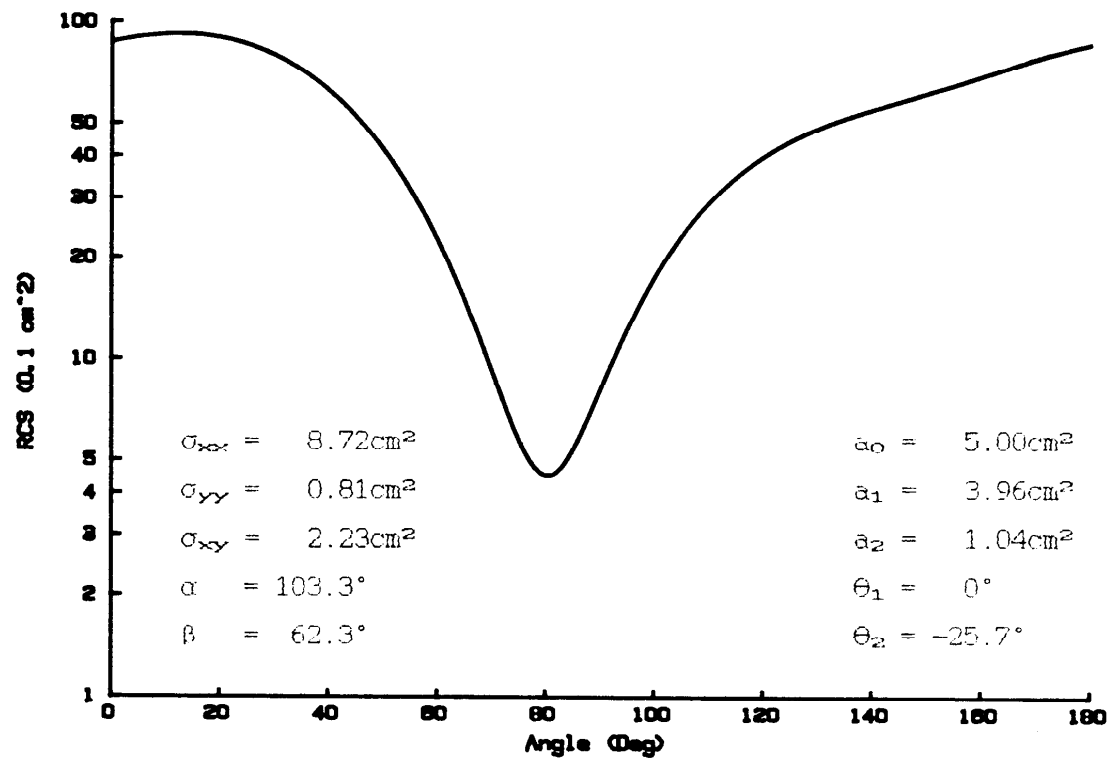
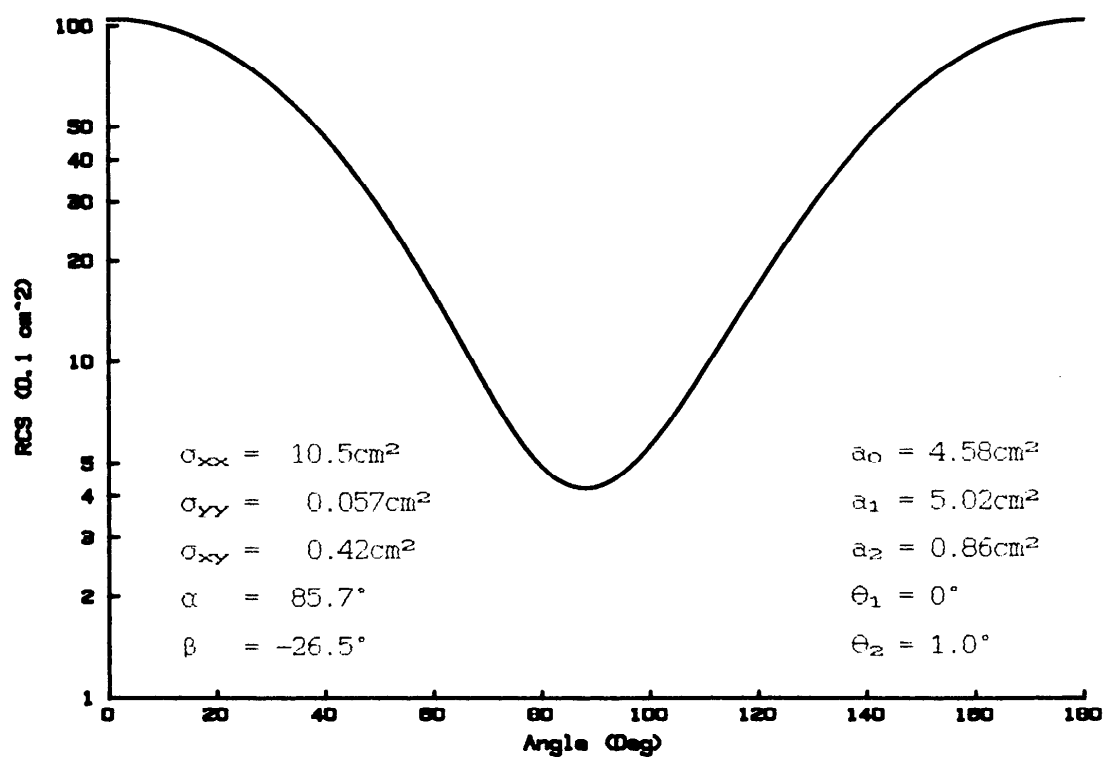


Figure 2.7 Model Curves for Non-Diagonal Matrices

a) Asymmetric curve



b) Approximately symmetric curve



Chapter 3

Experimental System Hardware

This chapter describes the hardware developed to measure the target parameters of the model derived in the previous chapter.

3.1 System Overview

The RCSs measured by this system were fairly small ($0.01 - 20\text{cm}^2$). To measure these accurately the background reflections had to be kept very low. For the error in a measurement to be less than 5%, the power from background reflections must be at least 1500 times smaller than the power from target reflections [Blacksmith et al, 1965].

To keep background reflections to a minimum, the system was designed to be used in the open air. This eliminated reflections from building walls and ceilings, but introduced problems with target movement and the thermal and mechanical stability of the system caused by wind.

By necessity, the system had to be very low cost, and so was constructed mainly from salvaged components that were available within the establishment.

The system was required to work at close range ($\sim 1\text{m}-2\text{m}$), so that low powers could be used and operation would be convenient. A pulsed system would need very short pulse lengths for such close ranges and be difficult to implement. A continuous wave (CW) technique was therefore chosen.

Linearly polarised radiation was used, as this corresponded directly to the radar systems currently in use for insect observation. The plane of polarisation needed to be rotated so that the polarisation dependence of the target RCS could be measured. It was simpler to rotate the target at constant aspect and avoid complications with rotating microwave joints.

A schematic diagram of the system is shown in Figure 3.1. It can be broken down into three parts:

- 1) the microwave circuit,
- 2) the receiver and signal conditioning
- and 3) the target support and rotation mechanism.

These parts will be detailed in sections 3.2, 3.3 and 3.4 respectively. Calibration of the system is discussed in section 3.5, and the experimental procedure described in section 3.6. System performance is discussed in chapter 5, after the software used to process the raw data has been described.

3.2 Microwave Circuit

The microwave circuit was very similar to that used by Riley [1985]. A schematic diagram is shown in Figure 3.1. Power from the microwave source propagates via the circulator and the horn to the target. Power reflected by the target is collected by the horn and returns via the circulator to the receiver, where it is detected. The circulator separates the incoming from the transmitted radiation. The directional coupler, attenuator and sliding short are used to provide adequate isolation between the transmitter and the receiver and will be discussed below.

Standard WG 16 rectangular waveguide and square flat flanges connected components. The plane of polarization was perpendicular to the long axis of the system box (see Figure 3.2).

The microwave source consisted of a Marconi Gunn diode oscillator type 6061A, powered by a Marconi power supply type 6590B. It had a nominal 20mW power output. The frequency range of the device was 8.0-11.3GHz and was controlled by the supply voltage and a micrometer screw plunger. It was calibrated using an accurate microwave frequency counter. The operating frequency was 9.4GHz (= 3.21cm).

The circulator used was a standard X-band microwave radar unit, type NJC 3901A from JRC. It had a maximum insertion loss of 0.5dB between the ports in the 'forward' direction and 25dB isolation between the ports in the 'reverse' direction. On its own, this was not good enough for the needs of the system, as power leaked from the transmitter directly to the receiver through the circulator, overwhelming any actual signal.

The expected power returned from the intended targets, calculated using the radar equation, was in the range 10nW-10pW. The transmitter leakage power must be at least an order of magnitude smaller. Using the transmitted power of 20mW, the required isolation between the transmitter and the receiver was

$$10 \log (20\text{mW} / 1 \text{ pW}) = 103 \text{ dB}$$

Thus an additional method for improving the isolation was required.

The technique used here was to cancel the unwanted radiation with another wave equal in amplitude but in antiphase [Blacksmith et al, 1965]. Using the directional coupler, attenuator and sliding short, a small portion of the transmitted was extracted, altered in phase and amplitude and returned to the receiving pathway. The attenuator and sliding short were adjusted to give a 'null' in the received power with no target present. The method only works with a spectrally pure source and the adjustment was very sharp and easily missed.

The cancellation was very sensitive to small changes in frequency and component dimensions. The system was mounted inside a thermally insulated box (Figure 3.2, plates 1.1, 3.1) which supported the absorber horn and the microwave target support ring and drive mechanism and protected the microwave components from sharp changes in temperature. In still conditions the system remained correctly adjusted ('nulled') for about 5 minutes. However, wind disturbed the null since the resulting pressure differential between the inside and outside of the box changed its shape which was transmitted to the waveguide mounted in the box. This was reduced by not rigidly fixing the waveguide to the box but still limited times when data could be collected.

A Plessey ANT163 precision die cast rectangular horn was used to direct the radiation at the target. It had a quoted gain relative to an isotropic radiator of 15 dB. Its dimensions are shown in Figure 3.3. As noted in section 2.1, the minimum range

$$R_f = 2 D^2 / \lambda.$$

For this horn, D^2 is about 100cm^2 , giving $R_f = 62.5\text{cm}$. The target had to be at least this distance from the horn.

To reduce unwanted reflections from the surroundings, a wooden horn lined with Plessey type AF 30 microwave absorber was placed on top of the feed horn, with the mouth just below the target (Figure 3.4 and Plate 3.2). The absorber horn reduced sidelobes of the feed horn considerably while maintaining the field at the aperture as a good approximation to a plane wave [Garnham, 1970]. With the absorber horn in place, the system could not detect objects (such as the computer monitor) placed upon the system box.

The two-way beam pattern was measured using a steel ball-bearing suspended on thin nylon thread and is shown in Figure 3.5. (The E- and B-planes are cross sections through the centre of the horn parallel and perpendicular to the plane of

polarisation respectively.) The central 10cm by 10cm area was evenly illuminated to within 3dB. The target was placed within this area.

There was a small (5%) periodic vertical variation with a wavelength of approximately 1.6cm. Since there was nothing above the system box, this variation could not have been caused by a standing wave and was therefore probably due to the absorber horn aperture. Since the targets had an approximate diameter of 0.75cm the field could have varied by 2.5% over the vertical extent of the target and this probably contributed to the errors in the RCS measurements (see chapter 5).

3.3 Receiver and Analog Signal Conditioning

The receiver was taken from a Decca radar transceiver type 65160. It had a nominal noise figure of 10dB. It was not designed for continuous wave applications and this meant some performance degradation. However, no other receiver was available due to limited funds.

A block diagram of the receiver and signal conditioning is given in Figure 3.6. The receiver used an intermediate frequency (IF) of 60MHz and the IF amplifier had a logarithmic gain characteristic. IF drift was prevented by the action of an automatic frequency control (AFC) circuit. The output of the receiver was passed via additional buffer and filter circuitry to the analog to digital convert (ADC) and hence to the computer, where it was stored.

3.3.1 Modification of Receiver AFC Circuit

The standard AFC circuit only operated when the radar transmitted a pulse and therefore needed to be modified. It was disabled for most of the receiving period to prevent possible interference from other microwave sources. The operation of the receiver is described in the radar technical manual [Decca]. Only the modifications to the AFC circuit will be discussed here.

A schematic diagram of the appropriate portion of the AFC circuit is shown in Figure 3.7. Normally, the circuit was disabled by TR51 conducting. When the radar magnetron was active, a positive going pulse, called the swept gain pulse, appeared at AB. This pulse reduced the gain of the receiver so that it was not overloaded by the transmitted signal. D51 conducted, and as soon as C54 charged up to peak level, the positive voltage at D51 cathode caused TR51 to cut off and the AFC circuit was

enabled. After about $1\mu\text{s}$, the charge acquired by C54 leaked through R55 and the circuit reverted to its normal condition.

AB was not connected in this application. Instead, the base of TR51 was tied directly to ground. TR51 was therefore cut off and so allowed the AFC to operate continuously. The connection of AB to the main IF board was also removed. This had no effect on the circuit operation but prevented possible interference.

3.3.2 Analog Signal Conditioning

Because the receiver was not designed for CW applications its bandwidth was too wide and the standard video output could not be used. Instead, the output was taken from an alternative connection which suffered from a large DC offset voltage. The analog signal conditioning removed this offset and reduced the bandwidth of the complete system.

A portion of the schematic diagram of the IF amplifier is shown in Figure 3.8. It can be seen that the output passed through capacitors C22 and C26 which cut off the DC component of the output signal. Therefore a continuous signal input to the receiver resulted in zero output. This was not suitable for a CW application. Instead, the output was taken from the connection labelled 'Test Noise Figure'. This was DC coupled but suffered from an offset voltage of about $+11\text{V}$ superimposed on the signal. A DC level adjust circuit removed the offset before the signal was digitised.

The bandwidth of the receiver was optimised for the radar pulse widths, and could be set at 18MHz or 5MHz. This was too wide for a CW application. Ideally, to reduce the noise, the bandwidth should be very narrow for a CW system (See Skolnik [1981]). Rather than modify the receiver, the 5MHz bandwidth setting was used and additional filtering was performed later, before the signal was digitised.

The majority of the 11V offset was removed by a buffer mounted on the receiver. Fine adjustment and filtering was carried out by a similar external buffer. A schematic diagram of the receiver buffer is given in Figure 3.9. The input was buffered by IC1 to avoid loading effects on the receiver. The signal passed through a simple low pass RC filter (3dB rolloff at 480Hz) to a summing amplifier IC2. An offset voltage, derived from an O4BJ precision voltage reference by IC4 and its associated components, was subtracted by IC2. The signal then passed via an attenuator, a 10dB amplifier formed by IC3 and coaxial cable to the external buffer.

A schematic diagram of the external buffer is given in Figure 3.10. The signal, buffered by IC1a, was filtered using a proprietary switched capacitor fifth order Bessel filter integrated circuit, with a dB rolloff at 18Hz. This rolloff frequency was chosen as half the digitisation frequency, f_n , since frequencies below higher than f_n appear after sampling as spurious frequencies below f_n . (This phenomenon is called aliasing.) The digitisation frequency was set by the rotation speed of the ring (see section 3.4.1). An offset voltage derived from two O4BJ precision voltage references and a potentiometer was added to the signal by the summing amplifier IC1b. A simple RC passive filter, buffered by IC1c, then removed the residual clock ripple of the earlier switched capacitor filter. The signal passed to the output via an attenuator and a 7dB amplifier consisting of IC1d and its associated components.

The $\pm 7V$ and $+24V$ supply for the receiver buffer were taken from the receiver power supply. The power supply for the external buffer was supplied by a $\pm 12V$ external supply and was regulated by IC3 and IC4.

The output suffered from an unstable voltage offset (even with no power being transmitted by the source). Tests showed that on their own the buffers were stable. Therefore the instability occurred within the receiver. As it was not designed for DC operation it was not surprising that this was the case. No attempt was made to modify the receiver as it was thought this would probably be detrimental to its performance. However, the problem severely compromised the performance of the system.

3.3.3 Receiver Power Supply and Tuning Voltage

The receiver required power supplies of $+24V$, $\pm 7V$ and a variable tuning voltage between $-21V$ and $-35V$. These were derived from the mains supply using standard integrated circuit power supply regulators. A schematic diagram is given in Figure 3.11. The tuning voltage provided coarse receiver tuning; the AFC provided the fine tuning automatically when within range.

3.3.4 Analog to Digital Converter

The output of the circuit was fed to a Tecmar ADC type AD211 hosted by an Apple II+ microcomputer. The specifications of this 12 bit converter are given in Table 3.1. Only one channel was used and sampling was triggered by the computer. Although the sample voltage was expected to be in the range 0 – 5V, the converter did

no work correctly on a unipolar range, so a bipolar range of $\pm 5\text{V}$ with the digital output in two's complement form was used. This effectively reduced the converter resolution to 11 bits but was irrelevant as the software only used the 8 most significant bits (see Section 4.2.1).

Table 3.1 Specifications of Tecmar ADC Type AD211

1	12 bit accuracy and resolution
2	30 kHz conversion rate standard
3	Jumper selectable input ranges: $\pm 10\text{V}$, $\pm 5\text{V}$, 0V to 10V , 0V to 5V
4	Output formats: two's complement, binary, offset binary
5	Includes high-speed sample and hold
6	No user adjustments

3.4 Target Support and Rotation Mechanism

It was imperative that background reflections from the target support be reduced as far as possible. This therefore had to be of very low RCS but still capable of holding the target firmly and rotating smoothly.

An expanded polystyrene ring, radius 534mm, large enough to fit around the mouth of the absorber horn and so be out of the illuminating beam, was used as the main support, with the target suspended in the centre with thin nylon thread (Figure 3.12 and Plate 3.2). The ring was rotated using an electric motor and the angular position was measured using an optical encoder.

3.4.1 Target Support Ring

The ring rotated on four bearings mounted on the system box, with four rollers keeping it centralised to the absorber horn. The lower surface of the ring was lined with hardboard to prevent the bearings wearing a groove in the soft polystyrene. The outer surface was lined with self-adhesive cloth tape to prevent wear. The upper surface was covered with the optical encoder.

The ring was driven via a rubber belt and gear mechanism by a 240V AC electric motor (which had previously seen service in an automatic washing machine as the water pump!) (Figure 3.13 and Plate 3.3). The ring rotated about once every

thirteen seconds. This was the maximum speed at which the ring would rotate smoothly.

For the first few measurements, the target was held by a single thread of thin, nylon fishing line. It was found that the target tended to rotate by twisting the line and often fell off. Instead, a small nylon net, supported with four nylon threads was used (Figure 3.12). The target was placed on the net and a fifth thread used to hold it steady. This held the target lightly but firmly and was not detectable by the system.

The ring and associated mechanism were shielded from microwave radiation by the absorber horn and were not detectable.

3.4.2 Optical Position Encoder

The top of the ring was covered in white card marked with a pattern of 512 2mm wide black lines (Figure 3.12 and Plate 3.2). As the ring rotated, the lines were detected by optical sensors (each consisting of an infra-red LED and phototransistor housed in a moulded package) mounted on a fixed bar (Figure 3.14 and Plate 3.4). The 'head up' sensor detected when the single black line of the inner edge passed below it, and the 'count' sensor detected when each line of the outer edge passed. The output of the sensors, conditioned by a circuit, was fed to the games port of the Apple II+ microcomputer. The angular position of the ring was deduced by counting the number of lines that had passed below the 'count' sensor since the 'head up' sensor had last detected a line. With $512 = 2^9$ lines, the count was conveniently coded as a binary integer for storage by the computer and had an angular resolution of 0.7° . The position of the lines was drawn to an accuracy of $\pm 1\text{mm}$ relative to the zero line, an absolute angular accuracy of $1/10$ degree. Since the ring rotated once every 13 seconds, the frequency at which the angular position of the ring was sampled was 40Hz.

A schematic diagram of the conditioning circuit is given in the Figure 3.15. Both channels were identical. Infrared light from the light emitting diode (LED) was reflected by the ring surface back to the phototransistor. The output was fed to a comparator IC1. With correct setting of the sensitivity (adjusted by the potentiometer), the output of the comparator was high (+5V) when white was below the detector, and low (0V) when black was below it. The signal, now TTL compatible, was inverted and buffered by IC2a before being passed to a single bit input of the

Apple II+ games port. An indicator LED was also driven via IC2b, an inverter/buffer, to allow easy adjustment of the sensitivity. The +5V power supply was taken from the host computer.

As the system had to operate outside, sometimes in bright sunshine, the optical encoder bar was surrounded by a light-tight shield so that it was not swamped by extraneous light.

3.5 System Calibration

Because the system did not remain stable for long periods, a calibration was performed before every target measurement. A *measurement cycle* consisted of a calibration followed by a measurement.

A *standard target* was used to calibrate the system. A measurement of the standard target could be done quickly, thus minimising the time between calibration and target measurement and so minimising the error caused by system drift. The target chosen was a thin copper wire stretched across a diameter of the ring. The RCS of a thin wire varies with orientation, Φ , as $\cos^4(\Phi)$ [Crispin & Seigel, 1968]. (Since the wire was stretched across the complete aperture, it was not evenly illuminated over all its length and the $\cos^4\Phi$ relationship did not hold precisely.) The RCS variation gave a good range for the calibration and the phase angle provided a measure of the plane of polarisation.

An absolute calibration of the standard target was derived from measurements of steel spheres of known RCS [Schaefer, private communication]. The spheres and the standard target were measured using the system in a short period of time. A calibration curve was fitted to the sphere data (Figure 3.16), and the RCS of the standard target at each orientation sampled was calculated using this curve (Figure 3.17). (The software required to do this is discussed in chapter 4). The resulting standard target data was used to calibrate all further measurements.

3.6 Experimental Procedure

The system was moved outside, switched on and then left for one or two hours to stabilise. With the microwave source off, the external buffer output offset set near zero, but so that it was always positive. (This was so that the noise would be sampled

correctly. The software set negative voltages to zero. If the noise regularly went negative, a biased average would be calculated.)

A measurement cycle consisted of the following procedure:

- 1) The zero offset was first checked and reset if necessary as described above.
- 2) With the microwave source on, but with no target, the system was 'nulled'.
- 3) The standard target was mounted and the ring set rotating. Data from five revolutions of the standard target was recorded on the computer.
- 4) With the standard target removed, the null was checked. If the null had begun to drift slightly, it was reset (see below). Otherwise, the cycle was restarted at step two.
- 5) The insect target was mounted on the net, aligned with its long axis parallel to the standard target, head towards angle zero. The ring was set rotating and data from ten revolutions of the target were recorded by the computer.
- 6) The null and zero offset were rechecked.

In step 4, the null was sometimes reset without recalibrating the system. It was found that if the null had just begun to drift, it could be readjusted without affecting the calibration significantly. However, once it had started to drift, then the null would be lost quite quickly. Since there were many cases when the null had just begun to drift at the end of the calibration, it was felt justified to readjust the null slightly to prevent it drifting completely during the target measurement. (Note that the *zero offset* could **not** be readjusted in this manner.) The error introduced by this procedure was not significant compared to the errors from other sources (see chapter 5) and greatly increased the number of measurements that could be accepted.

The video output of the receiver was monitored on an oscilloscope. Due to the logarithmic characteristic of the receiver, the 'noise band' was wide with no input signal and narrow when a signal was present. To 'null the system', the attenuator and sliding short were adjusted until the noise band was as wide as possible on the oscilloscope. This corresponded to minimum power entering the receiver.

A complete cycle took four to five minutes. If the null or zero offset drifted excessively, or the target moved, the measurement was discarded. The raw data was stored on computer floppy disk for later analysis.

Figure 3.1 Schematic Diagram of RCS Measuring System

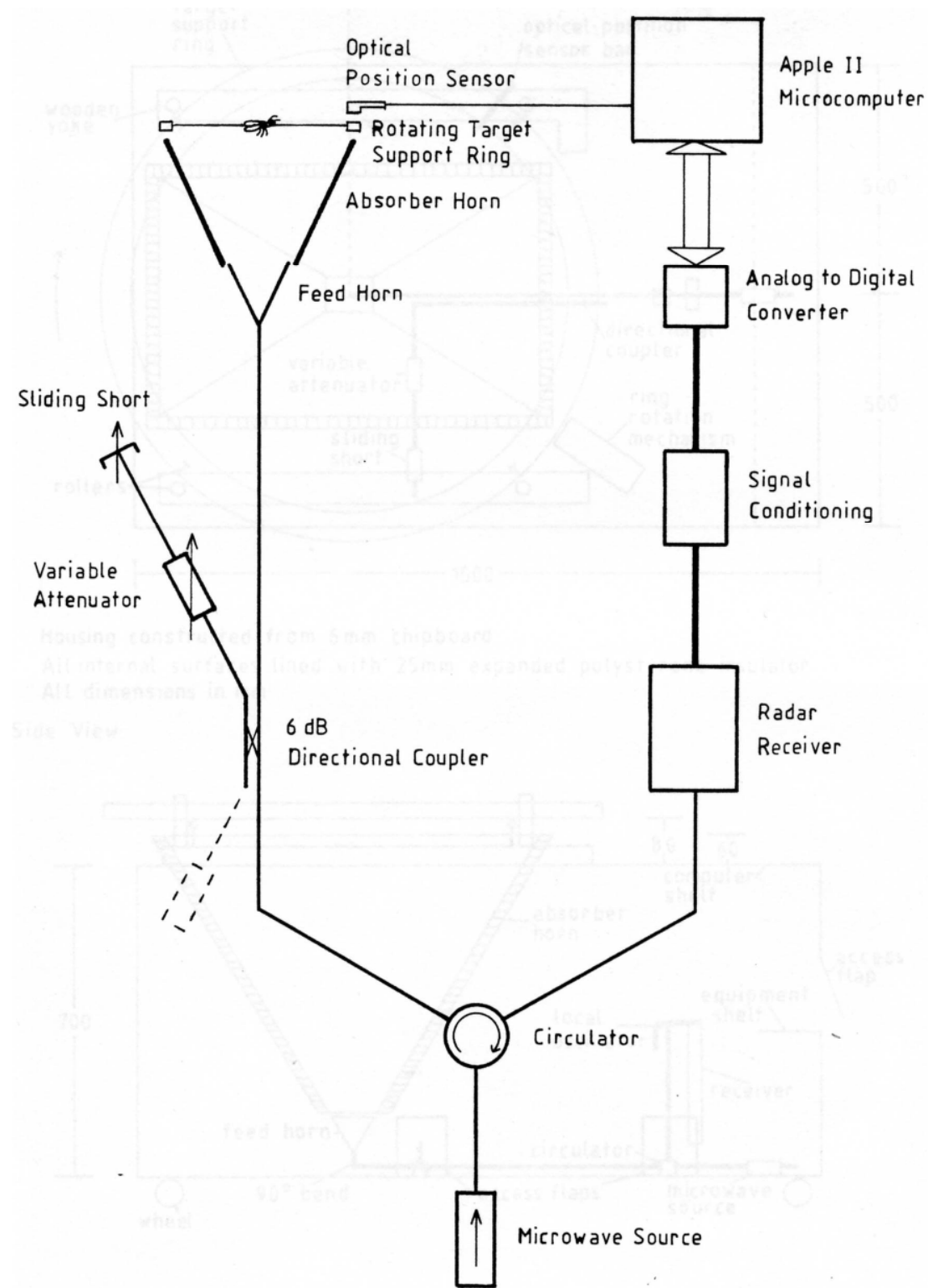
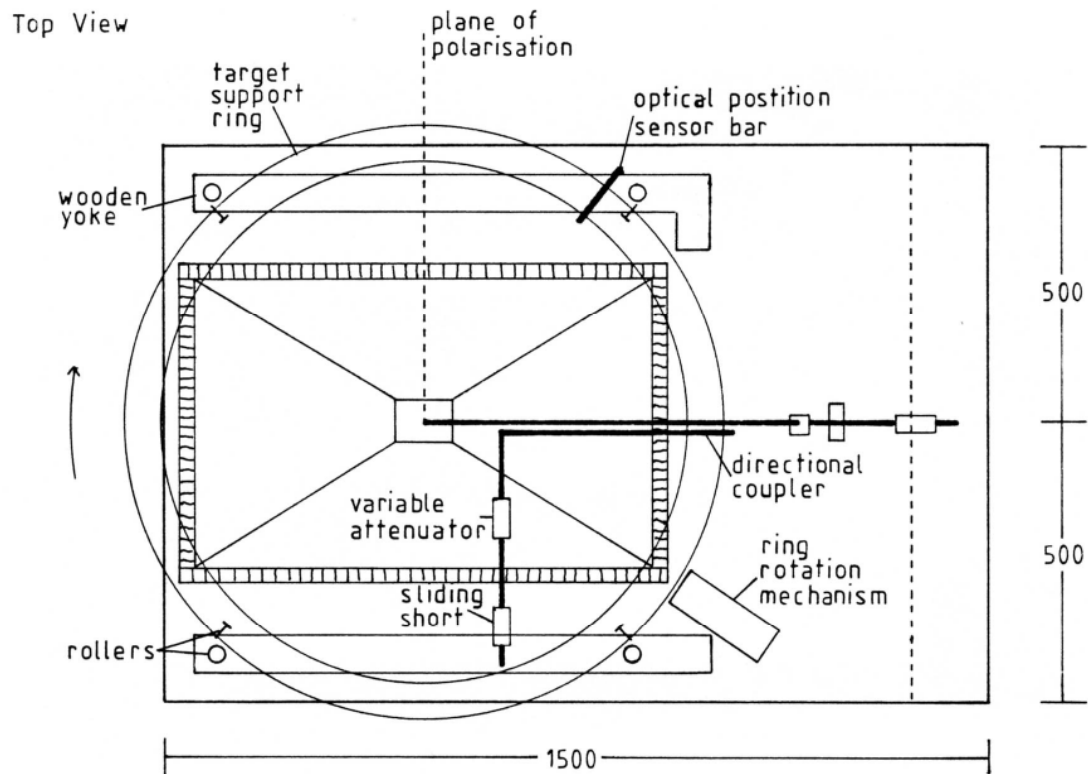


Figure 3.2 Diagram of RCS Measuring System and Housing



Housing constructed from 6mm chipboard

All internal surfaces lined with 25mm expanded polystyrene insulator

All dimensions in mm

Side View

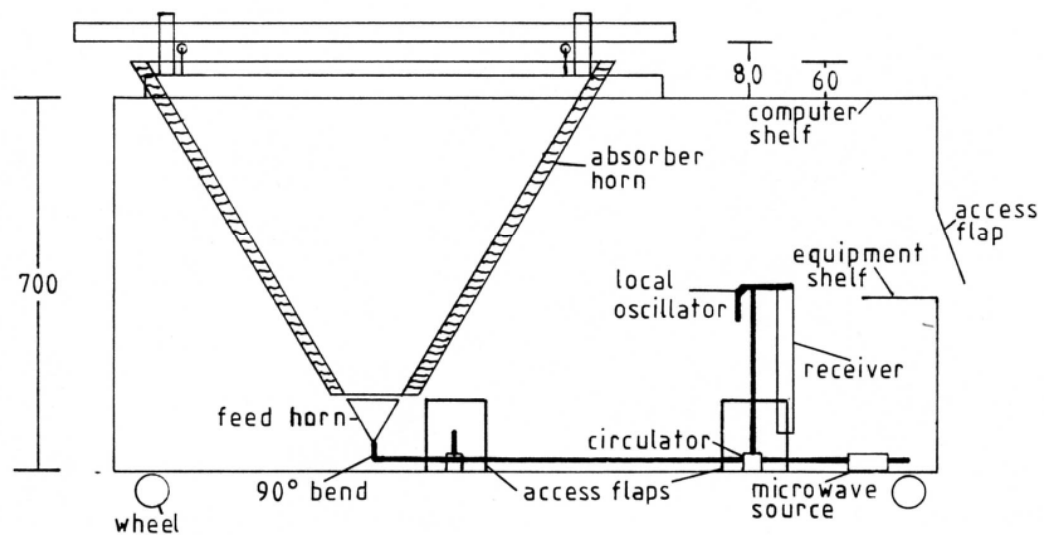


Plate 3.1 RCS Measuring System with Side Removed

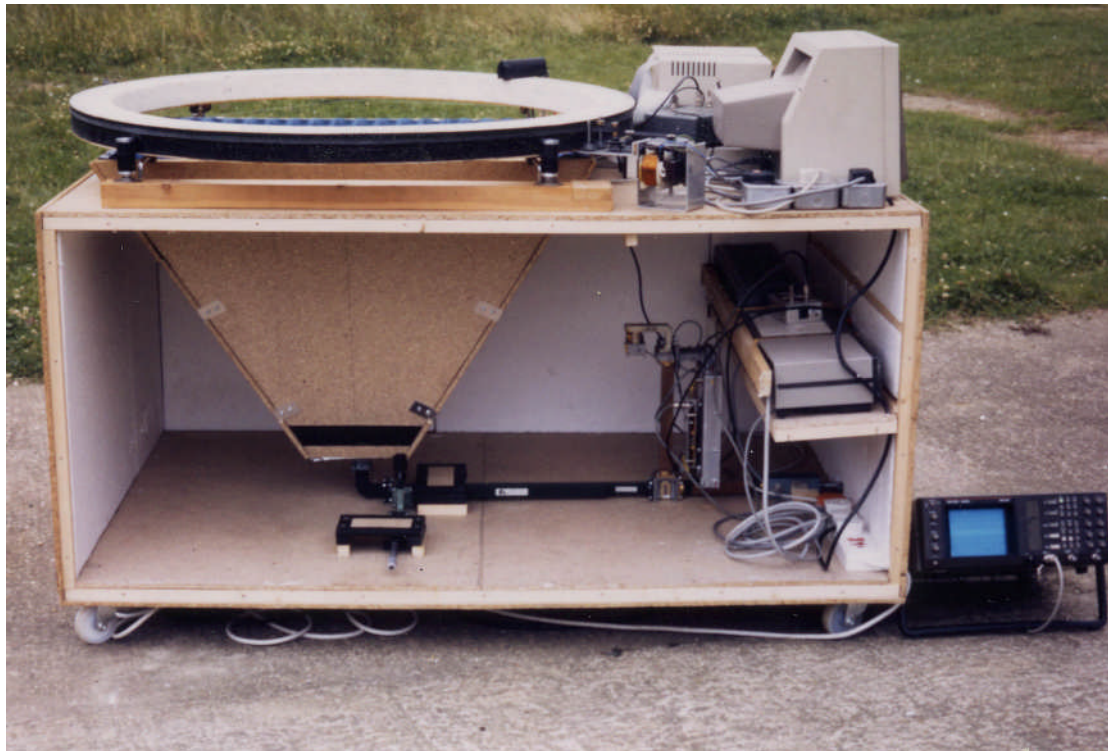


Plate 3.1 RCS Measuring System with Side Removed

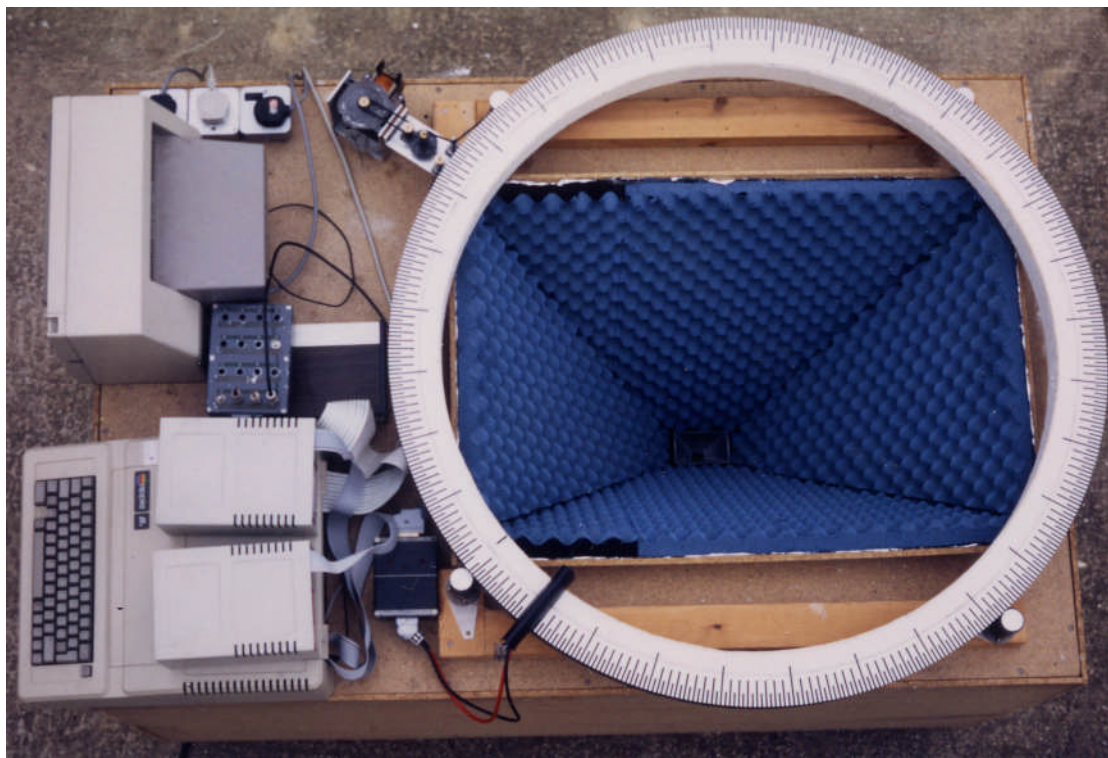


Figure 3.3 Diagram of Plessey ANT 163 Rectangular Horn

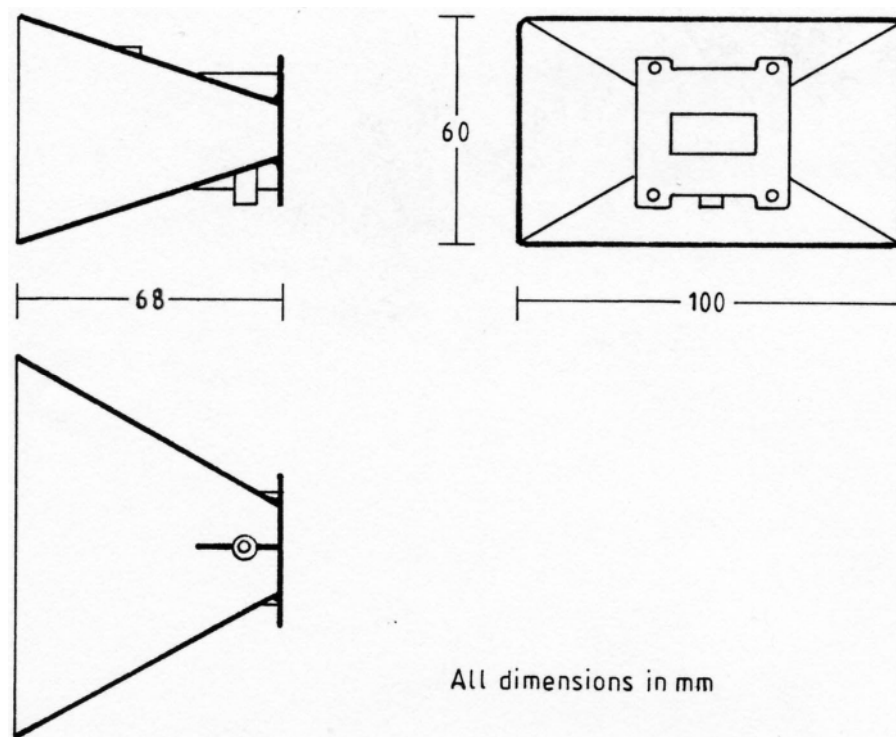


Figure 3.4 Diagram of Absorber Horn

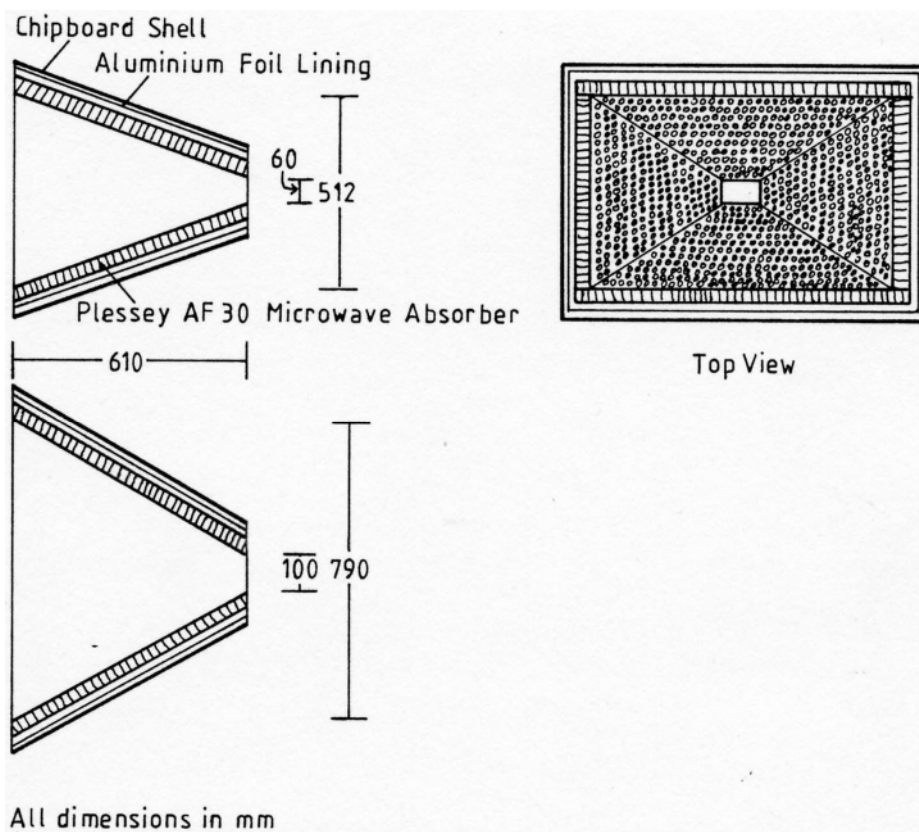


Figure 3.5 Beam Shape

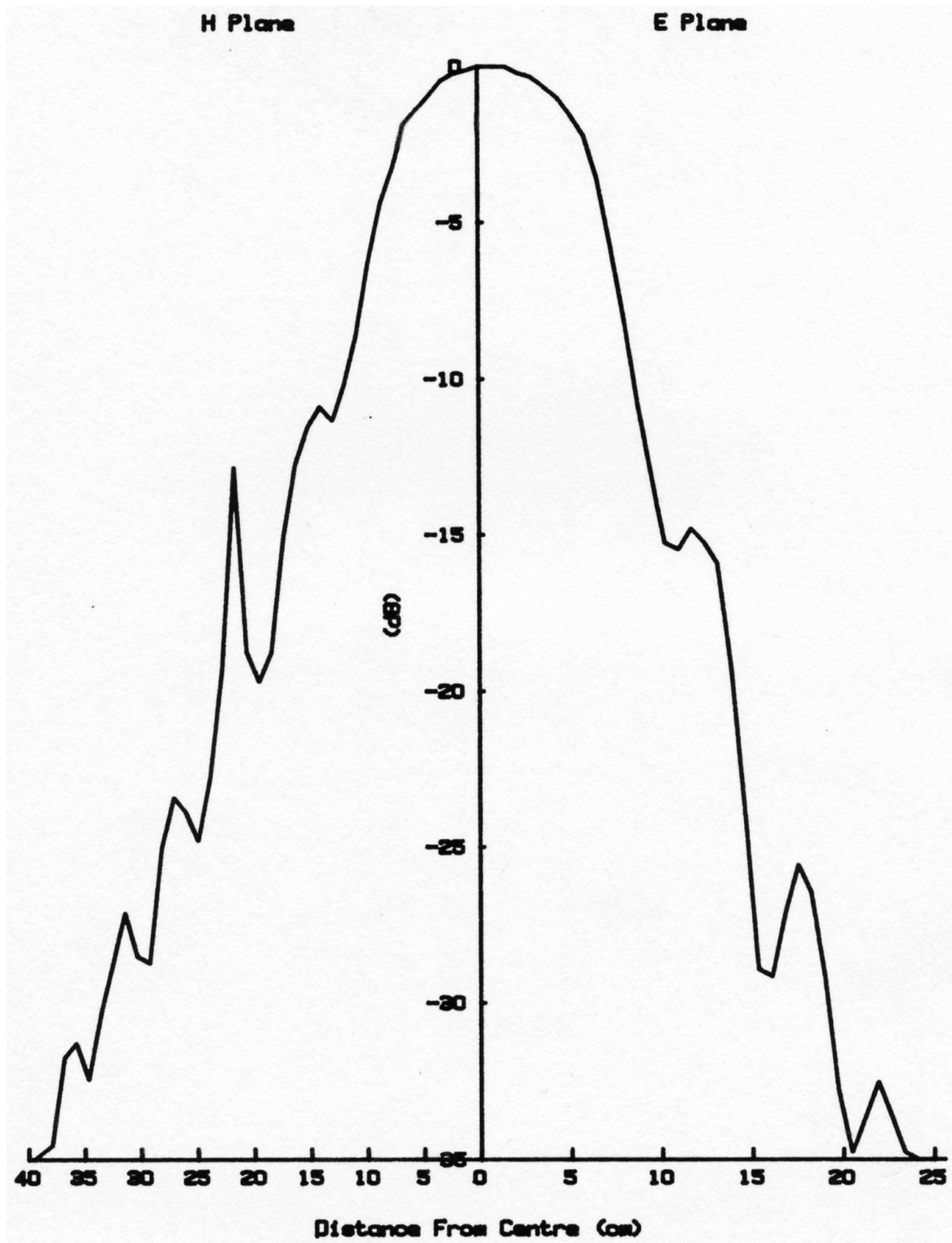


Figure 3.6 Block Diagram of Receiver, Receiver Buffer and External Buffer

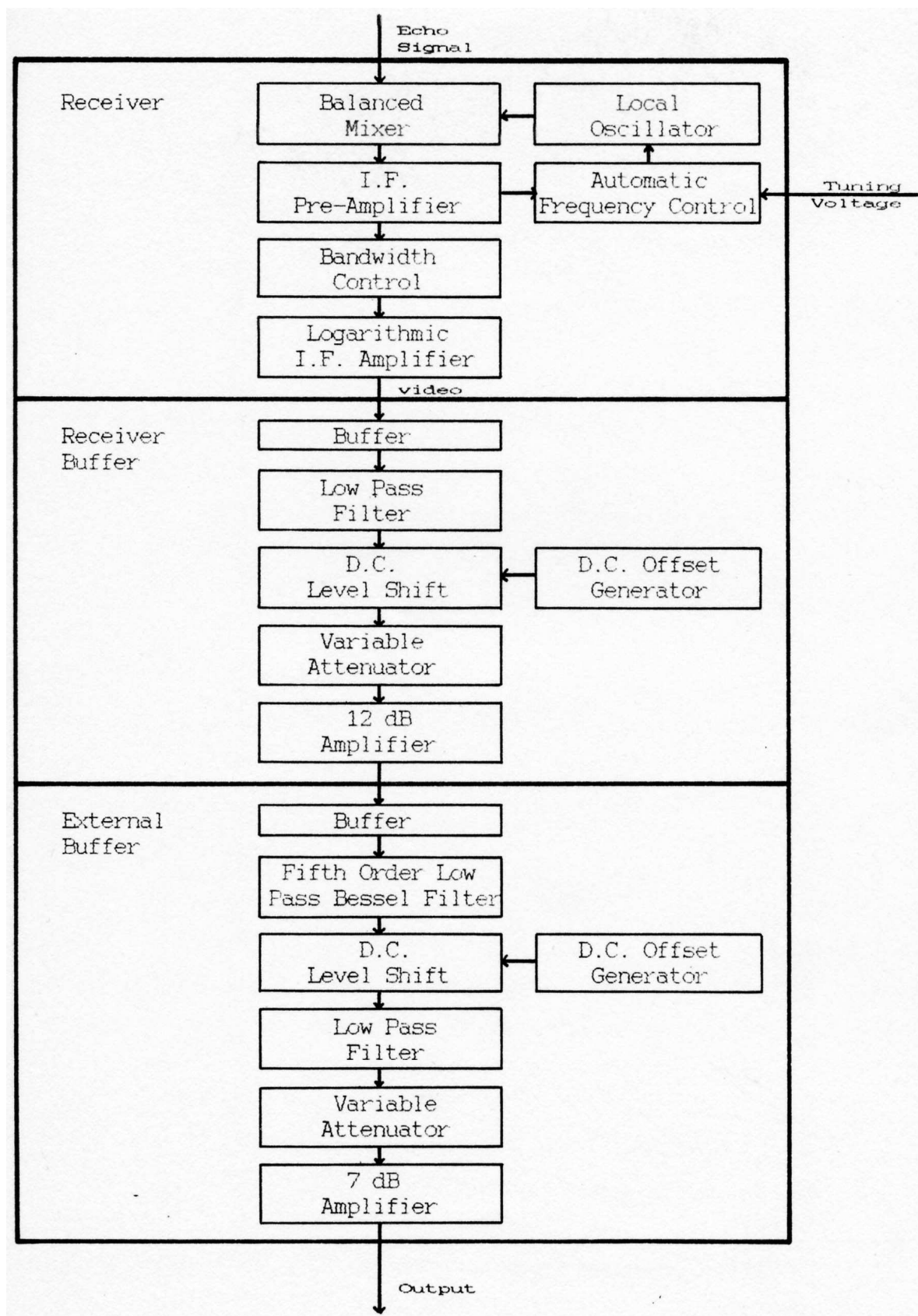


Figure 3.7 Schematic Diagram of Modified Section of AFC Circuit

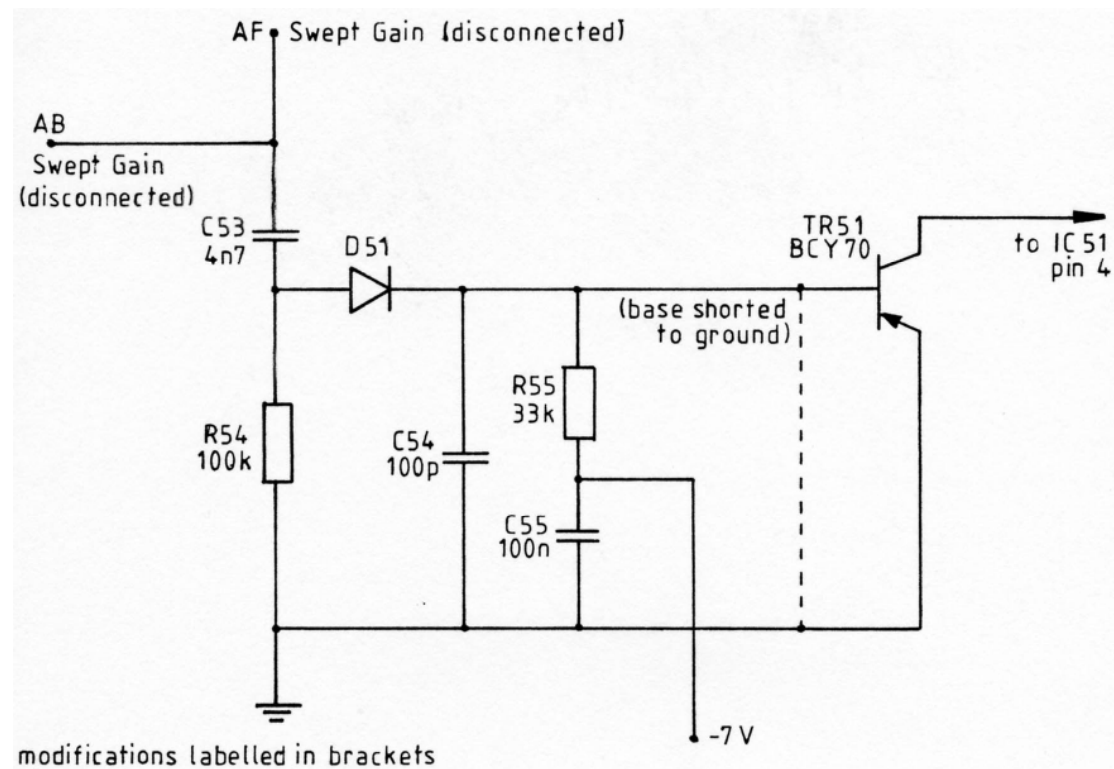


Figure 3.8 Schematic Diagram of Video Output Section of IF Amplifier Circuit

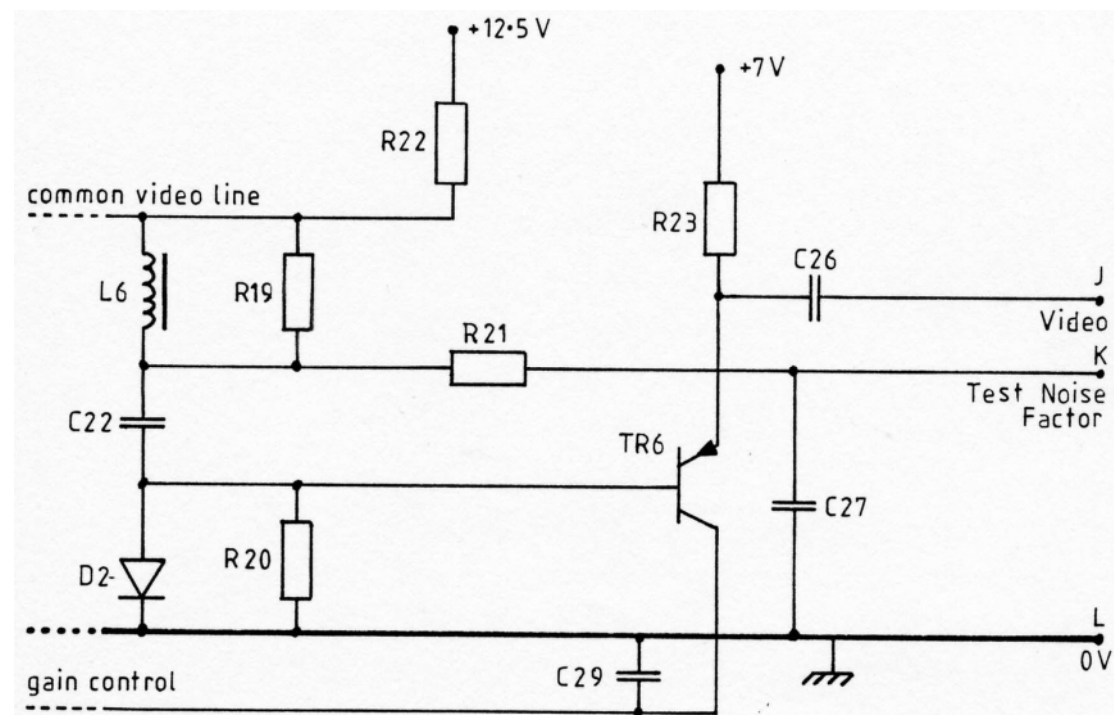


Figure 3.9 Schematic Diagram of Receiver Buffer Circuit

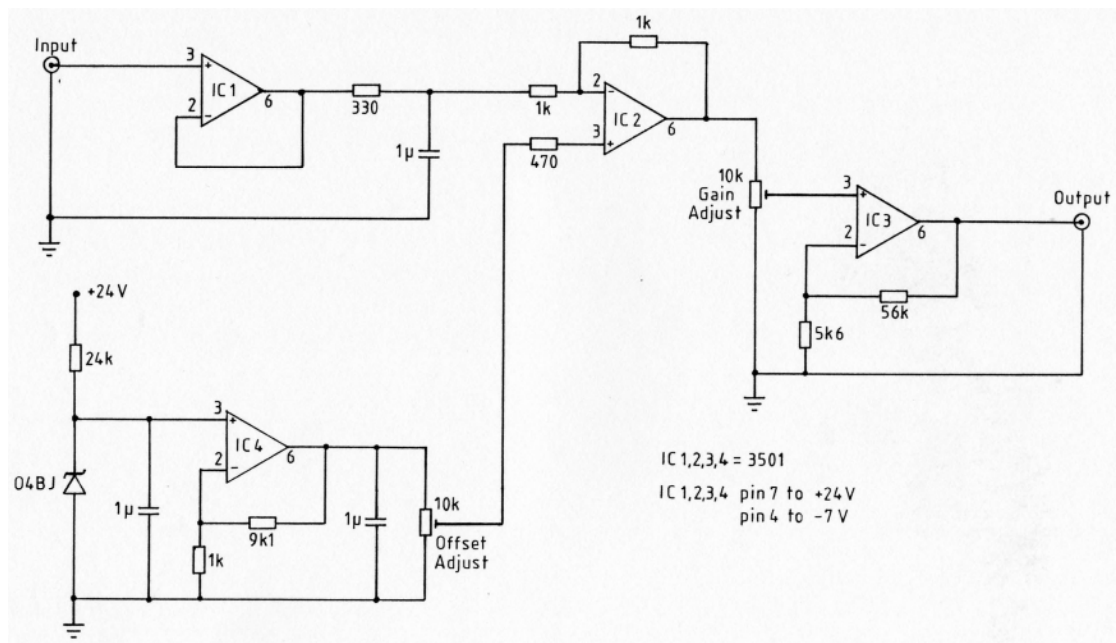


Figure 3.10 Schematic Diagram of External Buffer Circuit

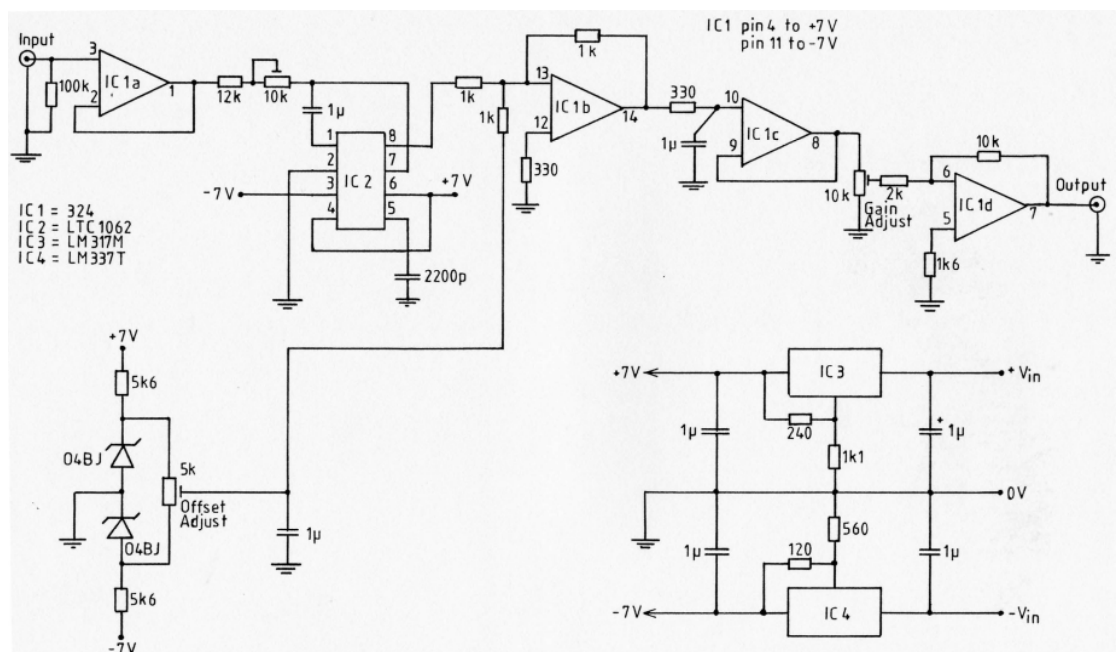


Figure 3.11 Schematic Diagram of Power Supply Circuits

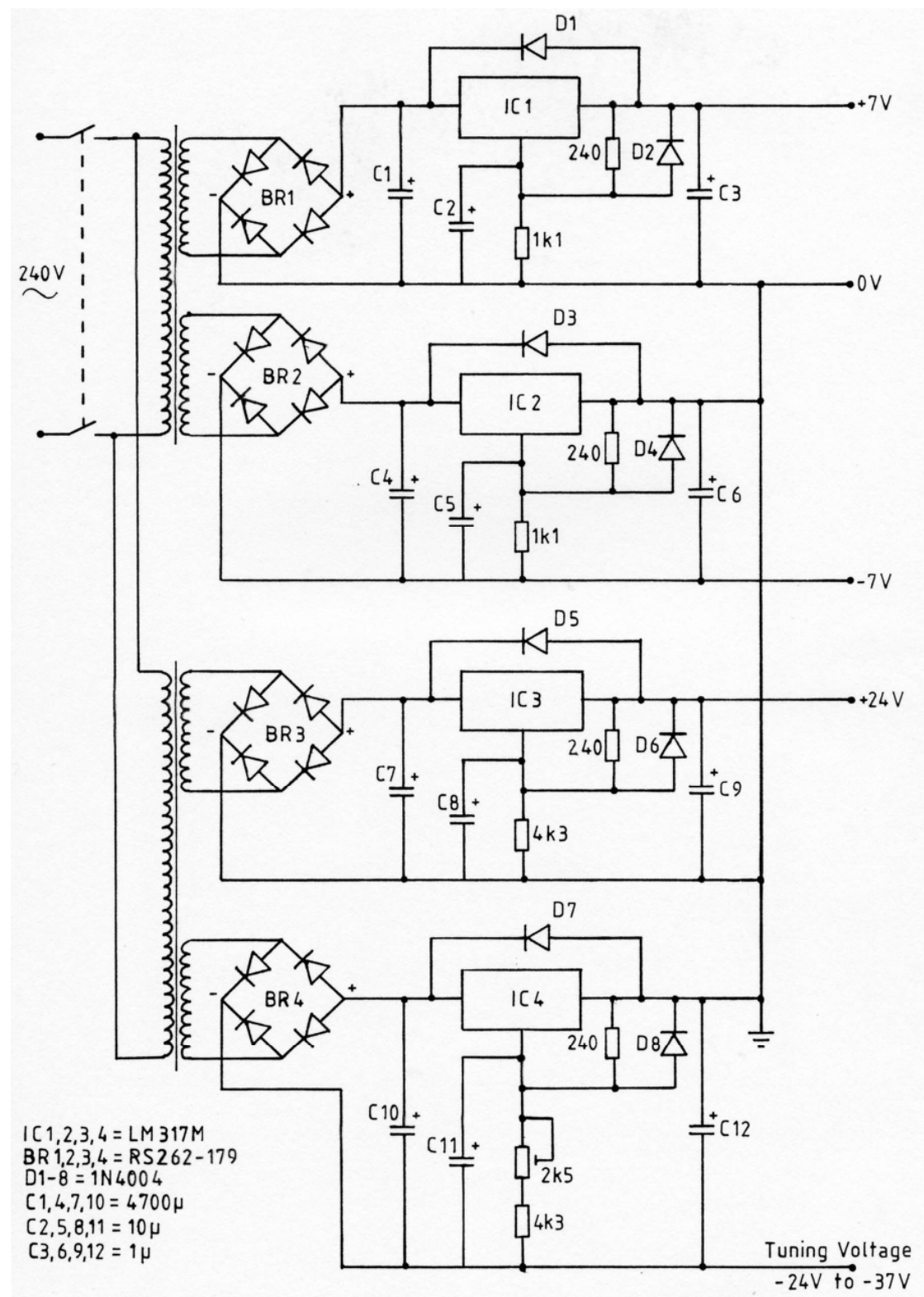


Figure 3.12 Diagram of Target Support and Rotation Ring

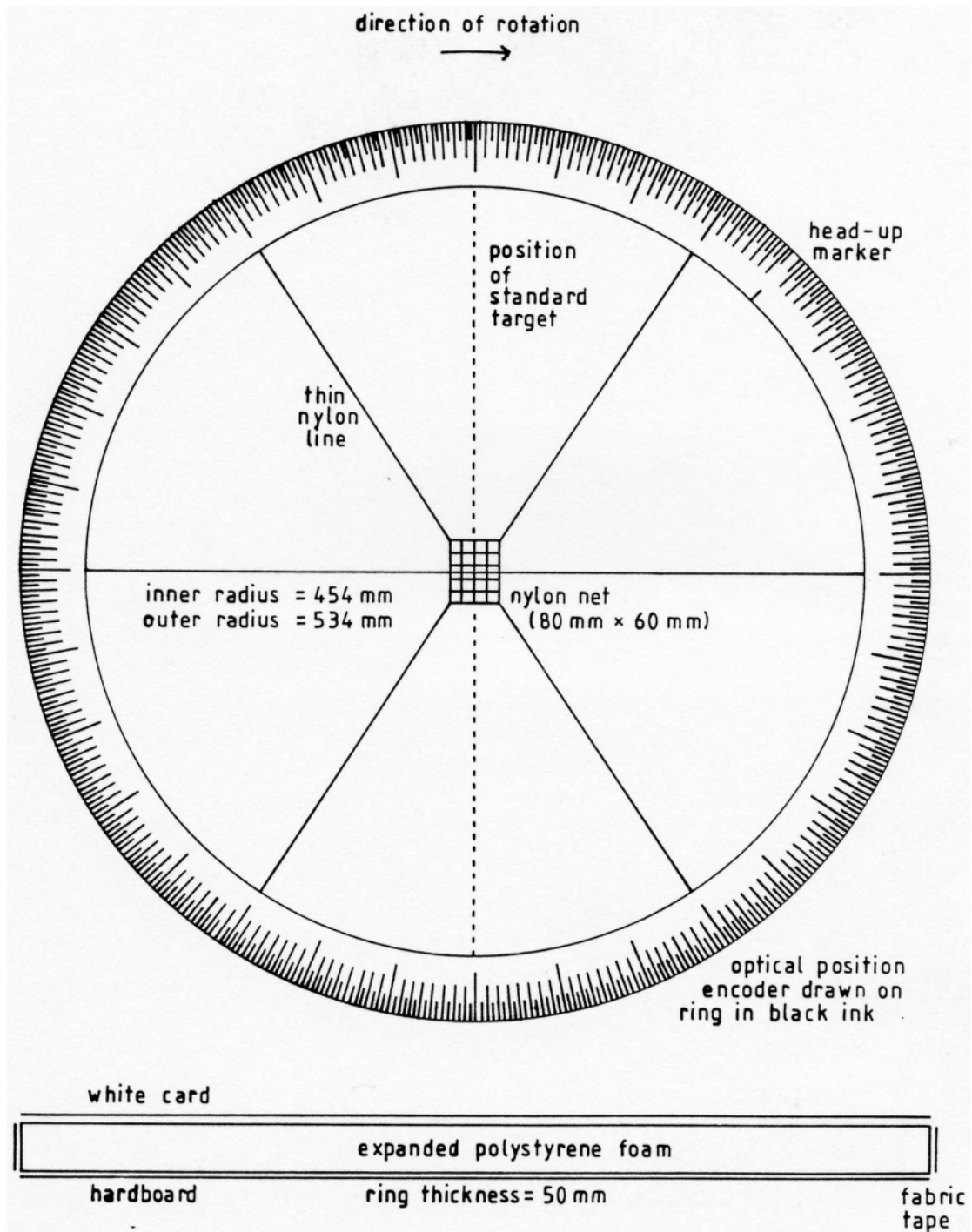


Figure 3.13 Diagram of Ring Rotation Mechanism

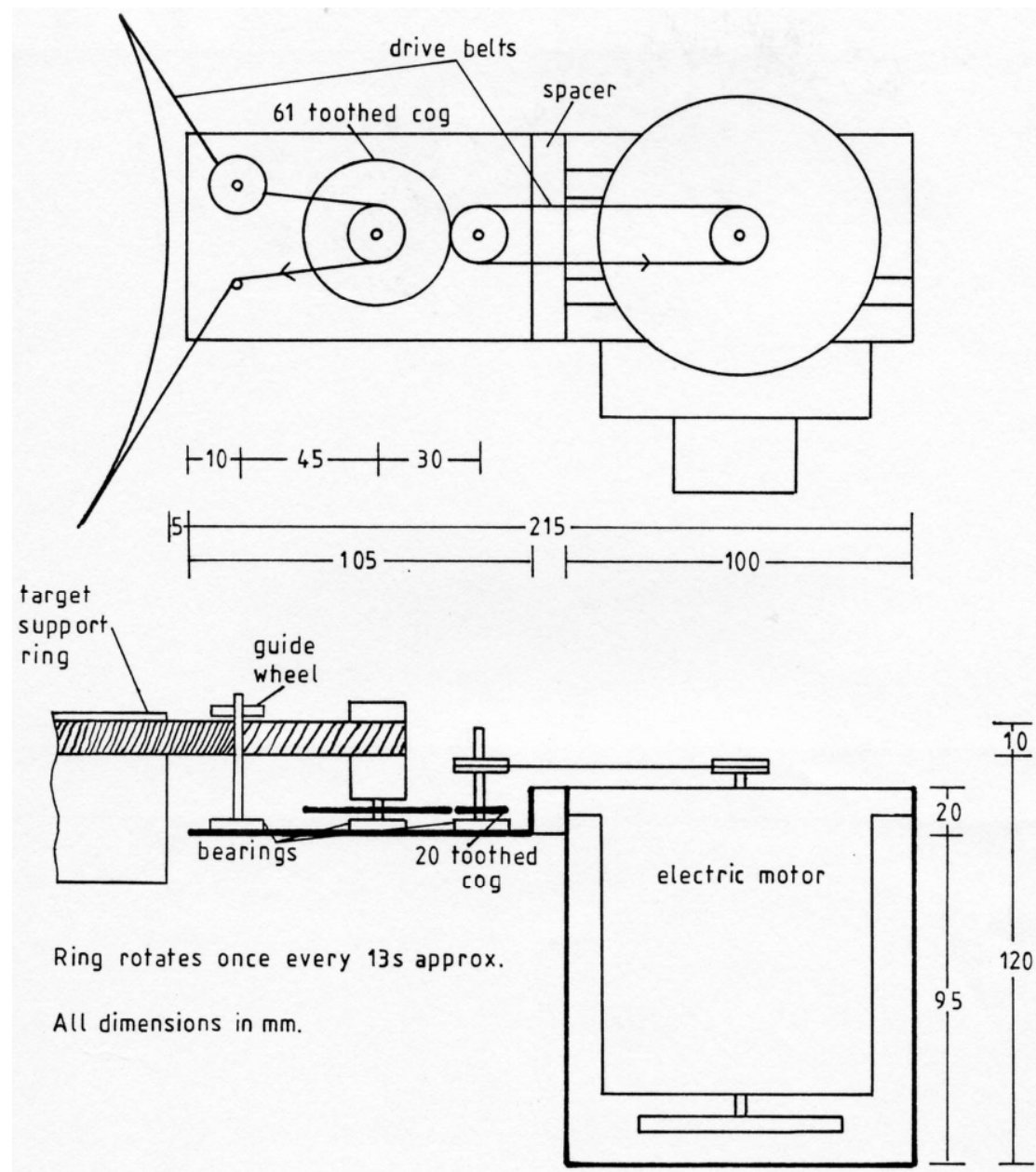


Plate 3.3 Ring Drive Mechanism

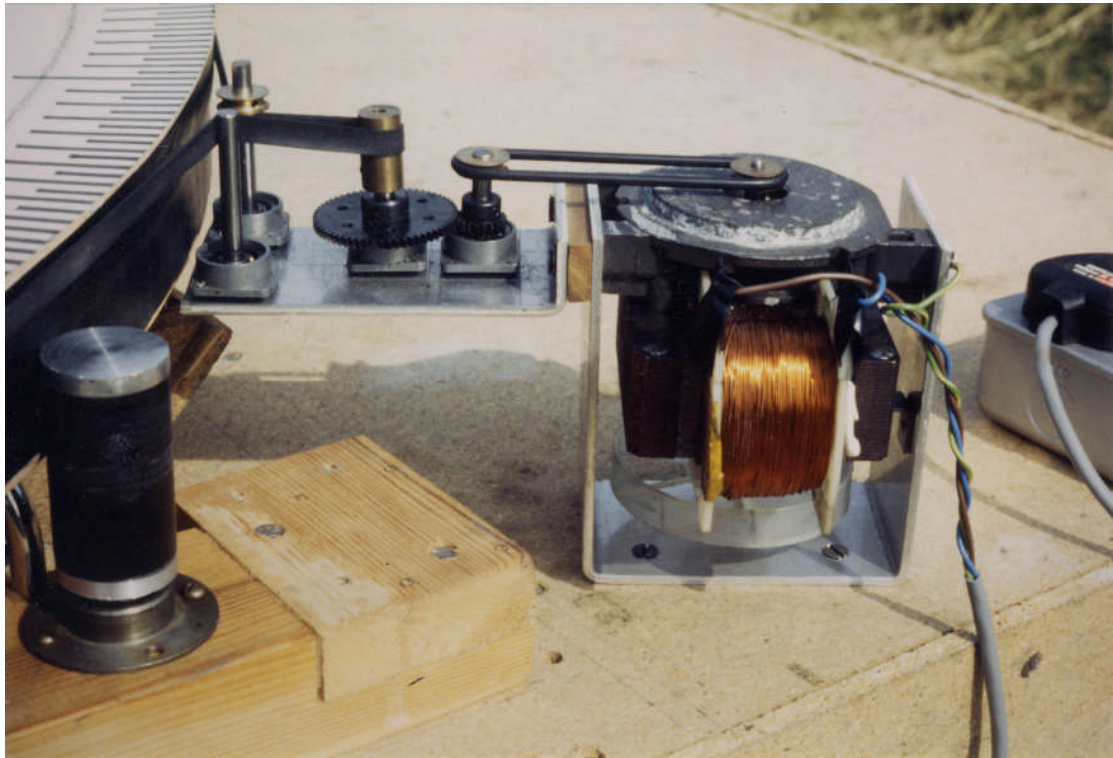


Plate 3.4 Optical Sensor Bar

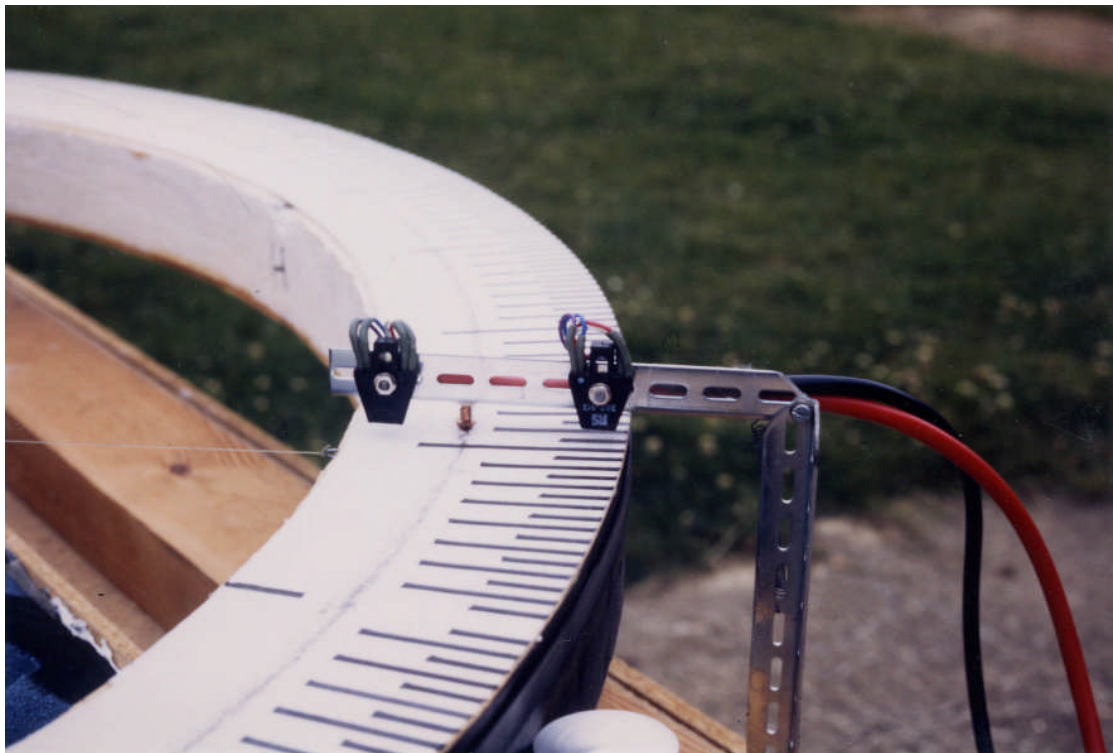
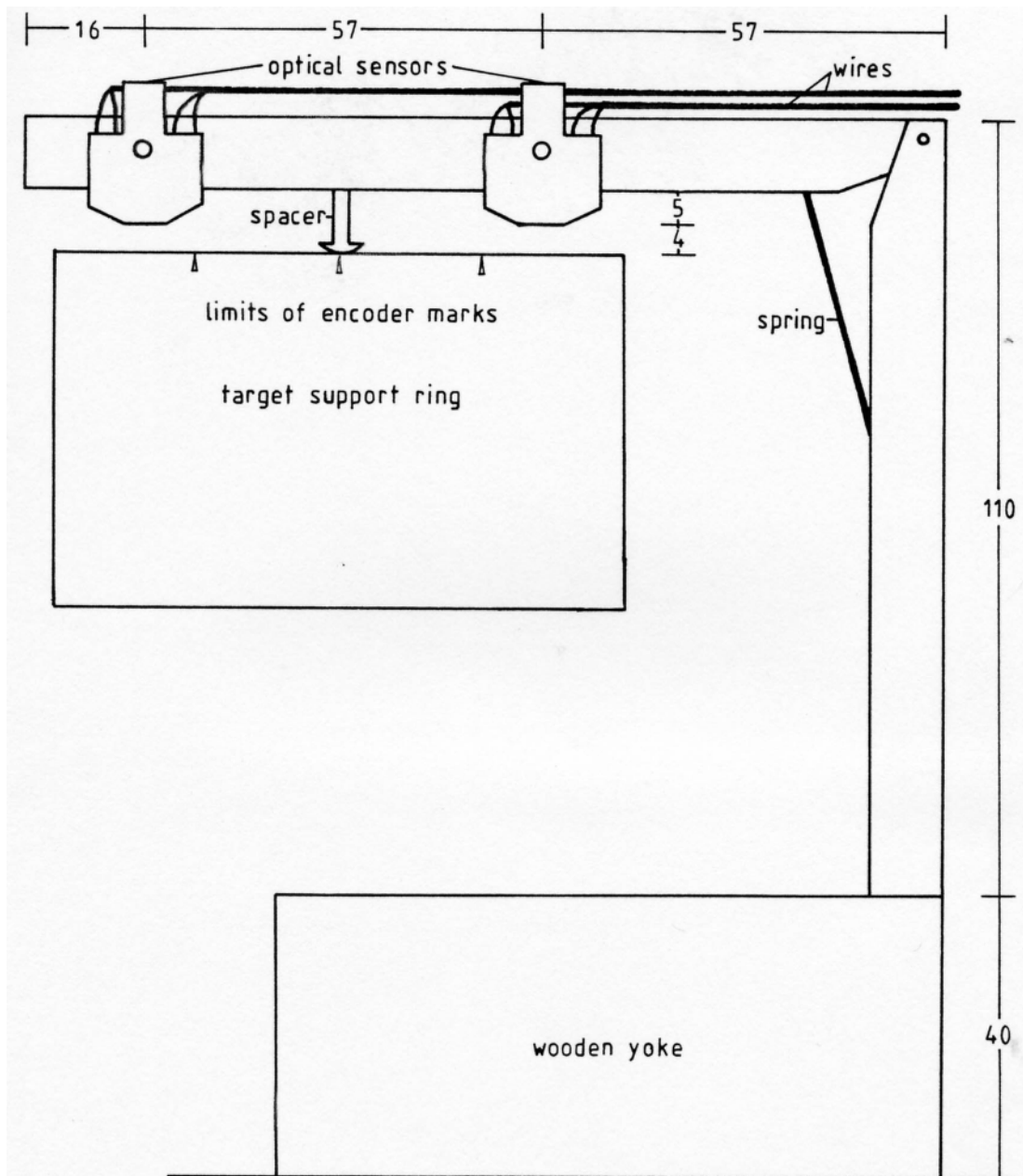


Figure 3.14 Diagram of Optical Position Sensor Bar



A black card cover (not shown) shades the sensors from extraneous light. The bar is set to be perpendicular to the edge of the ring. All dimensions in mm.

Figure 3.15 Schematic Diagram of Optical Position Sensor

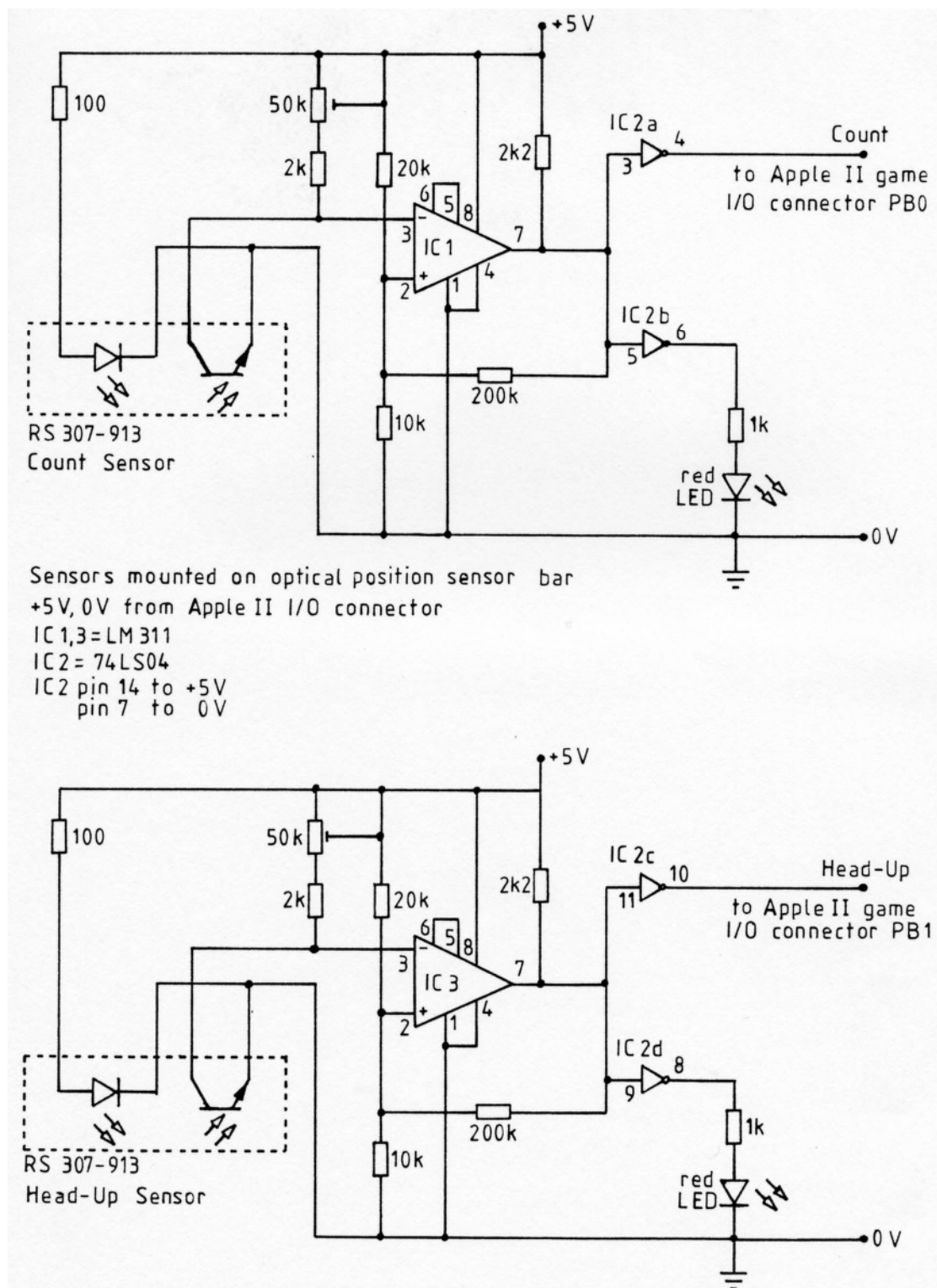


Figure 3.16 Sphere Calibration Curve

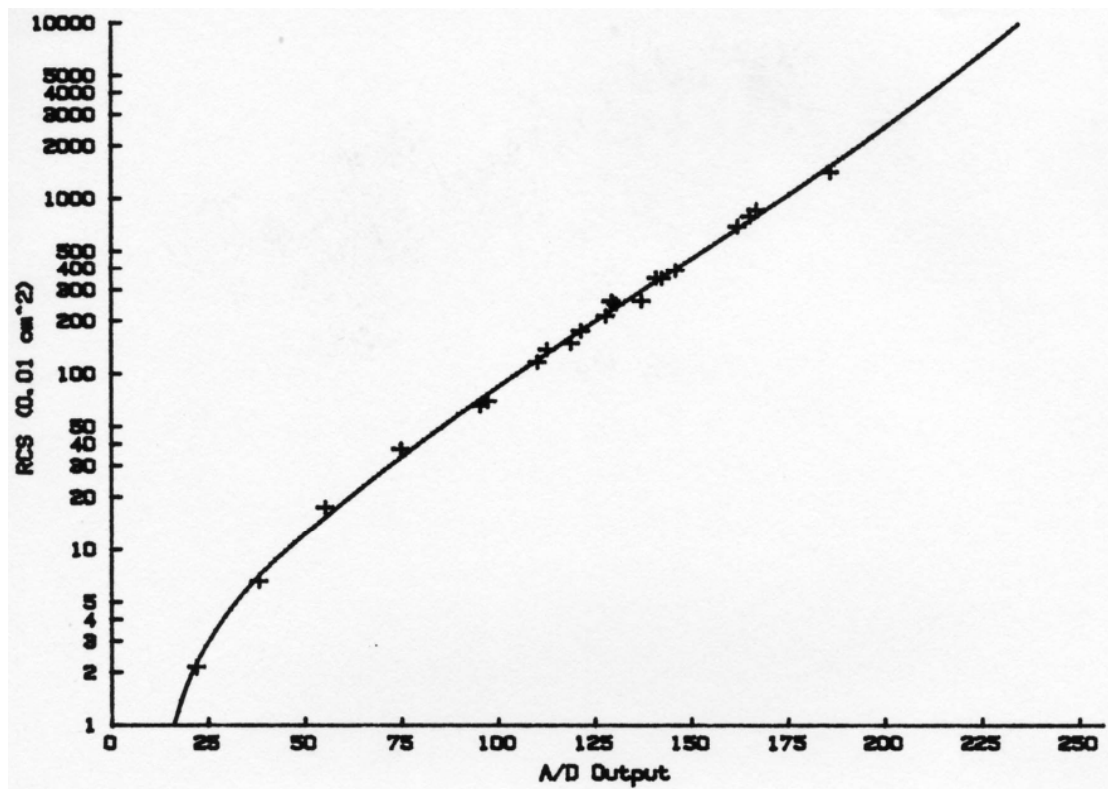
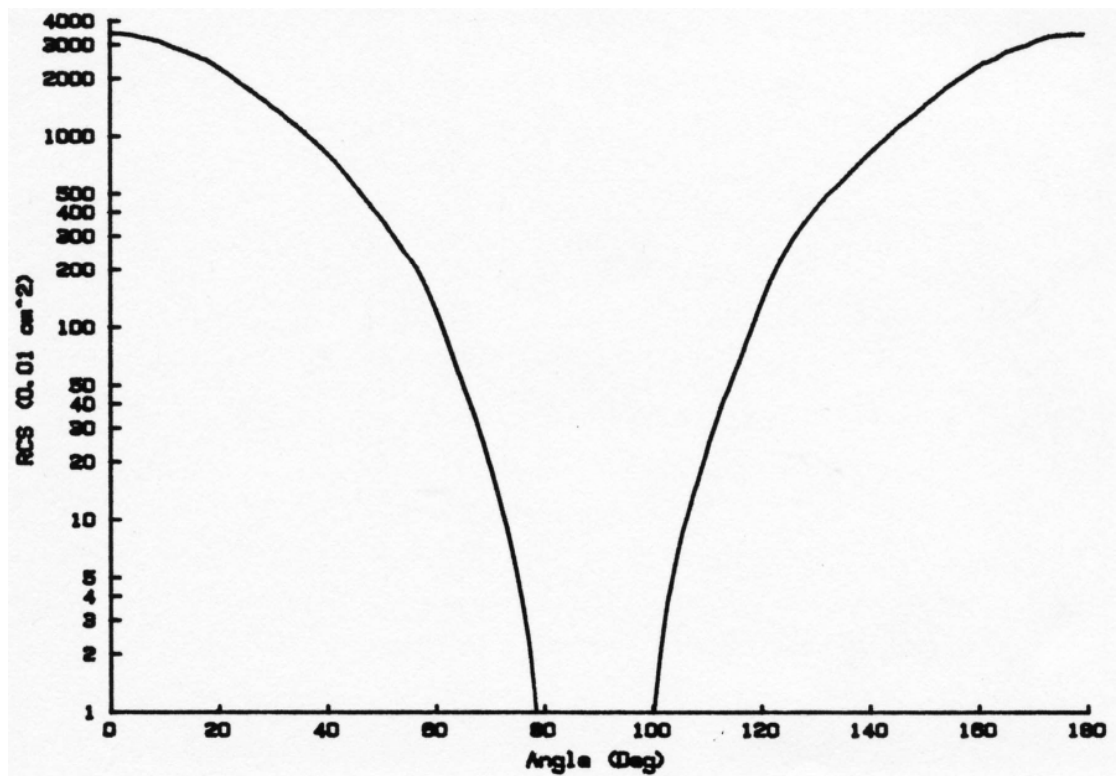


Figure 3.10 Schematic Diagram of External Buffer Circuit



Chapter 4

Experimental System Software

The software used to collect and analyse data from the hardware is discussed in this chapter.

4.1 Software Overview

All the software was developed on Apple II+ and Apple IIe microcomputers. The programs were written in Apple Pascal (a UCSD Pascal variant) or Assembler and executed using the Apple Pascal operating environment. There were three main programs:

- 1) 'RCS' (section 4.2), collected insect target information and data from a measurement cycle (see section 3.6);
- 2) 'Crunch' (section 4.3), averaged and calibrated the raw data;
- and 3) 'SM1' (section 4.4), fitted the parameters of the scattering matrix model (see chapter 2) to the calibrated data.

Data was stored on floppy disk between programs.

A few programs were needed for the calibration of the standard target and are discussed in section 4.5.

Many of the programs fitted a curve $f(x)$ to data (x_i, y_i) , $i = 1 \dots n$ (this denotes i takes all integer values between 1 and n) by calculating curve parameters so that

$$\sum \{y_i - f(x_i)\}^2$$

was minimised. This is called a *linear least squares fit* (LSF). The calculations tended to be numerically unstable and so a sophisticated algorithm from Nash [1979] was used. Discussion of the concepts and algorithm are deferred to Appendix A.

Two coordinate systems, defined in Figure 4.1, are used to describe the orientation of the ring. The 'natural' coordinate, Φ , is related to the 'hardware' coordinate, Φ' by the simple rotation:

$$\Phi = \Phi' - \theta_0'$$

where θ_0' is the orientation of the plane of polarisation in the hardware (Φ') coordinate system.

4.2 Program ‘RCS’

Data was collected by the program ‘RCS’ which performed the following tasks:

- 1) opened a data file on floppy disk, making sure there was enough room for several *target records* (i.e. a set of all the data associated with one target- see Table 4.1);
- 2) requested ancillary information about the insect target (detailed in Table 4.1 and Figure 4.2) which was entered at the keyboard and included in the target record;
- 3) enabled the hardware offset to be checked and adjusted before a measurement cycle;
- 4) recorded data from a measurement cycle and added it to the target record;
- and 5) stored the target record in the data file.

Up to 12 target records could be stored per disk.

To allow the hardware offset to be adjusted, the program displayed a regularly updated average of the digitised receiver signal. When set correctly, pressing any key allowed the program to continue.

The following actions were performed for a measurement cycle:

- a) pause while the hardware null was set;
- b) collect RCS data from five revolutions of the standard target (used to calibrate the measurements);
- c) pause while the hardware null was checked
- and d) collect RCS data from ten revolutions of the insect target.

If a problem occurred during a measurement cycle, the data could be discarded and the cycle repeated.

4.2.1 Function ‘rcsII’.

Data was collected from the hardware in all cases by a suitable call to the subroutine ‘rcsII’, which was written in Assembler. It could not *control* the hardware but only read the incoming signals from the receiver and the two optical sensors.

The leading edge of the lines drawn on the optical encoder defined the ring orientation accurately. The following actions were taken whenever a low to high transition on either of the two optical sensor inputs indicated that the leading edge of a line was below the sensor bar:

- 1) the ADC was immediately triggered to digitise a sample of the receiver signal;
- 2) a check was made to ensure that sampling was synchronised with the ring position;
- and 3) the 12 bit data from the ADC was truncated to 8 bits (1 byte) and stored.

512 samples per revolution were collected (one per line on the optical encoder). The start of a revolution was signalled by a transition on the 'head-up' optical sensor when the 'head-up' line came below the optical sensor bar. This enabled the function to synchronise data collection with ring position.

If a line was not detected, or a transition occurred when a line was not below the sensor bar, data collection became unsynchronised with the ring position and the number of lines detected during the revolution would be incorrect. The data was discarded and data collection resumed at the start of the next revolution.

The ADV returned a 12 bit value in 2's complement. Negative values were set to zero. If the datum was simply truncated to 8 bits, the most significant bit (MSB) would always be zero, thus reducing the effective resolution to 7 bits. To avoid this loss, the datum was treated as an 11 bit value (ignoring the MSB) when truncated.

A screen display showing the status of data collection and a crude representation of the incoming data was maintained to enable monitoring of the process in real time (see Plate 4.1). This allowed problems such as extraneous objects falling into the beam to be quickly identified.

The function terminated when data from sufficient revolutions had been stored, or too many synchronisation errors had occurred.

4.3 Program 'Crunch'

The program 'Crunch' averaged and calibrated the raw data collected by 'RCS'. It performed the following tasks:

- 1) A file of raw data was opened;

- 2) The RCS data collected from the standard target was averaged;
 - 3) The orientation angle of the plane of polarisation, θ_0' , was calculated from the standard target data;
 - 4) A calibration curve was constructed from the averaged standard target data and the table of RCS values for the standard target;
 - 5) The insect target data was averaged and calibrated;
- and 6) the insect target ancillary information and averaged RCS data (collected together as a record) were written to a new file on floppy disk and a summary printed.

The calibrated data could be plotted by the program 'Graph'. An example is shown in Figure 4.3.

4.3.1 Data Averaging

According to the theory (see section 2.4) the RCS is periodic in orientation, so that

$$\sigma(\Phi) = \sigma(\Phi + 180^\circ).$$

Raw data, d_{ij} , $i = 0 \dots 511$, $j = 0 \dots n_r - 1$, (where n_r was the number of revolutions) could be averaged to give the mean of the (uncalibrated) RCS, q_k at orientation $(180 / 256)k^\circ$, $k = 0 \dots 255$ (in the Φ coordinate):

$$q_k = \sum_j (d_{kj} + d_{(k+256)j}) / 2n_r, \quad j = 0 \dots n_r - 1, \quad k = 0 \dots 255.$$

Both the standard target data and the insect target data were averaged in this way. Note that, since the random noise was added within the receiver and the calibration curve was non-linear, averaging after calibration would 'skew' the mean value of a point.

The standard deviation, s_k , was approximately proportional to the mean q_k (i.e. the percentage deviation was approximately constant). Therefore, a *fractional standard deviation* (FSD), f_{sk} , defined by

$$f_{sk} = s_k / q_k, \quad q_k > 0$$

$$0 \quad q_k \leq 0$$

was calculated for each q_k of the insect target to indicate the percentage variation of the raw data at that orientation.

To reduce rounding error, the updating method was used to calculate the mean and variance [Lachenbruch, 1983]. For any data set x_i , $i = 1 \dots n$, the mean, m_i and variance, s_i^2 , are set to initial values

$$m_1 = x_1$$

$$s_1^2 = 0,$$

and updated with other data:

$$m_{i+1} = (i m_i + x_{i+1}) / (i + 1),$$

$$s_{i+1}^2 = [(i - 1) s_i^2 + i(x_{i+1} - m_i)^2 / (i + 1)] / i.$$

The required values are m_n and s_n^2 .

4.3.2 Calculation of Phase Angle θ_0'

The orientation of the plane of polarisation in the hardware coordinate, θ_0' , was calculated for each record. The standard target data was then rotated so that the i^{th} point, q_{STi} , corresponded to the averaged, measured signal returned by the standard target at orientation $(180 / 256) i^\circ$ in natural coordinates, thus ensuring that the absolute RCS data and the calibration data were measured relative to the same coordinate system..

The RCS of the wire used as the standard target was at a maximum and a minimum when the wire was parallel and perpendicular to the plane of polarisation respectively. To extract θ_0' , a LSF of a curve of the form

$$C(\Phi') = c_0 + c_{11} \cos 2\Phi' + c_{12} \sin 4\Phi'$$

$$= c_0 + c_1 \cos 2(2\Phi' - 2\theta_0')$$

to the averaged, uncalibrated data (q_{STi} , $180k/256^\circ$) from the standard target was performed. The phase angle was given by

$$\theta_0' = \tan^{-1}(c_{12} / c_{11}) / 2$$

(Note that although the normal range of the function $\tan^{-1}$ is -90° to $+90^\circ$, it can be expanded to -180° to $+180^\circ$ by noting the signs of c_{12} and c_{11} which are effectively the cosine and sine of the required angle.) Although $C(\Phi')$ did not fit the data very well, because the curve and the data shared the same basic shape and *symmetry*, the phase angle calculated was the one required.

To rotate the averaged data to the natural coordinate system, the k^{th} value became the i^{th} value:

$$i = (256 + k - 1) \text{ MOD } 256$$

where

$$l = \text{ROUND} (256 \theta_0' / 180)$$

(MOD denoting integer division and ROUND denoting rounding to the nearest integer). As data could only be rotated in units of $180 / 256^\circ$, a small phase error was introduced. A better correspondence between the calibration data and the standard target data could sometimes be obtained by increasing or decreasing the offset, l by one. The program therefore displayed the data on the monitor and allowed the offset to be manually adjusted. This adjustment made very little change to the calculated calibration curve, but did reduce the residual sum of squares significantly (see section 5.2). No manual adjustments were made to the value of θ_0' .

4.3.3 Construction of the Calibration Curve

Using the averaged data from the standard target and a table of the absolute RCS's of the standard target (see section 4.5), a calibration curve was constructed for each target record and used to calibrate the insect target data of the record. This procedure allowed RCS measurements to be made even though the absolute calibration of the system changed from day to day. The accuracy of the calibration system is discussed in section 5.1.

The table of absolute RCS's consisted of a set of 256 points, σ_{STk} , $k = 0 \dots 255$, with the k^{th} point being the RCS of the standard target (in cm^2) at orientation $(180/256)k^\circ$ in the natural coordinate system.

A cubic B-spline (a numerically stable form of a *piecewise cubic polynomial*, frequently used in curve fitting applications [de Boor, 1978]) was fitted to the data. A brief discussion of B-splines is given in Appendix A.1. They are defined over a non-decreasing sequence of values, called a *breakpoint sequence*. Cubic splines (order 4) were used with breakpoints set at -0.1 , 25 , 50 and 256 giving 6 independent parameters that could be adjusted by the LSF. Note that the lower limit of the interval was slightly negative, although $q \geq 0$. Otherwise $B(0)$ would not be defined. The calibration curve and data were displayed on the computer monitor. The middle two breakpoints (initially set to 25 and 50) could be adjusted manually and the calibration curve recalculated and redisplayed until the curve fitted the data well. The initial values were usually suitable.

It was found that performing a LSF on the points (σ_{STk}, q_{STk}) gave poor results because equal weight was given to an absolute deviation from the curve at all points along the curve. For example, a deviation of ± 0.5 on a value of 1 would be as significant as a similar deviation on a value of 10. A better result was obtained by fitting $B(q)$ to the points $(\log(\sigma_{STk}), q_{STk})$. Equal weight was then given to percentage deviation, so that, for example, a deviation of ± 0.5 on a value of 1 would be as significant as a deviation of ± 5 on a value of 10. The absolute RCS, σ , for a given measured signal, q , was then given by

$$\sigma = 10^{B(q)} \text{ cm}^2.$$

The average log residual,

$$l_r = \sqrt{\frac{\sum \{\log(\sigma_{STk} - B(q_k))\}^2}{256}}, \quad k = 0.. 256$$

was calculated to indicate the goodness of fit of the B-spline. A typical calibration curve is shown in Figure 4.4. The averaged insect target data was calibrated using this curve.

4.4 Program ‘SM1’

This program performed a LSF of the theoretical model

$$\begin{aligned} \sigma(\Phi') &= a_0 + a_1 \cos 2(\Phi' - \theta_1') + a_2 \cos 4(\Phi' - \theta_2') \\ &= a_0 + a_{11} \cos 2\Phi' + a_{12} \sin 2\Phi' + a_{21} \cos 4\Phi' + a_{22} \sin 4\Phi' \end{aligned}$$

to the insect target data $(\sigma_{Tk}, (180 / 256)k^\circ)$, $k = 0 .. 255$. The required model parameters were given by:

$$a_1 = \sqrt{(a_{11}^2 + a_{12}^2)},$$

$$\theta_1 = \frac{1}{2} \tan^{-1} \left(\frac{a_{12}}{a_{11}} \right),$$

$$a_2 = \sqrt{(a_{21}^2 + a_{22}^2)},$$

$$\theta_2 = \frac{1}{4} \tan^{-1} \left(\frac{a_{22}}{a_{21}} \right).$$

The model was rotated to the natural coordinate system:

$$\theta_1 = \theta_1' - \theta_0',$$

$$\theta_2 = \theta_2' - \theta_0'.$$

The resulting models were stored on floppy disk and a hard copy summary was printed.

As the deviations from the curve were approximately proportional to the absolute value of the curve, an attempt was made to fit the curve $\log \sigma(\Phi')$ to the points $(\log(\sigma_{Tk}), (180 / 256)k^\circ)$. However, as this is a *non-linear* problem, it is very difficult to solve and proved unfeasible to implement on an Apple II microcomputer (a solution had not been found for even one record in over two days!). However, since the model fitted the data very closely, good results were obtained with the LSF. The average residual,

$$A_r = \sqrt{\frac{\sum \left\{ \sigma\left(\frac{180k}{256}^\circ\right) - \sigma_{Tk} \right\}^2}{256}}, \quad k = 0..256$$

was computed to indicate the goodness of fit of the model.

The results were plotted by the program 'SMGraph'. A typical example is given in Figure 4.5.

4.5 Absolute Calibration of Standard Target

Four additional programs were needed to obtain an absolute calibration of the standard target:

- 1) Program 'ADRead' – a simple program used to measure the RCS of the steel spheres;
 - 2) Program 'BSPFit' – a program to perform a LSF of a B-spline to the sphere calibration data;
 - 3) Program 'Calibrate' – a modified version of the 'RCS' program used to collect the raw RCS data of the standard target;
- and 4) Program 'GenSTT' – a program to calibrate the standard target data.

As the RCS of a sphere is independent of orientation, only the receiver signal level was needed to be measured. Program 'ADRead' read the receiver signal using the ADC without reference to the ring position, calculated an average over several values and displayed it on the monitor. The target support ring did not rotate. (As discussed in section 5.1, when spheres were measured on the system in the normal

way, there was very little wobble due to uneven illumination.) Values for each sphere were recorded.

Program 'BSPFit' performed a LSF of the cubic B-spline curve $B(q)$ (with the same break-point sequence as in section 4.3.3) on the points $(\log(\sigma_{Si}), q_{Si})$ where q_{Si} was the average receiver signal level recorded and σ_{Si} was the absolute RCS of the i^{th} sphere. The residual sum of squares was calculated to indicate the goodness of fit of the curve. The calibration curve is plotted in Figure 3.16.

Program 'Calibrate' was identical to 'RCS' except that no calibration data or ancillary information was collected. It recorded and stored data from ten revolutions of the standard target.

Program 'GenSTT' was a modified version of 'Crunch'. Instead of calculating a calibration curve it used the one generated by 'BSPFit'. It averaged and calibrated the standard target data collected by 'Calibrate'. The phase angle θ_0 was calculated from the calibrated data which was then rotated to the natural coordinate in a similar manner to that described in section 4.3.2. The resulting table, σ_{STk} , $k = 0 \dots 255$, was stored, ready for use by 'Crunch' and is plotted in Figure 3.17.

Many attempts were required to calibrate the standard target since the system had to remain stable over a long period of time to allow measurements of all the steel balls and the standard target without readjustment.

Figure 4.1 Coordinate Systems

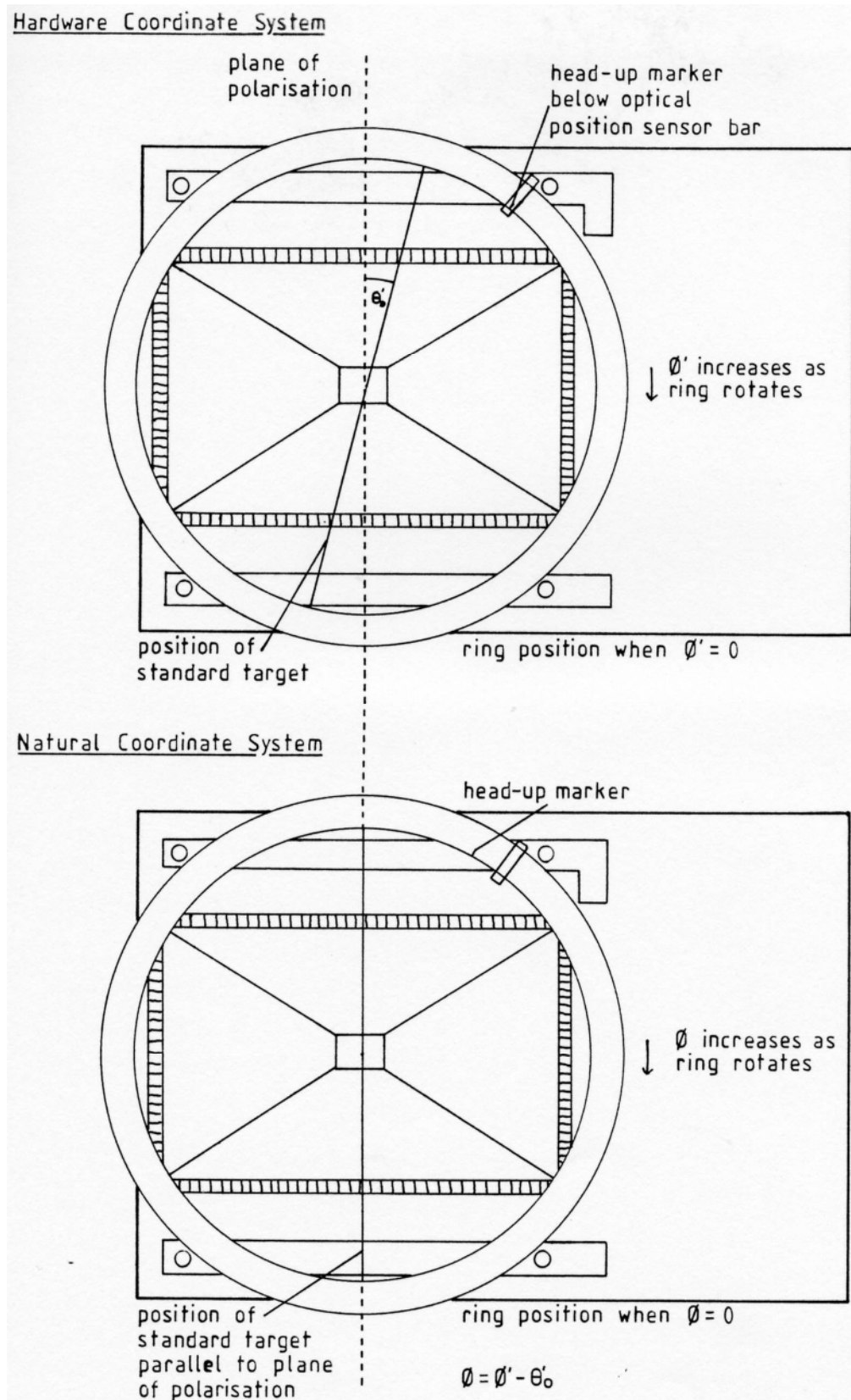


Figure 4.2 Measurements Taken from Insect Targets

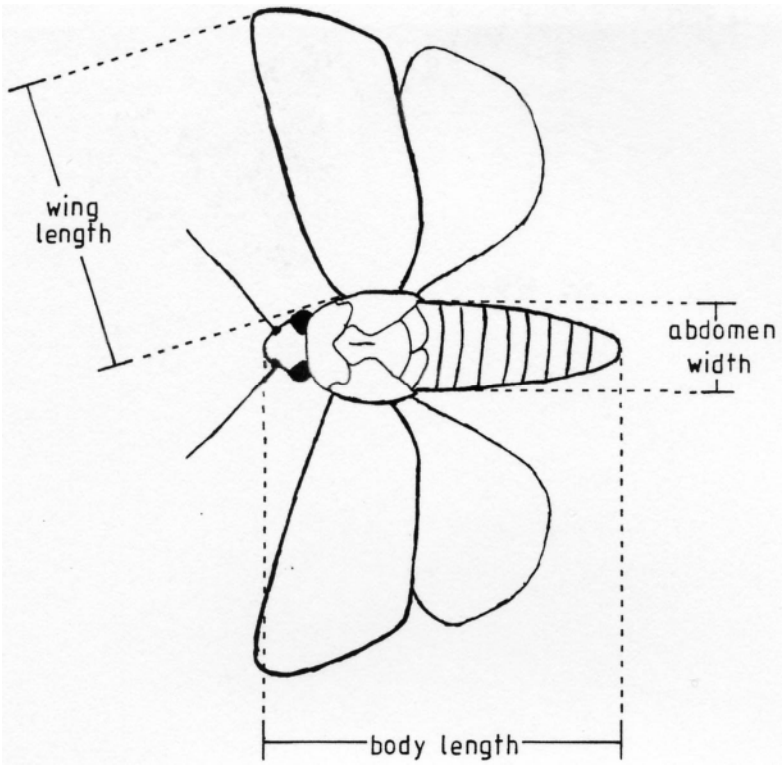


Table 4.1 Data Stored in Target Record

1:	Insect Number	{ A number unique to the target species }
2:	Species	{ A number specifying the target species }
3:	Body Length	{ in mm }
4:	Wing Length	{ in mm }
5:	Abdomen Length	{ in mm }
6:	Mass	{ in mg }
7:	Standard Target Data	{ Used for calibration }
8:	Insect Target Data	

Plate 4.1 Screen Display During Data Collection

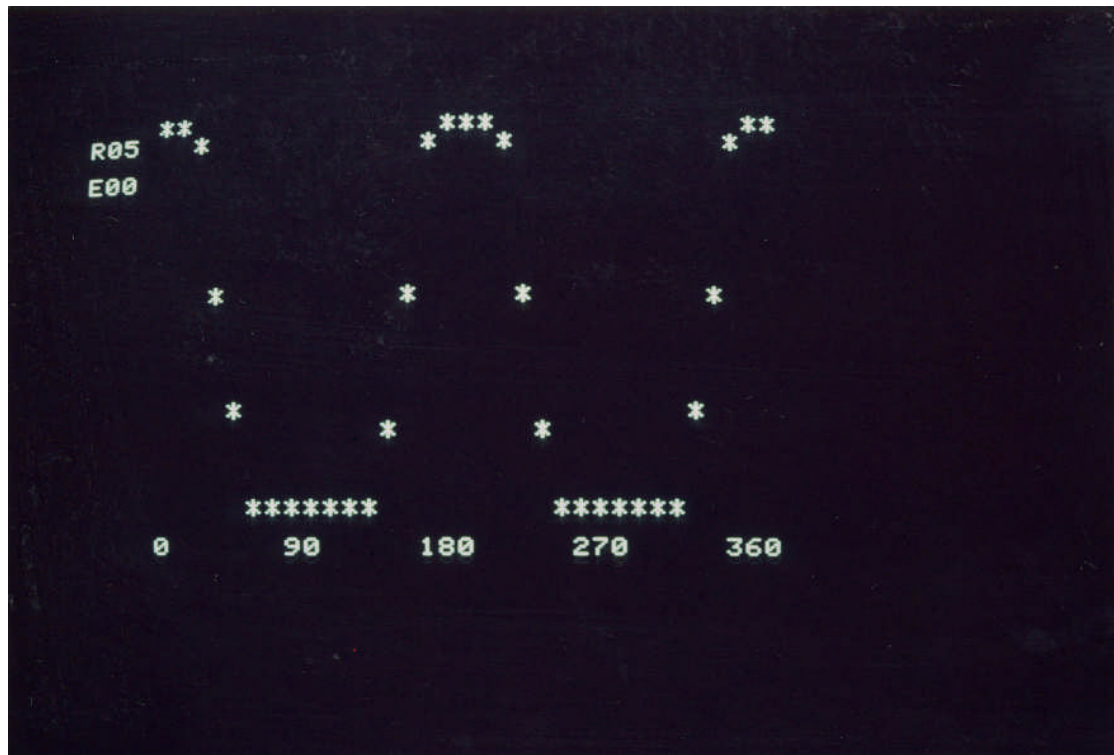


Figure 4.3 Example of Output from Program 'Graph'

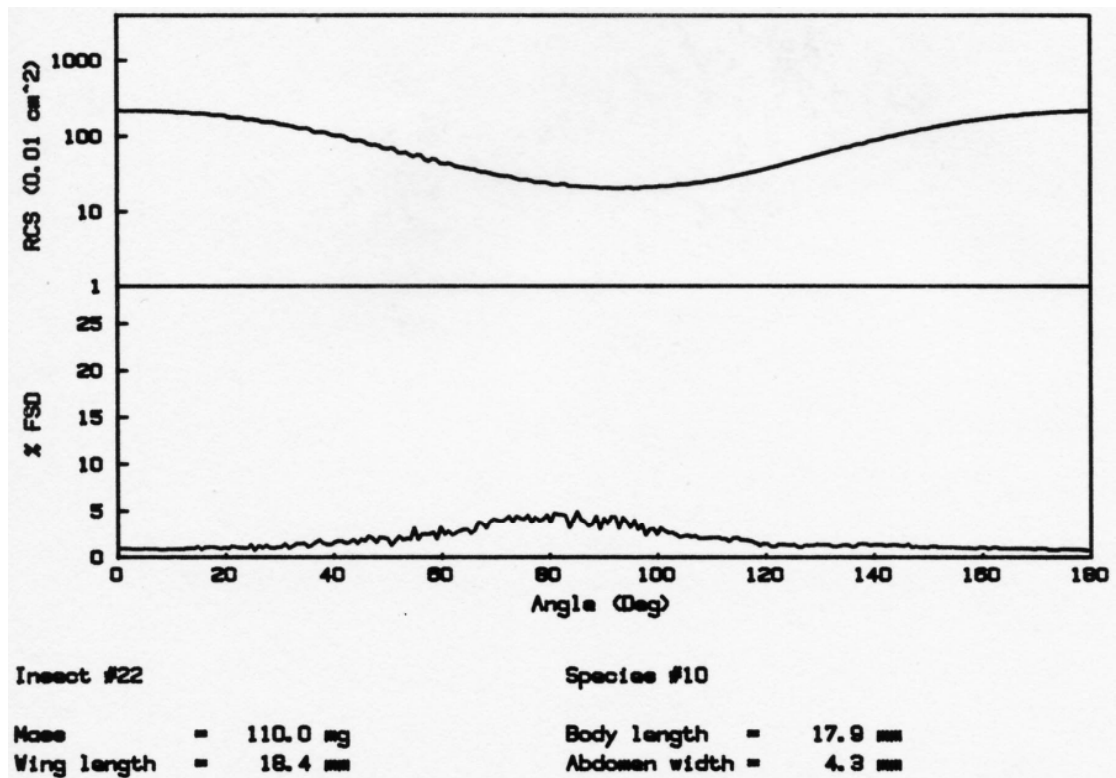


Figure 4.4 Typical Calibration Curve

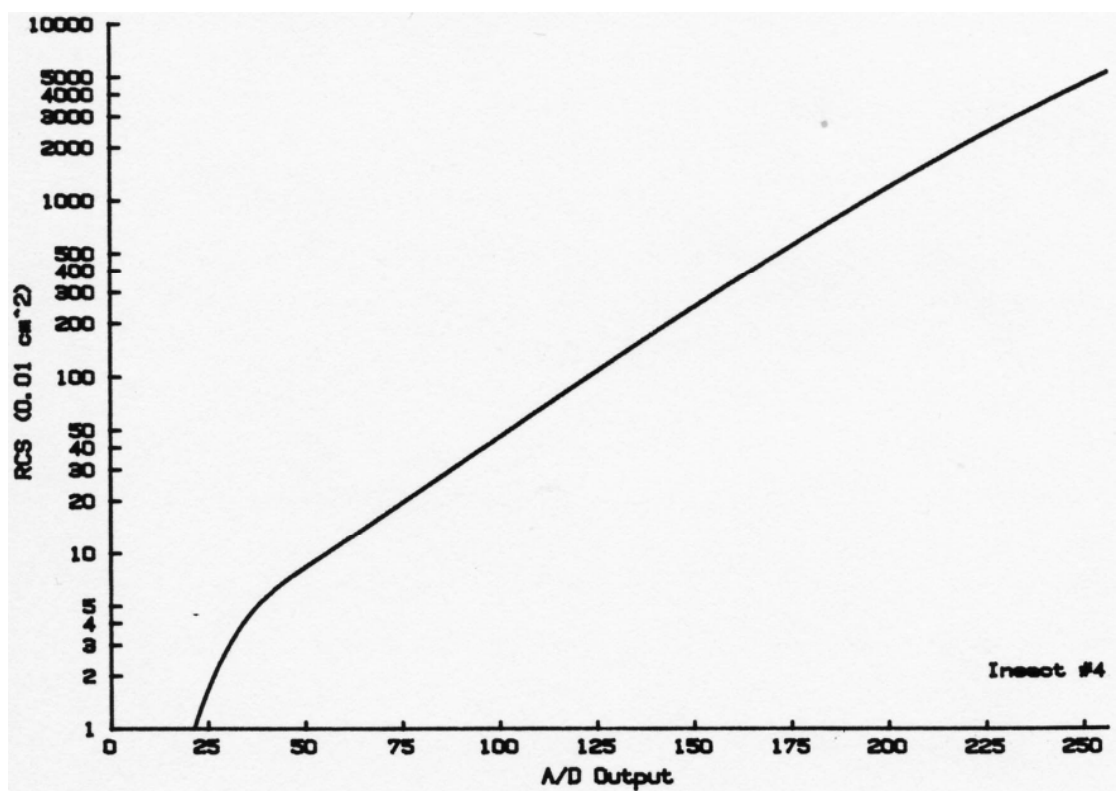
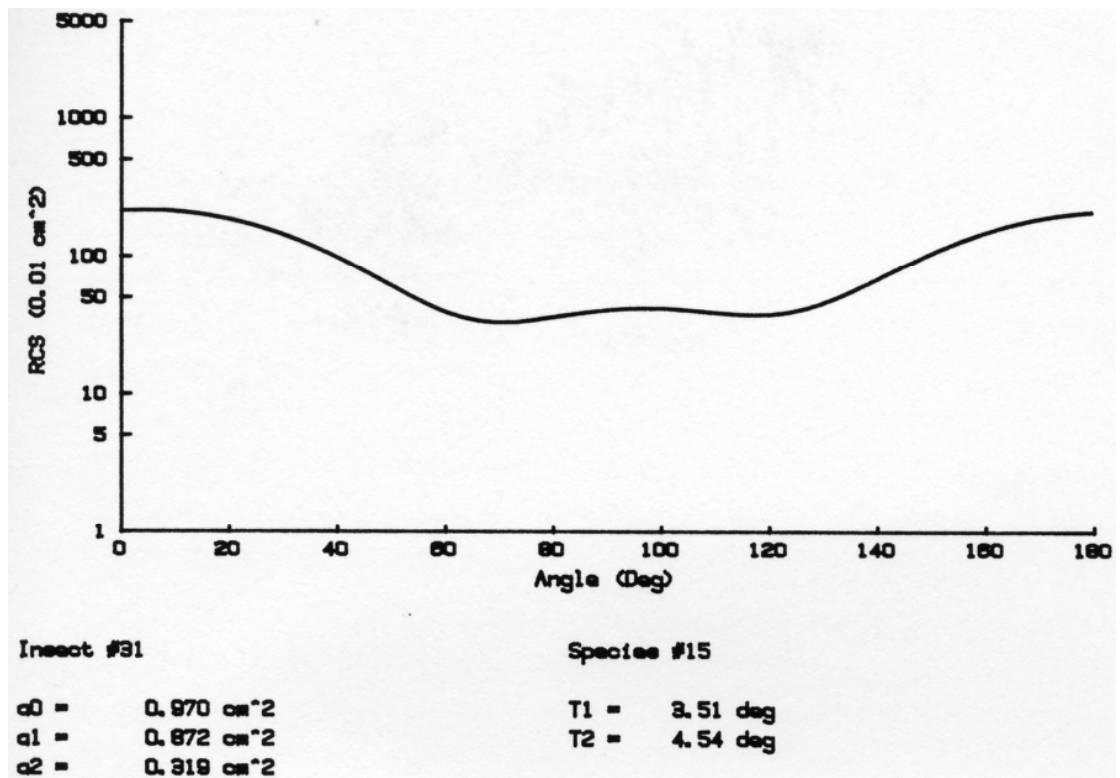


Figure 4.5 Example of Output from Program 'SMGraph'



Chapter 5

System Performance

Tests were performed on the system using a range of steel balls of known RCS and several thin wires of various lengths to assess system performance. Section 5.1 discusses the absolute accuracy of the RCS values. The accuracy of the orientation measurements is discussed in section 5.2. Section 5.3 assesses the accuracy of the measured model parameters. Section 5.4 describes the fractional standard deviation curves. Finally, section 5.5 discusses low amplitude modulations that were present on some of the data curves.

5.1 Accuracy of Absolute RCS Measurements

The accuracy of the RCS measurements was assessed by measuring several steel balls of known RCS with the calibrated system. Above values of 0.01cm^2 , the average error was 15%; the maximum error was $< 25\%$ (Figure 5.1). This degree of accuracy was the best that could be achieved with the equipment available and was enough to give useful results although detailed comparisons between two similar targets was not possible. Due to residual background reflections and receiver noise, no useful measurements could be made below 0.01cm^2 .

The RCS curves for the steel balls were flat (Figure 5.2), indicating that background reflections from the ring and target support net were not significant, otherwise, as the ring rotated, the reflected signal from the ring would vary with orientation, interfere with the target reflection and cause a modulation to appear on the RCS curve.

External background reflections could account for some of the measured errors. Tests for residual background reflections were performed by moving items around on and near the system housing and noting the variation of the received signal. No significant changes were observed. The signal was not disturbed by a person walking around the box, provided they did not lean over the absorber horn and so into the illuminating beam.

A typical calibration curve is plotted in Figure 5.3. All the calibration curves were of similar shape but varying positions, due to different settings of the system D.C. offset. Some slight hysteresis was present in the calibration data, due to

truncation error in the offset, l , of the calibration data (see section 4.3.2). If the offset were incorrect, then the curve traced out as the RCS decreased would be higher or lower than the curve traced out as the RCS increased. However, the average of the two curves was approximately the same as the curve traced out when the offset was correct. Therefore, the offset error had very little effect upon the calculated calibration curve.

The average log residual, L_r , (see section 4.3.3) ranged from 0.06 to 0.2 with an average of 0.07. Data with larger calibration residuals were discarded. High residuals were obtained on windy days because the wire vibrated in the wind.

Much of the error in the absolute measurements probably arose from background reflections within the microwave circuit and from receiver instability. The standard target calibration procedure greatly improved the accuracy of the system, which would have otherwise been extremely poor.

5.2 Accuracy of Absolute Orientation Measurement

Tests were performed on five thin wires with lengths from 2.0cm to 4.0cm in steps of 0.5cm to assess the accuracy of the orientation measurements and of the model parameters (section 5.3). The wires were aligned parallel with the standard target (to within $\pm 1^\circ$), so that their orientation angle θ_1 should have been equal to zero. An example is shown in Figure 5.4. The average value of θ_1 was -0.104° ; the maximum was 2.05° . The value of θ_0' , as measured by the system, was $6.71^\circ \pm 0.81^\circ$ (based on the 95% confidence interval calculated for the data). The orientation accuracy was therefore taken to be the maximum value of θ_1 measured, namely $\pm 2^\circ$. Since the maximum possible resolution of the optical encoder was 0.7° , this degree of angular accuracy was quite good considering the absolute accuracy of the RCS measurements from which it was derived.

5.3 Accuracy of Model Parameters

Model parameter errors affect the RCS curve in different ways, depending on the parameter. An error in θ_1 affects only the orientation of the target and does not affect the size or shape of the RCS curve. However, an error in θ_2 affects the shape of the curve by making it more or less symmetrical. An error in a_0 changes the average

value of the RCS curve but does not affect its shape. Errors in a_1 and a_2 affect the shape of the curve but not its symmetry or average value.

Since model parameters were estimated from the measured RCS data using a LSF, it was difficult to estimate the effect of errors on the results. An experimental assessment of the calculated model parameters was made using data from the thin wire targets mentioned above.

The RCS of a thin wire, σ_{TW} , is equal to

$$\sigma_{TW} = \sigma_{TWm} \cos 4\Phi$$

where σ_{TWm} is the maximum RCS [Crispin and Seigel, 1968]. The model parameters should be:

$$a_0 = 3 \sigma_{TWm} / 8;$$

$$a_1 = 4 \sigma_{TWm} / 8;$$

$$a_2 = \sigma_{TWm} / 8;$$

$$\theta_1 = 0;$$

$$\theta_2 = 0.$$

Although σ_{TW} cannot easily be calculated for thin wires of the order of one wavelength long [Crispin and Seigel, 1968], the ratios of the parameters are well defined:

$$a_1 / a_0 = 1.333,$$

$$a_2 / a_0 = 0.333,$$

$$a_1 / a_2 = 4.0.$$

For the wires measured, the average and maximum values of (a_1 / a_0) were 1.38 and 1.39, corresponding to percentage errors of 3.6% and 4.5% respectively. The average and maximum values of (a_2 / a_0) were 0.39 and 0.40, corresponding to percentage errors of 17% and 20% respectively. These ratios were systematically higher than the theoretical value. The average and minimum values of (a_1 / a_2) were 3.57 and 3.48, corresponding to percentage errors of 11% and 13% respectively. This ratio was systematically lower than the theoretical value.

The RCS curves were ‘flattened’ in the regions where the magnitude of the returned echo was small and so masked by the receiver noise. This has the effect of systematically increasing the value of a_2 relative to a_1 . The RCS curves of small insects were probably affected by this systematic error (see section 7.2.4).

The residual background reflections within the system could affect the model parameters. The effect, which would depend on the phase of the returned echo as well

as the amplitude, would vary for different targets, so increasing the scatter in the parameter measurements.

The measured percentage errors in the parameters a_0 , a_1 and a_2 were less than the measured percentage error in the absolute RCS's of the steel balls. However, the overall accuracy of the measurements of a_0 , a_1 and a_2 must be limited by the accuracy of the absolute RCS measurements from which they were directly derived. Therefore, the percentage errors in the parameters a_0 , a_1 and a_2 were estimated to be as accurate as the steel ball measurements, namely $\pm 25\%$ in absolute value. The relative values of (a_1 / a_0) , (a_2 / a_0) and (a_1 / a_2) were estimated to be accurate to $\pm 5\%$, $\pm 20\%$ and $\pm 13\%$ respectively.

The average and maximum values of θ_2 were 0.26° and 2.38° respectively. The average and maximum values of $(\theta_2 - \theta_1)$ were 0.26° and 0.76° respectively. The accuracy of θ_2 was similar to that of θ_1 and was therefore assumed to be the same, namely $\pm 2^\circ$. Note, however, that if a_1 or a_2 are small and hence highly inaccurate, the associated phase angle will also be inaccurate.

The average residual for the fitted model, A_r , (see section 4.4) was usually very small, with an average value of 0.15 and indicates that the model fitted the data well.

5.4 FSD Curve

A typical FSD curve is shown in Figure 5.5. In general the FSD increased as the RCS decreased. This was due to the receiver response. With small signals, the noise 'band' was quite wide, giving a large FSD. Due to the logarithmic response of the receiver, the noise 'band' becomes narrower as the signal increases, thus reducing the FSD.

The FSD curve of a rejected measurement of a locust is depicted in Figure 5.6. Note that the general shape was similar to that of Figure 5.5 except that it is phase shifted by 90° . This was because, for this target, the minimum and maximum RCS were near $\Phi = 0^\circ$ and $\Phi = 90^\circ$ respectively. The general shape was acceptable. However, the high peak values of the FSD suggest that during the measurement the system null probably drifted. This would cause the low RCS values measured to change during the measurement cycle and so increase the FSD. This measurement was therefore rejected.

The two sharp peaks at $\Phi \approx 35^\circ$ and $\Phi \approx 60^\circ$ resulted from an extraneous object such as a passing insect falling into the absorber horn. Even a small object close to the feed horn can return a large signal, which shows on both the FSD and the RCS curve as an anomalous peak. This did not occur very frequently but such measurements were rejected.

5.5 Modulation of RCS Curve

Many of the curves showed a low amplitude modulation superimposed on the main curve shape, as in Figure 5.7. These modulations resulted from aspect changes as the target was blown by the wind or was vibrated as the ring rotated. The first few targets were suspended in the ring centre by a single nylon line cemented to the thorax. This allowed the insect to rotate about the line and the modulations were therefore more severe. Later, targets were supported by a nylon net, thus reducing aspect changes and modulations. The error introduced by the modulations was not significant since the model fitting procedure had the effect of filtering them out. However, curves showing severe modulations of this type were discarded.

Figure 5.1 Comparison of Measured and Actual RCS

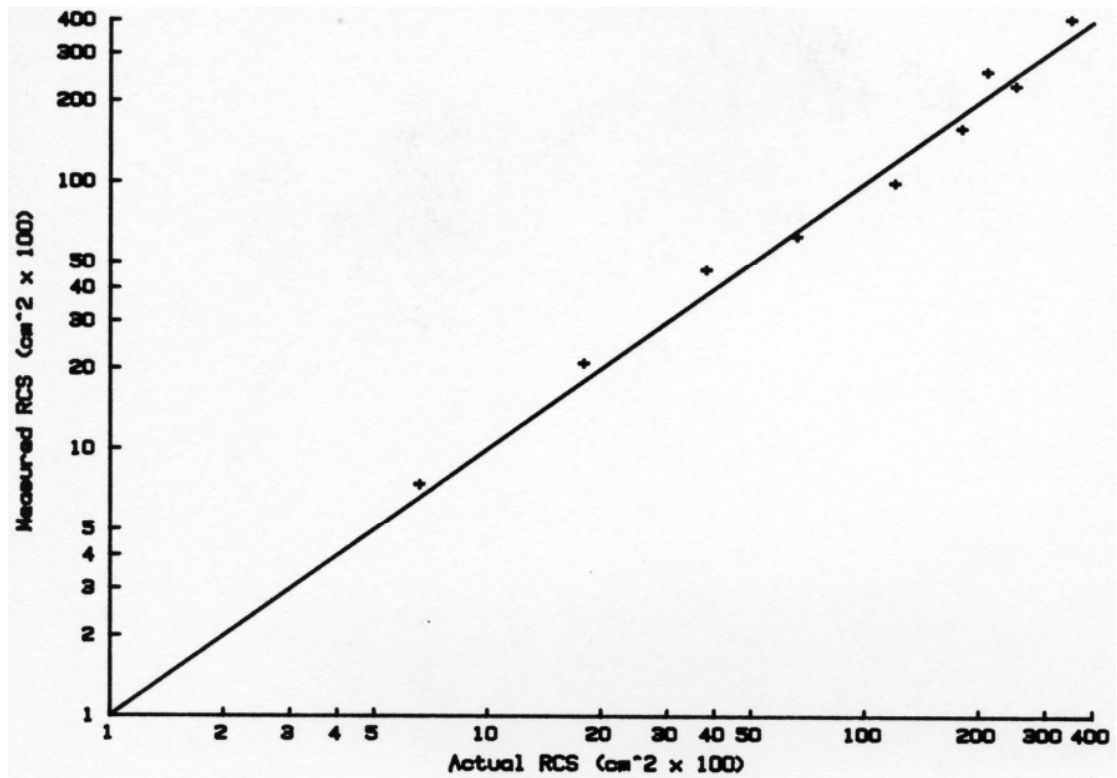


Figure 5.2 Measured RCS of 11.11 mm Steel Ball

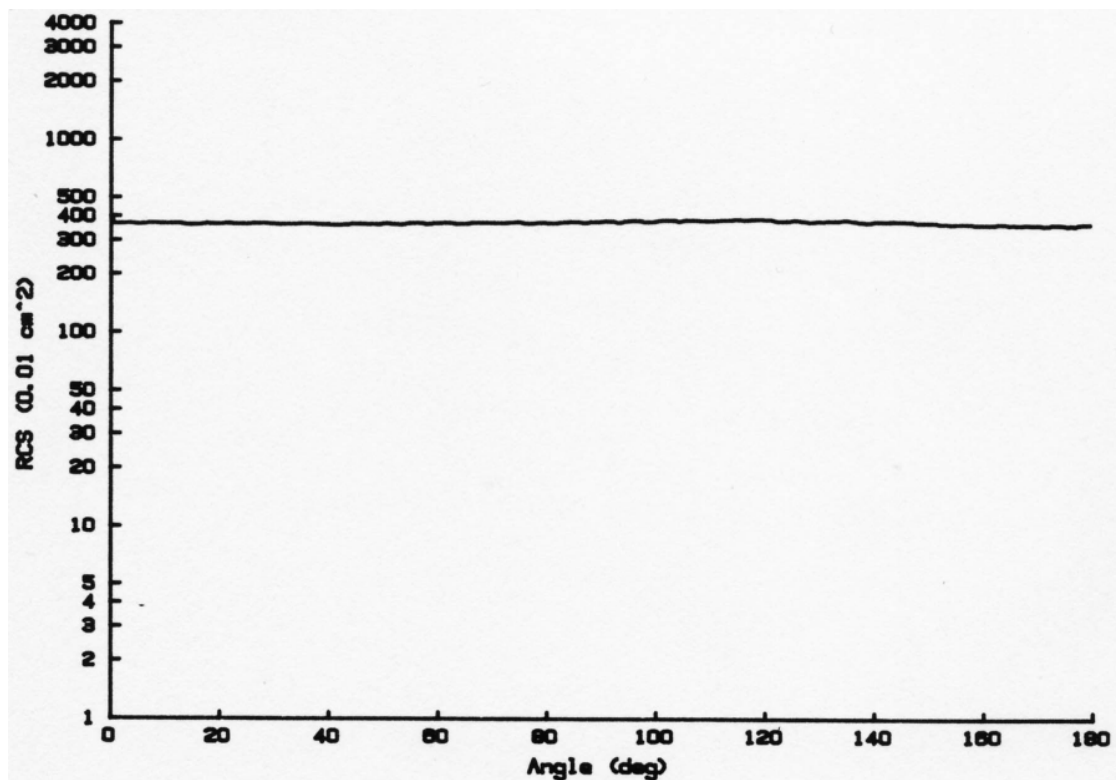


Figure 5.3 Typical Calibration Data and Curve

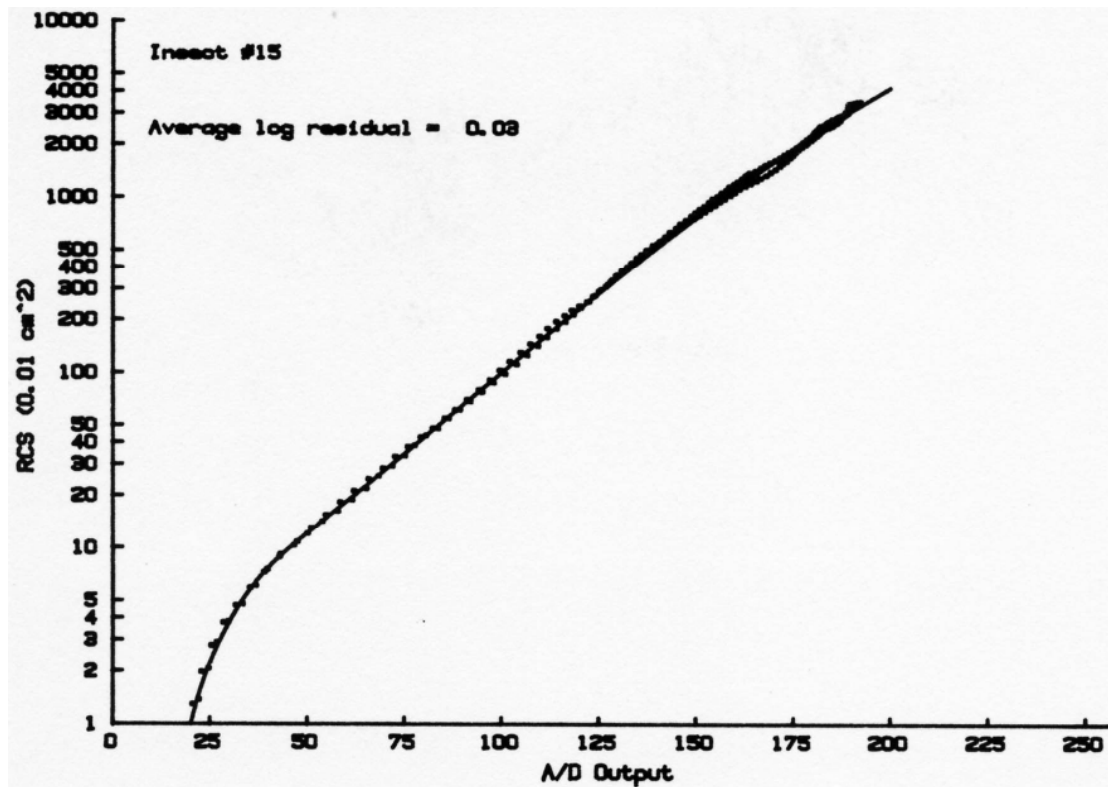


Figure 5.4 RCS Curve of Thin Wire

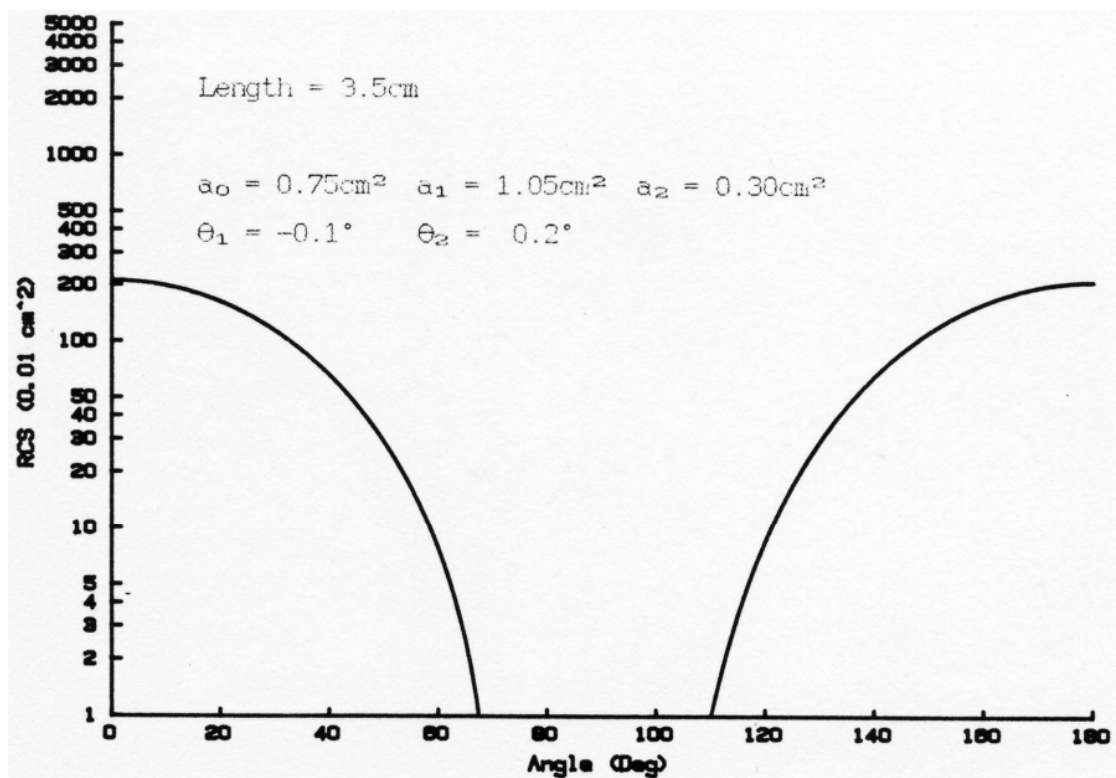


Figure 5.5 Typical FSD Curve

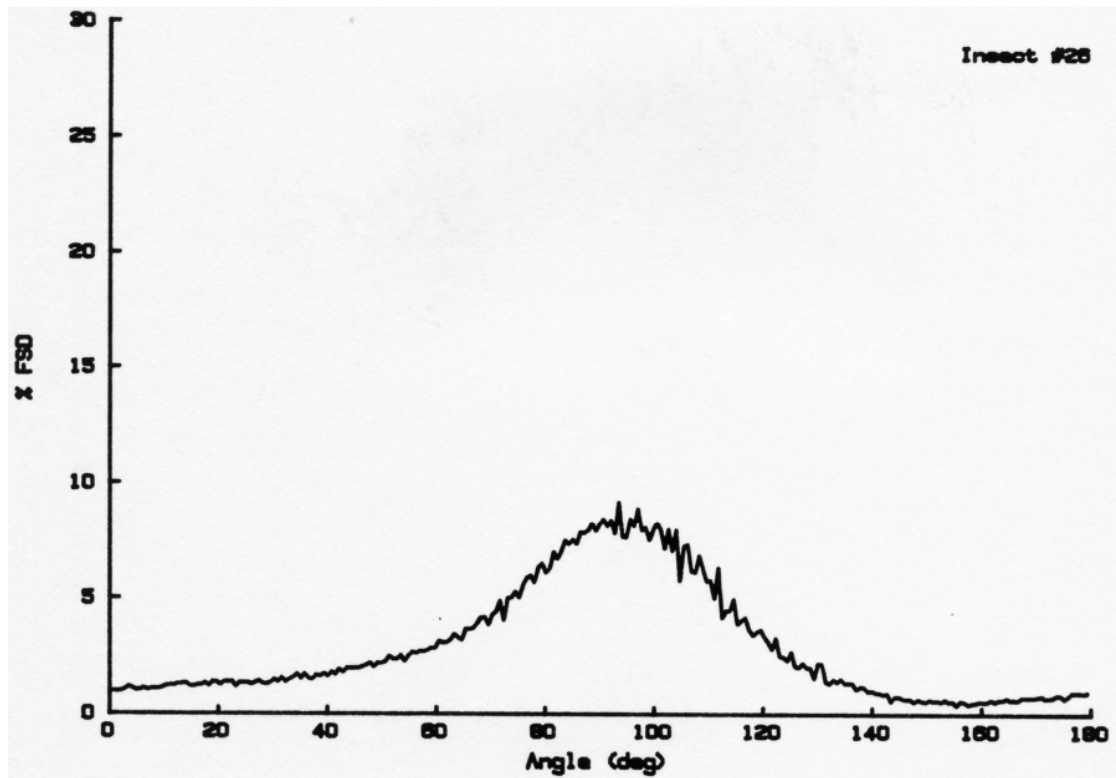


Figure 5.6 FSD Curve of Rejected Measurement

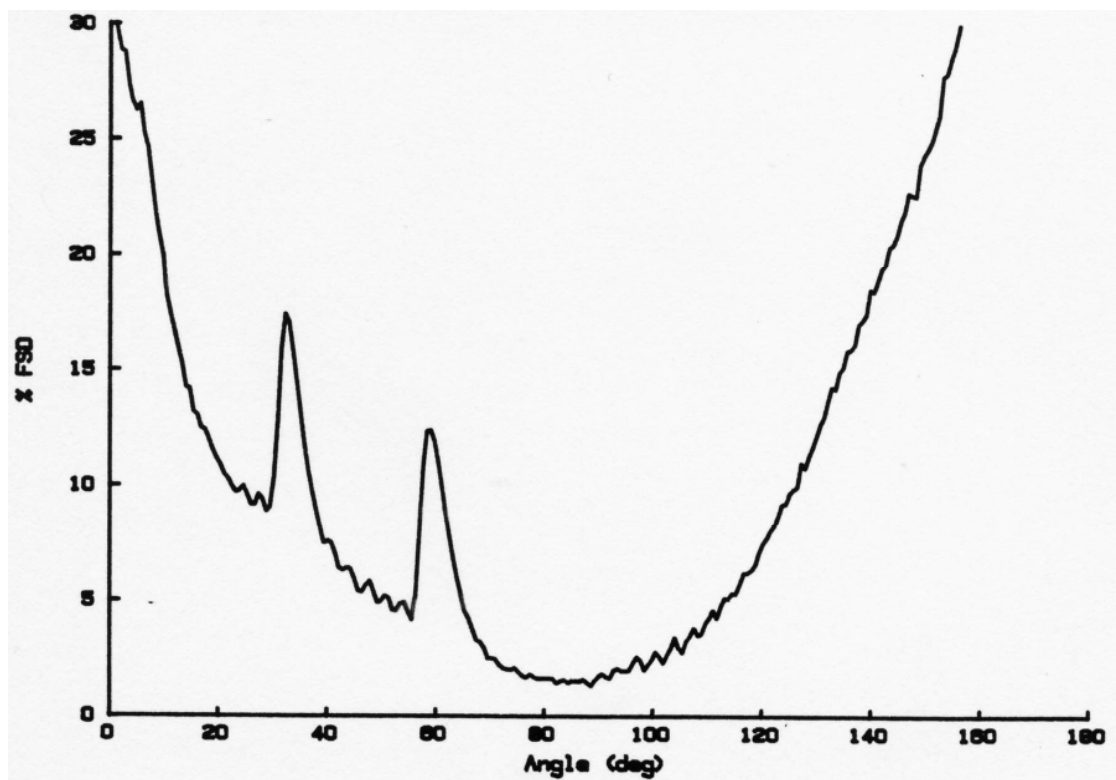
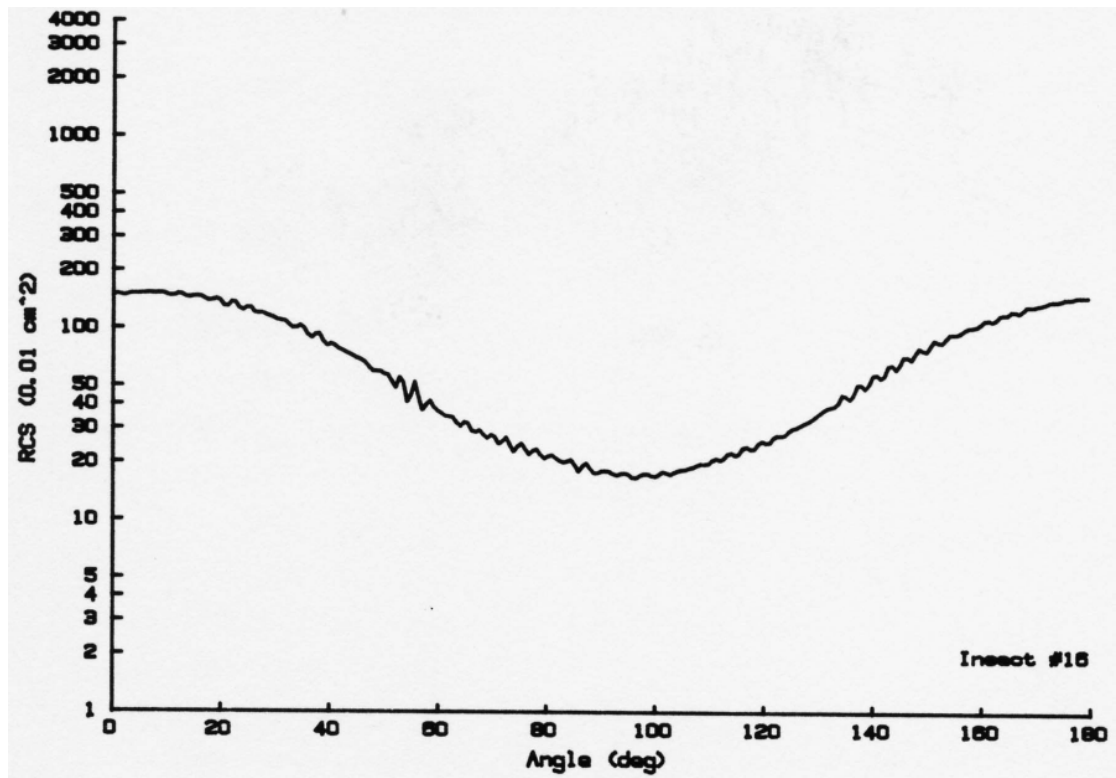


Figure 5.7 Low Amplitude Modulation on RCS Curve



Chapter 6

Experimental Insects

54 specimens representing 18 different insect species were measured using the system. In this chapter their acquisition and treatment are described. Section 6.1 details the species used. Section 6.2 describes the capture and care of the moths and section 6.3 describes the source and care of the other species used. Finally, section 6.4 describes the experimental procedure used to measure an insect target.

6.1 Species Used

For practical reasons, the insect species used either had to be caught in the immediate vicinity, or had to be easy to keep and be readily available from an insect supplier. Within these constraints, a wide range of insect species were selected to represent typical insect shapes and sizes observed by entomological radars. The 18 species are listed in Table 6.1. with their common English name, Latin name, the number of specimens used and the number and symbol used in the following chapter to denote the species on graphs. Full details of each individual used are given in Appendix B.

Table 6.1 Insect Species Used (in approximate order of mass)

Species	Number of Specimens	Species No. & Symbol
<i>Tipula oleracea</i> Linnaeus (Crane Fly)	2	1 (A)
<i>Alcis rependata rependata</i> Liiaeus (Mottled Beauty)	1	2 (B)
<i>Mesapamea secalis</i> Linnaeus (Common Rustic)	1	3 (C)
<i>Chorthippus brunneus</i> Thunberg (Common Field Grasshopper)	7	4 (D)
<i>Noctua janthina</i> Denis & Schiffermüller (Lesser Broad Bordered Yellow Underwing)	2	5 (E)
<i>Hepialus sylvina</i> Linnaeus (Orange Swift)	2	6 (F)
<i>Ochropleura plecta</i> Linnaeus (Flame Shoulder)	1	7 (G)
<i>Xestia xanthographa</i> Denis & Schiffermüller (Square-Spot Rustic)	2	8 (H)
<i>Autographa gamma</i> Linnaeus (Silver-Y)	3	9 (I)
<i>Amphipyra tragopoyinis</i> Clerck (Mouse Moth)	1	10 (J)
<i>Xestia c-nigrum</i> Linnaeus (Setaceous Hebrew Character)	1	11 (K)
<i>Aglais urticae</i> Linnaeus (Small Tortoiseshell)	2	12 (L)
<i>Noctua comes</i> Hübner (Lesser Yellow Underwing)	2	13 (M)
<i>Agrotis exclamationis</i> Linnaeus (Heart & Dart)	1	14 (N)
<i>Noctua pronuba</i> Linnaeus (Large Yellow Underwing)	13	15 (O)
<i>Danaus plexipus</i> Linnaeus (Monarch)	1	16 (P)
<i>Noctua fimbriata</i> Schreber (Broad Bordered Yellow Underwing)	1	17 (Q)
<i>Schistocerca gregaria</i> Forsk (Desert Locust)	11	18 (R)

6.2 Moth Species

Moths were caught using a standard Robinson mercury vapour light trap. The moth trap was sited in long grass in a suburban garden. It was switched on at dusk and switched off and emptied at approximately midnight. Each night about 10 moths were selected on the basis of species. Only one or two individuals of each species were used except for *N. pronuba*. This large moth was extremely common and so several individuals were used to enable a comparison to be made between members of the same species as well as between different species.

Moths were kept overnight in a Watkins and Doncaster insect rearing cage. Sugar solution was available *ad lib* so the insects could feed. Insects were kept for a maximum of 12 hours.

Mainly noctuid moths were caught and so the moths tested were biased towards the 'heavy-bodied' moths.

6.3 Other Species

Several adult specimens of *S. gregaria* were purchased from an insect supplier. They were kept in a heated tank with a 12 hour light/12 hour dark photoperiod and local vegetations was available *ad lib* on which to feed.

The *C. brunneus* and *T. oleracea* specimens were caught in nearby fields and used immediately.

The *D. plexippus* specimen was purchased as a pupa and reared in the laboratory. It was kept in a Watkins and Doncaster insect rearing cage and sugar solution was available *ad lib*.

6.4 Experimental Procedure

To avoid problems of desiccation and damage affecting the RCS measurements, the insects were used live but anaesthetised.

The anaesthetic apparatus consisted of a container with a gas injector (Plate 6.1). Insects were placed inside the container and carbon dioxide gas injected. When the creature was fully anaesthetised, after about 1-3 minutes depending on size, it was removed, weighed, its dimensions recorded (see Figure 4.2) and then measured on the

system using the procedure described in section 3.5. At first, the insects were weighed before anaesthetisation but it was found that they tended to defecate as the gas took effect, thus altering their mass by a small amount. Weighing the insects after they were immobilised eliminated this small error.

Initially, a target insect's thorax was cemented to a nylon line with superglue, the nylon line then being stretched across the ring so that the insect was suspended in the centre. This proved to be unsatisfactory as a target often became detached from the line and targets were very difficult to mount aligned with the body axis exactly parallel to the line. Useful data was collected this way, but the body axis alignment was often incorrect.

In later measurements, the insects were supported upon a net (see section 3.4.1). An insect was placed on the support net with its head towards the 'head-up' mark of the optical encoder so that the alignment of the body axis was parallel with the standard target position. It was difficult to define precisely the position of the body axis and so the alignment of the insects was to within $\pm 5^\circ$.

The error introduced by poor alignment is, in effect, a rotation by an unknown angle. This angle is therefore added to the phase angles θ_1 and θ_2 , but does not affect their difference.

Plate 6.1 Insect Anaesthetic Apparatus



Chapter 7

Results and Discussion

The results of the RCS measurements of the insect targets are presented and discussed in this chapter. The results are described in section 7.1 and discussed in section 7.2. Estimation of target parameters from the RCS data is discussed in section 7.3. Finally, conclusions are drawn in section 7.4.

7.1 General Trends

The target mass is a measure of the general target size and all the RCS parameters varied with it. Plots of the five parameters a_0 , a_1 , a_2 , θ_1 , θ_2 , and $(\theta_2 - \theta_1)$ against target mass are shown in Figures 7.1 to 7.5. These graphs summarise all the data obtained. The original data for the 54 individual specimens are presented in tabular form in Appendix B.

In general, the average RCS over orientation (a_0) of a target was larger than, but within an order of magnitude of, the RCS of an equivalent mass water sphere (EMWS). For comparison, the RCS of EMWSs was also plotted on Figure 7.1. The RCS patterns fell into three classes based on insect mass and are described below.

Example RCS curves are plotted in 'normalised coordinates where $\theta_1 \rightarrow \theta_2$, and $\theta_2 \rightarrow (\theta_2 - \theta_1)$ (see section 2.4).

7.1.1 Insects with Masses Below 250mg

The 29 targets in this mass class were a selection of small noctuid moths, *C. brunneus* and one or two other species. The RCS of EMWSs were in the top end of the Rayleigh scattering region.

The coefficients a_0 , a_1 and a_2 all increased with the mass; a_0 ranged from 0.1cm^2 to 2.4cm^2 , a_1 from 0.1cm^2 to 3.1cm^2 and a_2 from 0.002cm^2 to 0.9cm^2 . The values of the orientation angle θ_1 were within 10° of zero except for five specimens (insect numbers 1, 3, 4, 5, and 25) and at least two of these were known to have been misaligned (insects 1 and 3). Excluding the two misaligned specimens, the average value of θ_1 was -0.3° .

The values of the phase difference ($\theta_2 - \theta_1$) were within 6° of zero, with an average of -0.5° . An exception was insect 3, where a_2 was much smaller than a_1 and so θ_2 was probably spurious.

Generally, the curves, such as the one in Figure 7.6, had a single maximum at $\Phi \approx 0^\circ$, a minimum at $\Phi \approx 90^\circ$ and were approximately symmetrical ($\sigma(\Phi) \approx \sigma(-\Phi)$). The patterns obtained from some of the heavier *C. brunneus* specimens (Figure 7.7) had a small secondary maximum at $\Phi \approx 90^\circ$.

7.1.2 Insects with Masses Between 250mg and 1000mg

There were 15 targets in this class; all except two specimens in this mass class were of the species *N. pronuba*, the other two being individual specimens of *D. plexipus* and *N. fimbriata*. Unfortunately, large moths of other species were rather uncommon and none in the range 650mg – 1000mg were caught. The RCS of EMWSs were at the ‘knee’ in the RCS-mass curve in the lower end of the interference region.

The variation of a_0 , between 1.0 cm^2 and 2.7 cm^2 , was surprisingly small. In contrast, a_0 decreased from 2 cm^2 to 0.2 cm^2 . The third coefficient, a_2 , increased slightly from 0.3 cm^2 to 0.6 cm^2 . The values of the orientation angle θ_1 were within 10° of zero, except for three specimens (insects 38, 41 and 43). Insect 41 was known to be misaligned. For *N. fimbriata* (insect 43) the heaviest insect in this class, $\theta_1 \approx 90^\circ$. The average value of θ_1 (excluding insects 41 and 43) was -2.1° . The values of the phase difference ($\theta_2 - \theta_1$) were within 3° of zero, except for two specimens (insects 32 and 38), which were within 11° . However, for insect 32, a_2 was much less a_1 than and so θ_2 was probably spurious. The average value was 0.5° .

Most of the curves had a maximum near $\Phi \approx 0^\circ$ and $\Phi \approx 90^\circ$ with minima between (Figure 7.8). However, the curves of insects 29, 32 and 42 had only a single maximum and minimum. All the curves were approximately symmetrical, except for the curve of insect 39.

7.1.3 Insects with Masses Above 1000mg

The 11 insects in this class were exclusively *S. gregaria*. The RCS of EMWSs exhibited a deep null across this mass range (see Figure 7.1).

Unlike the RCS of the EMWSs, a_0 increase from 0.8cm^2 to 12.5cm^2 and a_2 0.6cm^2 to 3.2cm^2 . The values of the orientation angle θ_1 were around -90° with an average of -80.9° but were quite widely scattered with the largest deviation being 30° . The values of the phase difference ($\theta_2 - \theta_1$) were also quite widely scattered with an average of -6.8° and a maximum of -20° .

All curves had a primary maximum at $\sim 90^\circ$, a secondary maximum at $\sim 0^\circ$ (except for two insects 50 and 52, which had no secondary maximum) and the modulation was quite shallow. Figure 7.9 shows an approximately symmetrical curve, whereas others (e.g. Figure 7.10) were less symmetrical. (Note that since the curves are plotted in 'normalised coordinates' with θ_1 set to zero, the curve maximum occurs at $\Phi \approx 0^\circ$.)

7.1.4 Summary

The main results are summarised below:

1. The average RCS was generally larger, but within an order of magnitude of, the RCS of an EMWS.
2. Insects with masses below 250mg exhibited simple, symmetrical curves with a single maximum at 0° .
3. Insects with masses between 250mg and 1000mg exhibited more complex, approximately symmetrical curves with a primary maximum at 0° and a subsidiary maximum at 90° .
4. Insects with masses above 1000mg also had complex curves but with the primary maximum at 90° , a subsidiary maximum at 0° and shallow modulation. These curves were often asymmetrical.

7.2 Discussion

The data exhibited a large degree of scatter; more so than can be accounted for by experimental error. Insects have a complex and varied structure and much of the scatter is a reflection of the diversity of the size and shape of targets. Due to the experimental error, it was not possible to compare individual targets reliably. However, the data graphs show many interesting overall trends which are discussed below.

7.2.1 Average RCS

As has been noted above, the average RCS was approximated by the RCS of an EMWS, although the RCS on an EMWS was generally a little too small. Similar results have been obtained by other investigators [Riley, 1985] and confirms that an EMWS is a crude, but surprisingly good, model of an insect as observed by a radar.

7.2.2 Orientation Angle, θ_1

For most of the targets with masses below 500mg, θ_1 was within 5° of zero. This indicates that the orientation for maximum RCS is with the plane of polarisation approximately parallel to the body axis, as has been assumed in various studies [Riley and Reynolds, 1979, 1986; Bent, 1984]. However, above this mass (which was mainly *S. gregaria*), θ_1 was approximately 90° , but there was considerable scatter. For these targets, the orientation for maximum RCS was with the plane of polarisation approximately perpendicular to the body axis.

For a target with a plane of symmetry in the x-z plane, θ_1 will either be 0° or 90° , relative to the orientation of the symmetry plane (see section 2.4). An insect is approximately bilaterally symmetric about its longitudinal axis when viewed from below and thus it is reasonable to expect θ_1 to be near 0° or 90° (relative to its longitudinal axis), as was found. The change from 0° to 90° was probably due to interference effects. As the targets increased in size, $\sigma(0^\circ)$ started to get smaller (which is characteristic of the interference region) while $\sigma(90^\circ)$ was still increasing in size, until $\sigma(0^\circ) / \sigma(90^\circ) < 1$, at which point, θ_1 changed to 90° . It seems likely that as the target gets larger and larger, $\sigma(0^\circ)$ and $\sigma(90^\circ)$ will continue to vary and so $\sigma(0^\circ) / \sigma(90^\circ)$ will alternate between being less than and greater than one.

An asymmetric target has no obvious axis relative to which θ_1 is zero. The approximate symmetry of an insect's body can be disrupted by the positioning of the legs and antennae and also by curvature of the abdomen. This, in turn, may change the value of θ_1 relative to the longitudinal axis of the insect. No attempt was made to arrange the legs or antennae of the target moths when measuring their RCS, although the abdomen was kept straight. Since $\theta_1 < 5^\circ$ for the majority of moths, the data suggests that the leg and antennae position did not greatly affect θ_1 . These limbs probably contribute very little to the overall RCS, since they are very thin, contain

only small muscles [Chapman, 1982] and weight only a small fraction of the total body weight. (The weight of all the legs of a specimen of *N. pronuba* weighing 321mg was 5.4mg, so that the fraction of the body weight contributed by the legs was 0.02.)

S. gregaria however, has very large legs with large muscles in the femur [Chapman, 1982] and are a large fraction of the total body weight. (The weight of the two rear legs of one specimen of *S. gregaria* weighing 3072mg was 326ms so that the fraction of the body weight contributed by the rear legs was 0.1.) The legs will therefore have a considerable RCS and their positions will be critical. Although the legs were placed in approximately flying position for the measurements, it was obviously not possible to place them *symmetrically* and this probably explains some of the scatter in the values of θ_1 obtained. *S. gregaria* have long, flexible abdomens and it was possible for the abdomen to become curved during a measurement.. This curvature would disrupt the approximate body symmetry and could also account for some of the scatter in θ_1 . (Moth abdomens are shorter and less flexible but curvature of the abdomen may explain the large values of θ_1 obtained for some moths.)

7.2.3 Curve Symmetry

Except for the *S. gregaria* specimens, most curves were approximately symmetrical (i.e. $\theta_1 - \theta_2$ was near zero). However, this does not necessarily imply that the scattering matrix of the target is nearly diagonal (in coordinates such that $\theta_1 = 0$), since the method of measuring RCS using a rotating plane of polarisation and parallel reception is insensitive to the depolarising effects of the target (see section 2.4). However, since an insect body is approximately bilaterally symmetrical and the legs are a small fraction of the total body, there is probably little depolarisation and the scattering matrix is likely to be nearly diagonal ($\sigma_{xy} \approx 0$).

Many of the *S. gregaria* curves were not symmetrical, with large values of $\theta_2 - \theta_1$. As noted in section 7.2.2, the large rear legs of these insects probably contribute significantly to the RCS. Since the leg and abdomen positions tend to disrupt the approximate symmetry of the body, there is probably significant depolarisation and the scattering matrix is likely to have a significant off-diagonal component ($\sigma_{xy} > 0$). (It is not possible to estimate the size of σ_{xy} or the phase angle α because the model is insensitive to the off-diagonal component of the scattering

matrix.) Since an asymmetrical target is likely to have a non-diagonal scattering matrix as well as a large value of θ_1 , the latter may be associated with large values of $\theta_2 - \theta_1$, as was found.

A small number of moth targets exhibited large values of θ_1 and $\theta_2 - \theta_1$. They were probably poorly mounted on the support net and had curved abdomens when measured.

7.2.4 Curve Shape

The RCS curves of insects with masses below 250mg (excluding *C. brunneus*) were characterised by a single maximum and minimum. The RCS curves of insects with masses above 250mg (and also *C. brunneus*) were often characterised by dual maxima and minima. (The bodies of *C. brunneus* specimens were relatively long and thin, and the rear legs were relatively large, unlike other species measured in this mass class. It is likely that the differences in shape account for the differences in the RCS curves.) Since the majority of the curves were approximately symmetrical (as discussed in the previous section), it is assumed in further discussion that the off-diagonal components of the scattering matrix (σ_{xy} and α) make little contribution to the parameters of the RCS model and can be ignored.

The criteria for double maxima to occur in a symmetrical RCS curve is:

$$a_1 / a_2 < 4$$

(see section 2.4). A graph of a_1 / a_2 against target mass is shown in Figure 7.11. Below 250mg (and excluding *C. brunneus*, which had anomalous patterns) $a_1 / a_2 \geq 4$ with an average value of 7.0. However, many were near the critical value. Above 250mg and including *C. brunneus*, $a_1 / a_2 \leq 4$ with an average value of 3.2. The data suggests that, for insects with masses below 250mg, the phase angle, β , of the scattering matrix was such that $\cos \beta$ was just larger than $\sqrt{(\sigma_{yy} / \sigma_{xx})}$ (see section 2.4). As such insects increased in size, so β and $\sqrt{(\sigma_{yy} / \sigma_{xx})}$ increased until $\cos \beta < \sqrt{(\sigma_{yy} / \sigma_{xx})}$ and dual maxima appeared.

A possible explanation for an increase in $\sqrt{(\sigma_{yy} / \sigma_{xx})}$ has been described in section 7.22. An increase in β can be explained as follows: the x- and y- components of the reflected wave are derived from the illuminating radiation via different paths around the target (see [Crispin and Seigel, 1968]). For a small target (with respect to wavelength), the ‘path length difference’ between the two wave components will be

small compared to the wavelength. The two components will be in phase ($\beta = 0^\circ$) and the RCS curve will have a single maximum. As the target increases in mass, so the path lengths of the two components increases. Assuming that the path lengths are different and increase in proportion to the target size (i.e. in proportion to $\text{mass}^{1/3}$), the difference between the two will also increase. Thus the two wave components will vary between being in phase (when the path length difference is a whole number of wavelengths) and in antiphase (when the path length difference is a half number of wavelengths). The RCS curve will swap between having a single maximum when the components are in phase to having a double maximum when the components are in antiphase, changing from one to the other when the phase difference reaches the critical value, $\cos \beta_c = \sqrt{(\sigma_{yy} / \sigma_{xx})}$.

Considering the systematic error that was evident in measurements of thin wires (see section 5.3) it is likely that there are systematic errors in the measured values of a_1 / a_2 . Since the low values of RCS tend to be clipped. RCS curves for small targets tend to have ‘flattened’ minima, which tends to force a_1 / a_2 closer to the critical value of four. However, the ratio should be more accurate for large targets which have higher RCS’s, and the general trend of decreasing with a_1 / a_2 increasing mass is probably correct.

7.2.5 Differential RCS

Two parameters that can be simply derived from the model parameters are

$$S_{xx} = a_0 + a_1 + a_2$$

and

$$S_{yy} = a_0 - a_1 + a_2.$$

For a target with a symmetrical RCS curve, $S_{xx} \equiv \sigma_{xx}$ and $S_{yy} \equiv \sigma_{yy}$ (see section 2.4). The estimated error in these parameters was similar ($\pm 25\%$) to that of the model coefficients since they are directly related to σ_{xx} and σ_{yy} , which were measured with this degree of accuracy. The differential cross section, in analogy to the differential reflectivity of weather radar [Seliga and Bringi, 1978] is defined as

$$S_d = S_{xx} / S_{yy}.$$

The estimated error in this parameter was $\pm 50\%$, since it is a ratio. Note that low values of S_{yy} tended to be increased because the system ‘clipped’ low values of RCS

(see section 5.3). Plots of these parameters against target mass are shown in Figures 7.12 and 7.13.

In section 2.4, the X-axis was defined to be such that θ_1 was set to zero. For the majority of targets, this was parallel to the body axis so that the X-dimension was the body length and Y-dimension was the abdomen width. However, for the *N. fimbriata* and *S. gregaria* specimens it was approximately perpendicular to the body axis and so the X-dimension was the abdomen width and the Y-dimension was the body length. The data is presented in this form as this is how it would be measured by a field radar (that obviously cannot know the orientation of the x-axis to the body axis).

It can be seen that there is a dip in S_{xx} as mass increases. Clearly, this dip is due to interference region scattering effects, which could be expected since the X-dimension is of the same order as the wavelength.

The S_{yy} graph shows no similar dip but increases smoothly. This indicates Rayleigh scattering, although the curve shows that it is at the top of the region. This is consistent with the Y-dimensions which were generally smaller than the wavelength. (Note that for the *N. fimbriata* and *S. gregaria* specimens, the Y-dimension, the body length, was much larger than the wavelength. However, S_{xx} for these species, where the X-dimension was the abdomen width, fitted well onto the S_{yy} trend and were consistent with the Rayleigh scattering interpretation.)

Despite the large error of S_d , a relationship with mass is shown in Figure 7.14. The *S. gregaria* specimens appear anomalous because, by definition, $S_{xx} \geq S_{yy}$ which means that, for all except the *N. fimbriata* and *S. gregaria* specimens, S_{xx} and S_{yy} were associated with parallel and perpendicular polarisation but this was reversed for the other specimens. (For *N. fimbriata*, S_d was near one and so not obviously anomalous.) If a new differential cross section is defined such that the numerator is the parameter associated with parallel polarisation and the denominator is the parameter associated with the perpendicular polarisation:

$$S_D = S_d = S_{xx} / S_{yy}, \theta_1 \approx 0^\circ$$

$$1/S_d = S_{yy} / S_{xx}, \theta_1 \approx 90^\circ$$

(this affects insects 43-54 which are *N. fimbriata* and *S. gregaria* records) then a straight line is evident (Figure 7.15). A straight line LSF of $\log S_D$ against $\log m$

(where m is the mass in mg) was performed. The resulting line, drawn on Figure 7.15, was

$$\log S_D = 3.22 - 1.08 \log m$$

It must, however, be appreciated that this line requires knowledge of θ_1 relative to the body axis which is not directly available to a field radar.

The relationship with mass could be a spurious result due to the particular set of insects measured or the measuring system itself. The set of insect species used exhibited a wide range of body sizes and shapes. It seems unlikely that such a strong relationship over such a large range could be an artefact of the set of insects used. The most likely fault in the measuring system that could give rise to an apparent relationship between S_D and mass is the systematic clipping of small values of RCS. This would mainly affect the small values of S_{yy} . However, if this were so, the slope of the line would be positive, not negative. It is therefore highly likely that the relationship between S_D and mass is not spurious.

A plot of S_d against axial ratio (defined as body length divided by abdomen width) reveals no clear relationship (Figure 7.16). The scatter is so large that it can't be accounted for by the error in S_d . A plot of the mass adjusted differential cross-section S_D' , where

$$\log S_D' = \log S_D - 3.22 + 1.08 \log m$$

against axial ratio (Figure 7.17) still shows no obvious relationship. Clearly, S_d is insensitive to the axial ratio in the interference region. Obviously the axial ratio effects the differential cross section but, at least in the low interference region, its effects are completely dominated by the overall mass of the target.

7.3 Estimation of Target Parameters from RCS Curves

The results show that the RCS of an insect target is a complex function of the insect's construction and is highly variable and complex. The possibility of using the RCS pattern to estimate the target orientation, mass, axial ratio, the likely effect of aspect variations and field conditions on measurements and hence the capability of identifying insect targets are now discussed in detail.

7.3.1 Orientation

In all cases, an orientation angle (with an ambiguity of $\pm 180^\circ$) was easily obtained. This ambiguity cannot be resolved from the RCS parameters alone. However, using other information such as the direction of displacement of the target, the correct heading can often be resolved [Riley and Reynolds, 1986].

In this data, θ_1 was measured with respect to the insect body axis and it was found that, in general, θ_1 was either near 0° or 90° . Using a vertically pointing radar, θ_1 is measured relative to a ground direction and it is assumed that θ_1 is 0° with respect to the body axis. A potential error of 90° is therefore made with some of the larger targets. If the curves exhibit dual maxima (i.e. $a_1/a_2 < 4$), the average RCS is above 2.5cm^2 and the differential cross section is less than 10, then the measured orientation must be used with caution and checked using other available information, such as the target displacement direction.

The average value of θ_1 , excluding misaligned targets and specimens of *N. fimbriata* and *S. gregaria*, was -0.9° with 95% confidence limits of $\pm 7.2^\circ$ [Sokal and Rohlf, 1981]. The data therefore indicates that orientation can be measured using vertical rotating dipole antennas to $\pm 8^\circ$ accuracy. Inaccuracies arise from the curvature of the insect body and, in the case of insects with large limbs, from the limb position.

7.3.2 Mass

The curve of the RCS of an EMWS could be used to estimate the mass of a target from its average RCS. However, as can be seen from Figure 7.1, it can only be within a factor of five and would tend to overestimate the mass. However, it is likely that this would improve for small (Rayleigh region) targets.

In the mass range studied (40mg – 4000mg), a better mass estimator was constructed using a_0 . A simple LSF parabola was fitted to $\log a_0$ (where a_0 is in cm^2) against $\log m$ (where m is the mass in mg) (Figure 7.18):

$$\log a_0 = -3.62 + 2.22 \log m - 0.262 (\log m)^2.$$

The inverse of this curve is

$$\log m = 4.24 - \sqrt{(4.17 - 3.82 \log a_0)},$$

and gives an estimate of the mass to within a factor of three, in the valid range $0.1\text{cm}^2 < a_0 < 10\text{cm}^2$, based upon the 95% confidence limits of a predicted value of a regression curve [Sokal and Rohlf, 1981]. (A LSF parabola of the form $\log m = f(\log a_0)$ was calculated but it was found that low values of m corresponded to two values of a_0 . The curve was therefore rejected.)

An alternative estimator is S_{yy} . The LSF parabola of $\log S_{yy}$ (where S_{yy} is in cm^2) against $\log m$ (where m is in mg):

$$\log m = 2.54 + 0.766 S_{yy} + 0.179 (\log S_{yy})^2.$$

(Figure 7.19) valid in the range $0.01\text{cm}^2 < S_{xx} < 10\text{cm}^2$, also gives a mass estimate to within a factor of three, based upon the 95% confidence limits, as above.

Measuring the absolute value of RCS in the field with a radar is often a problem. A given value of received radar power could be due either to a large target at the edge of the illuminating beam, or a small target in the centre of the beam. This potentially large error makes estimation of the target mass very unreliable. However, nutating beam radars that can determine the position of the target within the beam and so correct for beam illumination can reduce this error considerably [Bent, 1984].

The differential RCS, S_D , is also related to the mass (see Figure 7.15). However, using this line to estimate the mass of the target faces many problems. Differential RCS is based upon a ratio of two parameters of the RCS model and therefore suffers from twice the percentage error of a single parameter and there is considerable scatter about the fitted straight line. Finally, S_D requires some knowledge of θ_1 relative to the insect longitudinal body axis. Although this can be estimated from the heading of the insect and the curve shape, it adds further uncertainty to the mass estimate. However, since a ratio is required to estimate S_D , the absolute values of the RCS model parameters are not required. The ratio can be found using ordinary radar without correcting for the target's position in the radar beam and so could provide an order of magnitude mass estimate when no other was possible.

7.3.3 Axial Ratio

A simple measure of a target shape is its axial ratio. From theory, it is clear that the RCS curve is dependent on the axial ratio. For example, the RCS curve of a sphere (axial ratio = 1) is independent of the polarisation (so that $S_d = 1$) while the RCS curve of a thin wire (axial ratio = ∞) is proportional to $\cos^4 \theta$ (so that $S_d = \infty$). It

was hoped that a simple empirical relationship could be found between the axial ratio and S_d to enable the axial ratio of the target to be estimated. Unfortunately, as shown in section 7.2.5, this was not the case for insects in the target range presented.

Wing beat frequencies that sometimes modulate the RCS's of flying insects are due to the variations in body shape and not directly to the wings (which have negligible RCS) [Schaefer, 1976]. This indicates that the RCS's of insects are very sensitive to small changes in body shape. It is therefore likely that the effect on RCS of body shape overwhelms the effect of aspect ratio. It is also possible that the scattering matrix (and hence RCS) of a body is a complex function of the aspect ratio in the interference region, since this is a characteristic of Mie scattering. It is therefore unlikely that the aspect ratio of insects, which are of the order of the radar wavelength in size, can be estimated easily from the RCS curve.

7.3.4 Effect of Aspect

The RCS system described in this thesis was not capable of measuring the variation of RCS with aspect. However, published data of measurements of insect RCS's at varying aspects offer some insight. Data from measurements of the aspect dependence of the RCS of two locust species and a moth (using horizontal polarisation) [Riley, 1973] and a range of insect species (using both horizontal and vertical polarisation) [Schaefer, 1976] are reproduced in Figures 1.1 and 7.20. Although this data is for insects viewed horizontally, since the body shape is quite similar when viewed horizontally or vertically, the aspect dependence of the insect RCS when viewed vertically probably shares similar features to the aspect dependence when viewed horizontally. (However, the detail will probably be different.)

A vertically pointing radar views insects approximately 90° to the longitudinal body axis (i.e. 90° on the data in Figures 1.1 and 7.20). The RCS of smaller, moth targets, were fairly insensitive to aspect variations about 90° , changing by $<20\%$ for an aspect change of $\pm 10^\circ$. This suggests that variations from horizontal of flying moths will not greatly affect the RCS, as measured by a vertically pointing radar. Data derived from theoretical calculations of the aspect dependence of the scattering matrix of prolate spheroids supports this premise (see Figure 7.21 and Table 7.1). (Note that the refractive index of the spheroids was that of ice and was therefore probably

different from that of insects.) However, the RCS of the larger, locust targets was sensitive to variations about 90° , changing by up to 80% for an aspect change of $\pm 10^\circ$. This suggests that variations from horizontal of flying locusts will greatly affect the RCS, as measured by a vertically pointing radar.

The size difference between the two types of target probably accounts for the different aspect behaviour. Small moths with body sizes in the high Rayleigh scattering region exhibit relatively smooth variations of RCS with aspect. However, locusts, which have body sizes in the interference scattering region, exhibit rapid and complex variations of RCS with aspect that are characteristic of scattering in this region.

7.3.5 Field Measurements

In the field, flying insects are subjected to wind and air turbulence and actively manoeuvre to accommodate conditions. These movements will change the viewing aspect and the shape of the insect, so affecting the RCS measured by the radar. If the frequency of rotation of the radar antenna dipole (which rotates the plane of polarisation) is slow compared to the rate of change of viewing aspect or body shape, the RCS is likely to change dramatically during a single revolution, causing large errors in the model parameters derived from the data. Vertically pointing radars are used because insects tend to fly in a constant, horizontal plane, thus minimising aspect variations. However, the rotation rate should be fast enough so that the movement of a target during a complete rotation is negligible.

Current radars have dipole rotation rates of approximately 10kHz, so the target must be approximately stationary for a period of the order of 0.1s. Since the RCS of targets with body sizes in the Rayleigh region are not sensitive to aspect changes around 90° to the body axis (see section 7.3.4), the small changes that may occur in a period of 0.1s probably will not affect the model parameters derived from such data, especially if data from several revolutions is averaged. However, the RCS of targets with body sizes in the interference region is highly sensitive to aspect changes; a small change in aspect can make an enormous change in RCS. It is therefore likely that even the small aspect variations that occur in 0.1s may greatly affect the RCS, causing inaccuracies in the model parameters derived from the data. Averaging may improve the accuracy, but it is unclear if such an average would be unbiased,

considering the dramatic and complex changes that can occur for small changes in aspect.

The model parameter that can be most accurately determined the orientation angle, θ_1 . This is because it describes the overall *phase* of the pattern, i.e. the orientation of the absolute maximum and minimum. Even if the pattern is considerably distorted due to aspect variations, provided the orientation of the absolute maximum and minimum is preserved (as it usually is), the phase can be recovered. The model function can be regarded as a Fourier series, with θ_1 as the phase of the *fundamental component* of the function. Distortions will add higher harmonics but will generally change the phase of the fundamental by only a small amount. However, care must be taken when interpreting the value of θ_1 for large insects, since the angle may not correspond to the orientation of the body axis (see section 7.3.1).

7.3.5 Target Identification

The above discussion implies that the RCS curve provides a direct measure of target orientation and mass, but not axial ratio. Obviously, the target orientation gives no inherent indication of the target species. Figure 7.22 is a chart of the range of a_0 for every species measured (in approximate order of increasing mass). The overlap between species shows that the average RCS differentiates poorly between species. Targets can be assigned to a broad mass class (e.g. to within a factor 3) and can be used to differentiate between targets of significantly different masses (e.g. between *H. sylvina*, mass ~100mg and *N. pronuba*, mass ~ 400mg, a factor of 5 difference in mass).

The wing beat frequency that is often observed to modulate the returned echo has been suggested as a possible parameter to help identify the target species [Schaefer, 1976]. However, again there is much species overlap and intraspecific variability and the wing beat frequency is, itself, correlated with mass [Greenwalt, 1962].

Separately, then, the RCS curve parameters and the wing beat frequency can only differentiate between species that differ considerably in mass. Thus if, for example, only one or two species are present that differ significantly in mass, radar could easily differentiate between them. However, if many species of insect are

present, it would not be possible to distinguish between species of similar mass, but it may be possible to differentiate between groups of species with significantly different masses.

However, when all the parameters are used together, single species or families of species may tend to cluster with similar values of all the parameters. Discriminant function analysis can take advantage of these clusters [Sokal and Rohlf, 1981]. A linear function of the parameters (called the *discriminant function*) can be constructed that generates a characteristic value for each particular cluster and distinct values for each separate cluster. The discriminant function can then be used to indicate to which cluster a particular individual belongs, based upon its parameter values. However, this approach requires data from many individuals of each species and could not be applied to this data.

7.4 Conclusions

The following conclusions can be drawn:

1. Useful information about insect targets can be extracted from the RCS although it is complex and highly variable.
2. The orientation of an insect can be measured to within $\pm 8^\circ$, with an ambiguity of 180° . Large insects will sometimes have an error of 90° but the RCS pattern usually enables such cases to be recognised.
3. Within the mass range measured (40mg – 4000mg), an estimate of the mass, m (measured in mg) to within a factor of three can be obtained from a_0 (measured in cm^2) via the function

$$\log m = 4.24 - \sqrt{(4.17 - 3.82 \log a_0)}, 0.1\text{cm}^2 < a_0 < 10 \text{ cm}^2$$

or S_{yy} from (measured in cm^2) via the parabola

$$\log m = 2.54 + 0.766 S_{yy} + 0.179 (\log S_{yy})^2, 0.01\text{cm}^2 < S_{yy} < 10 \text{ cm}^2$$

4. No reliable estimator of the axial ratio of an insect target was found.
5. The data suggests that individual RCS curve parameters can be used to assign the target to a broad mass class (i.e. within a factor of 3) and can differentiate between insect targets that differ significantly in mass (e.g. a factor of 5 or more).

Figure 7.1 Graph of a_0 Against Mass

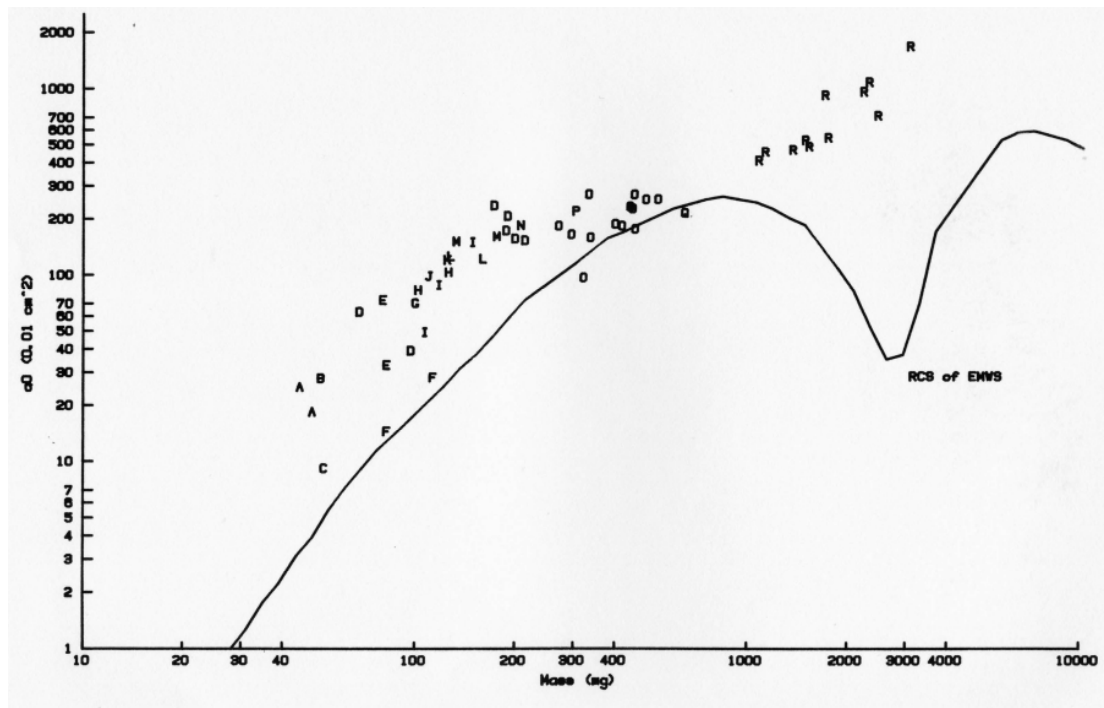


Figure 7.2 Graph of a_1 Against Mass

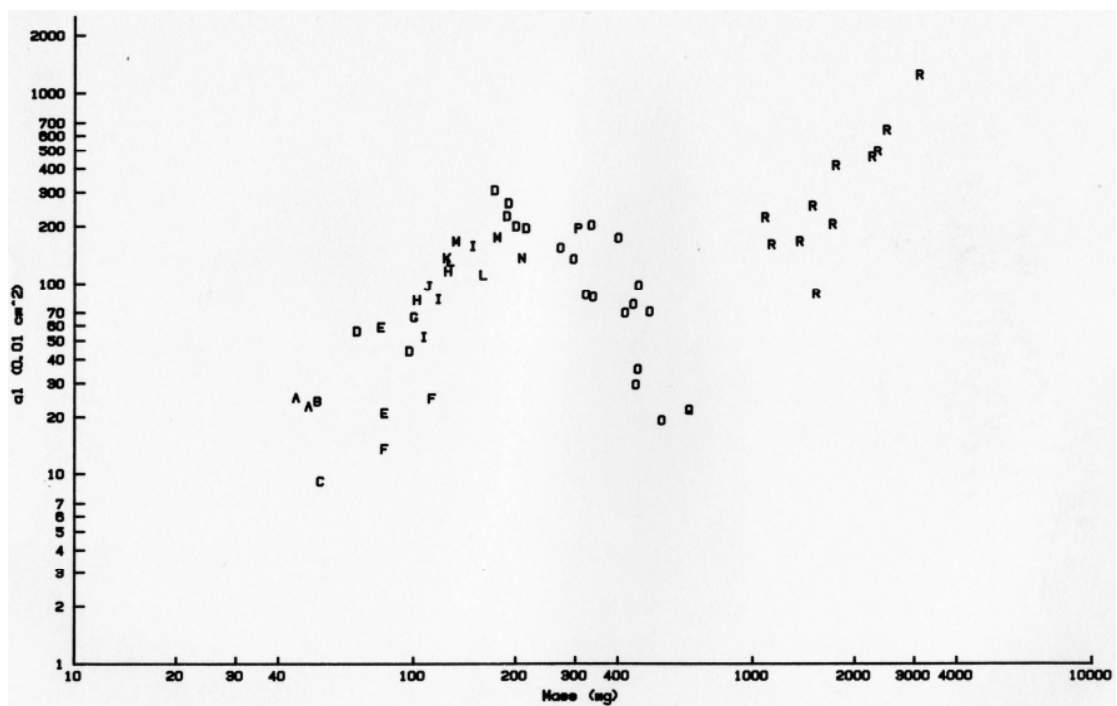


Figure 7.3 Graph of a_2 Against Mass

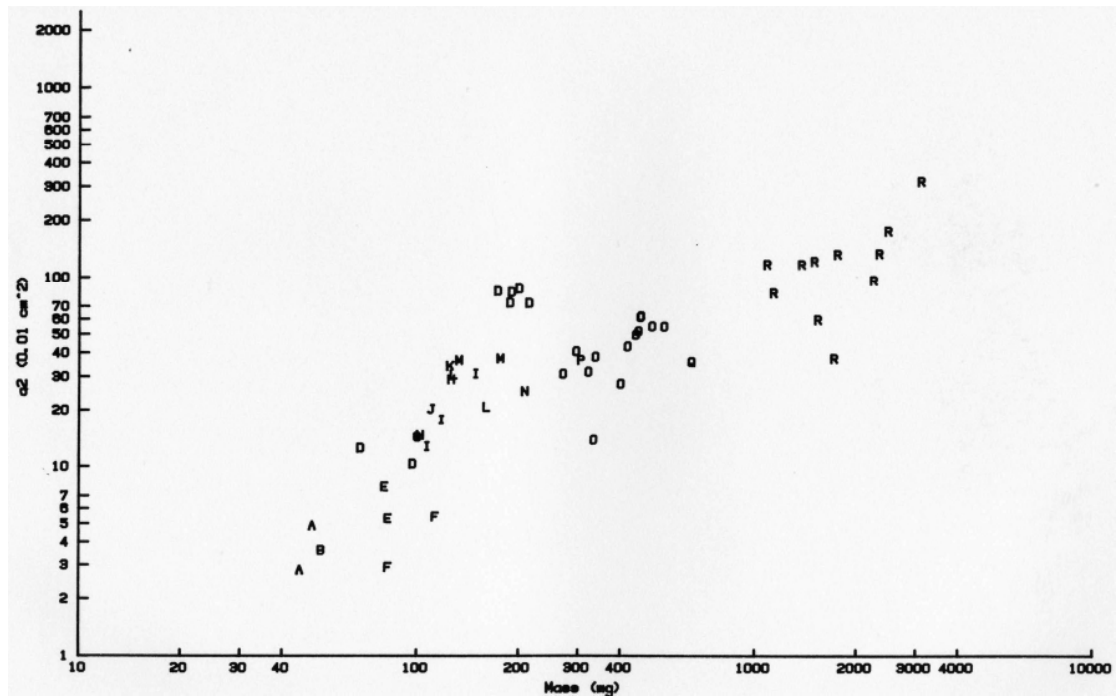


Figure 7.4 Graph of θ_1 Against Mass

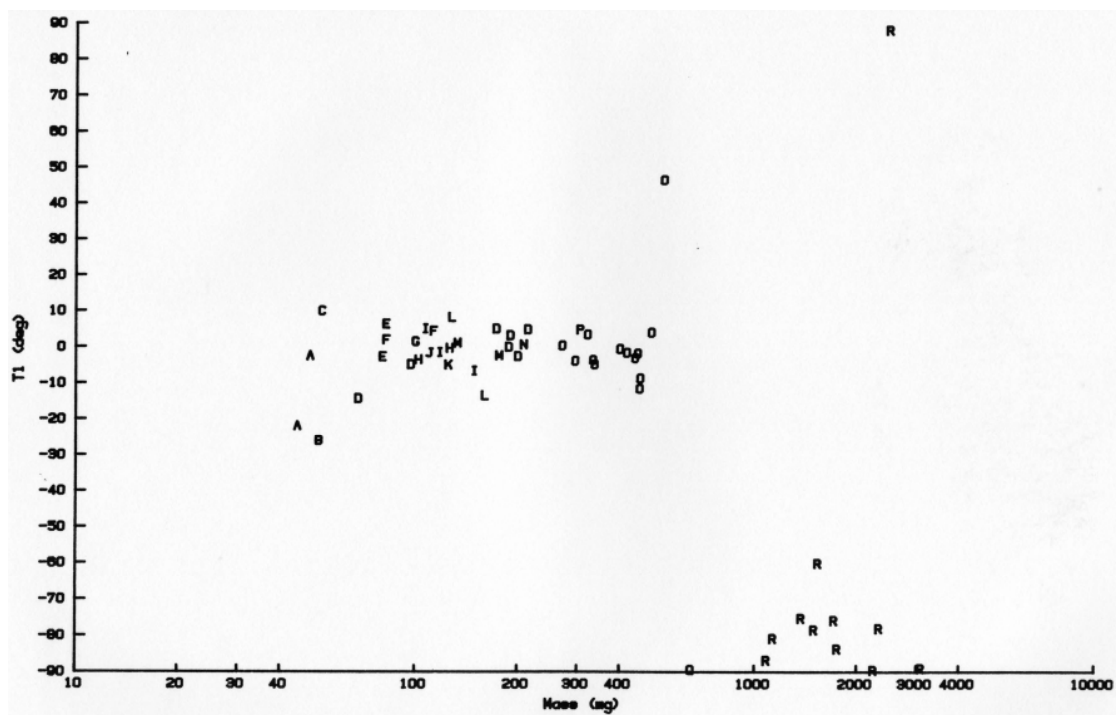


Figure 7.5 Graph of $(\theta_1 - \theta_2)$ Against Mass

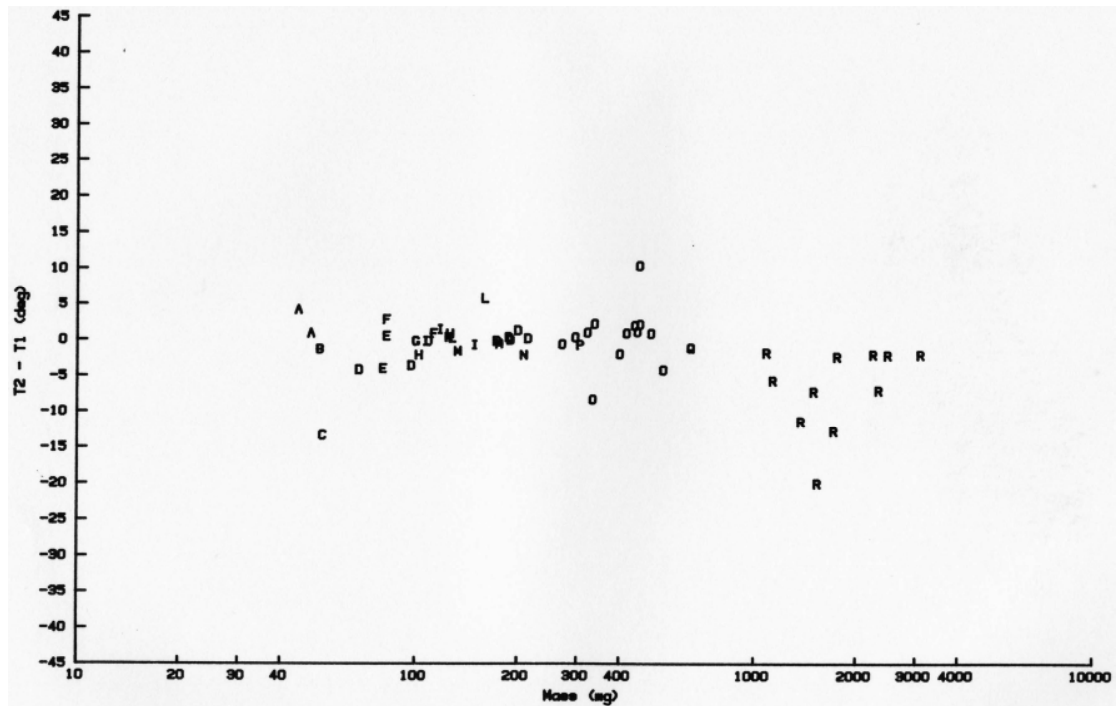


Figure 7.6 RCS for Target Mass < 250 mg

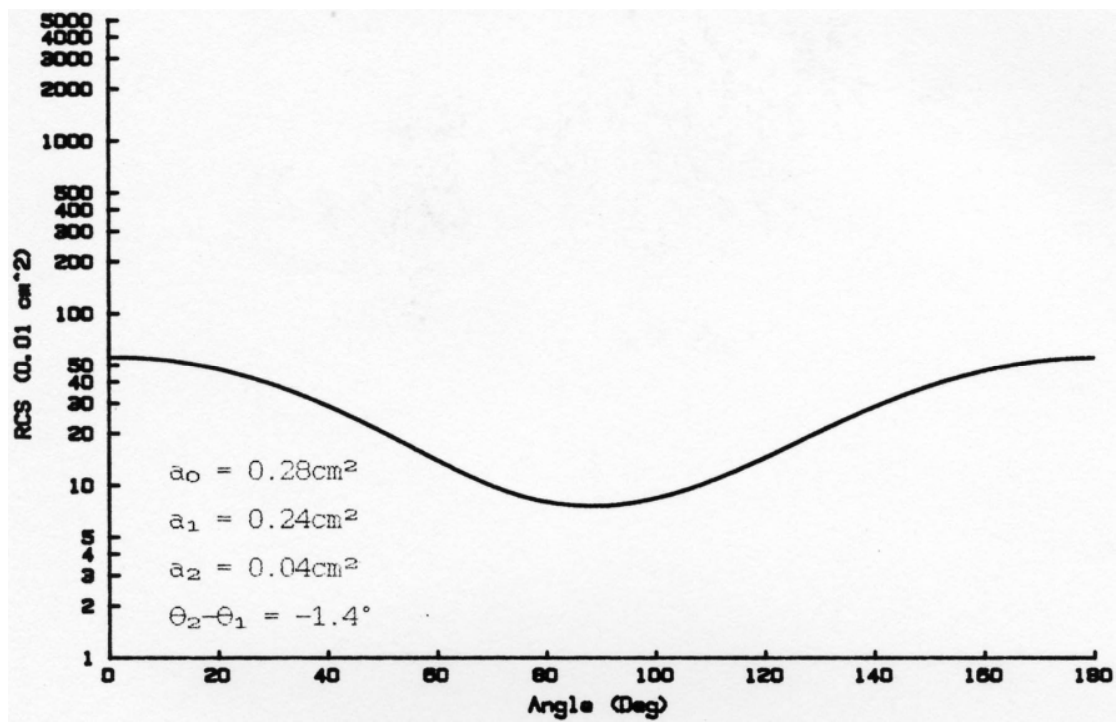


Figure 7.7 RCS of *C. brunneus*

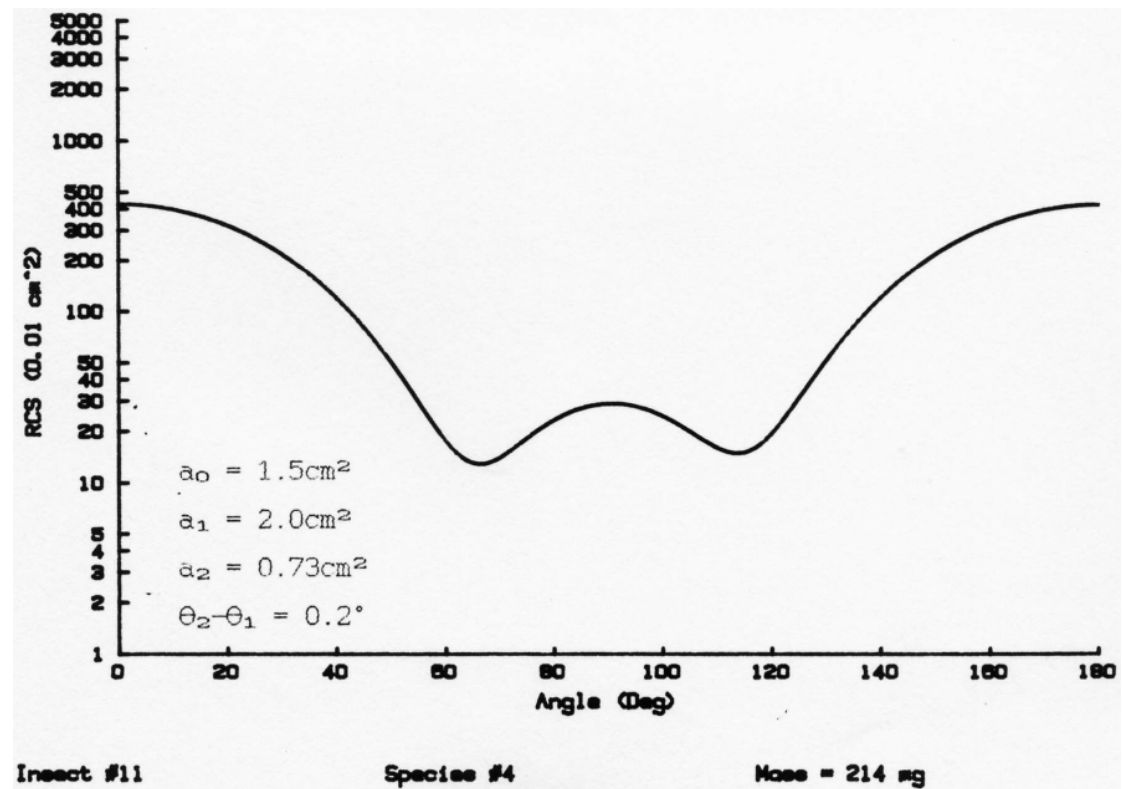


Figure 7.8 Graph of RCS when $250\text{ mg} < \text{Target Mass} < 1000\text{ mg}$

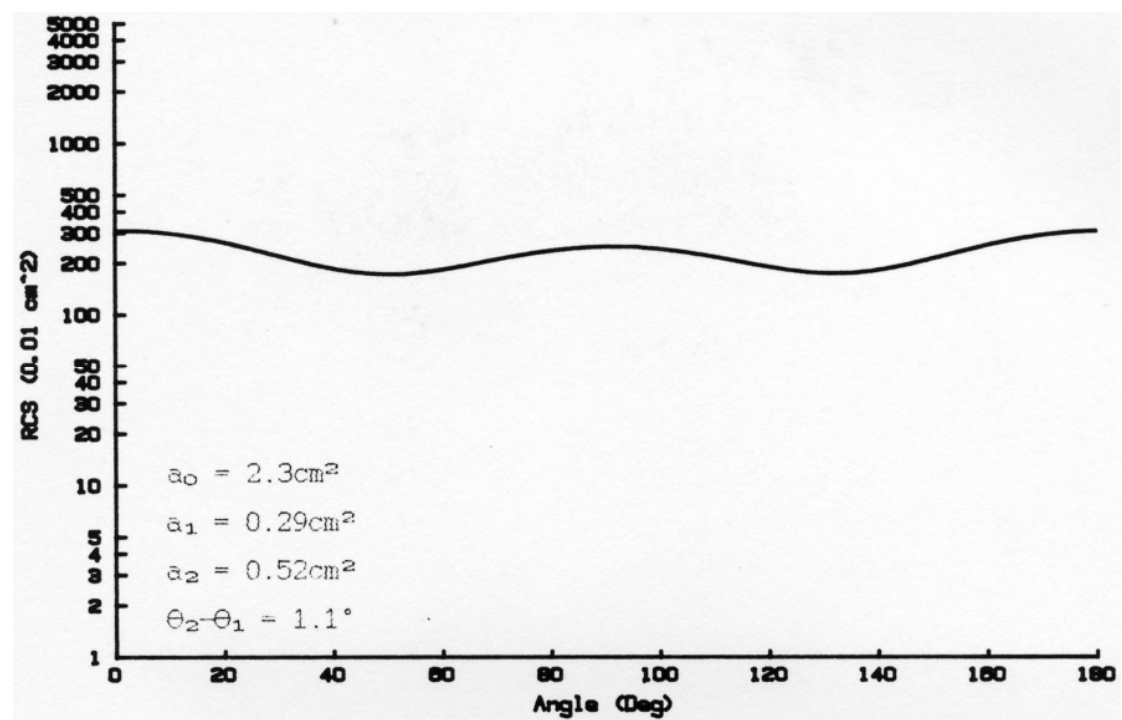


Figure 7.9 Symmetrical RCS when Target Mass > 1000 mg

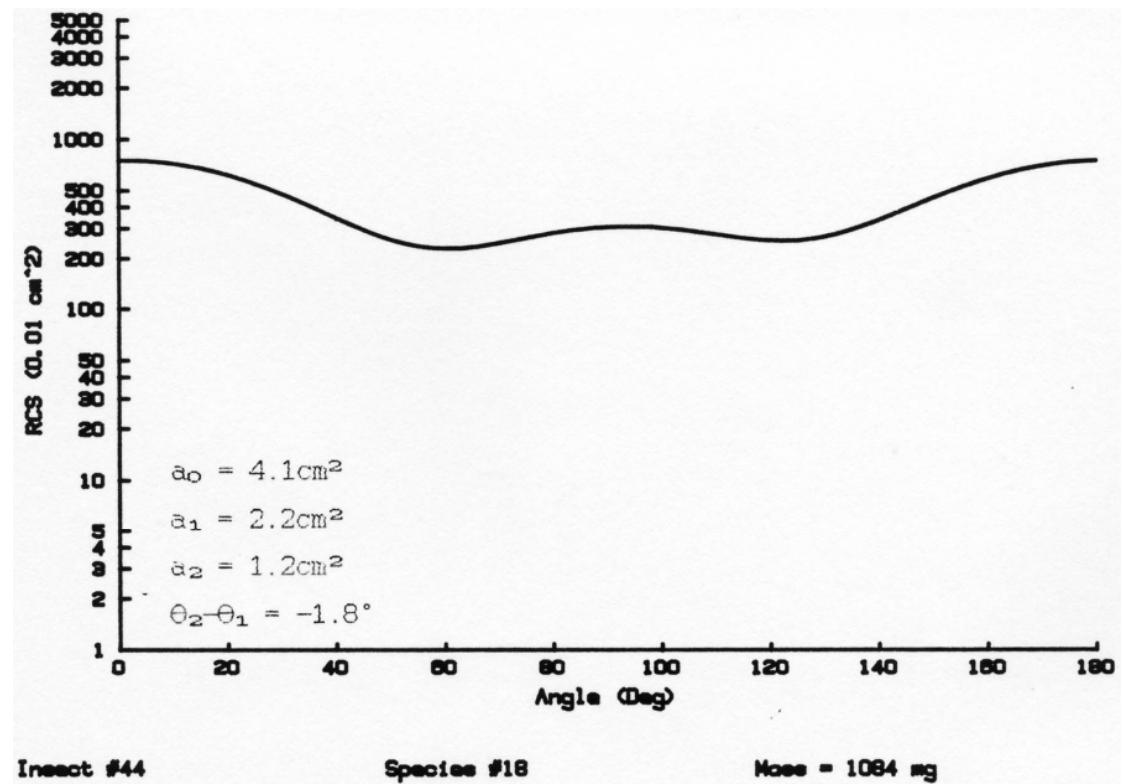


Figure 7.10 Asymmetrical RCS when Target Mass > 1000 mg

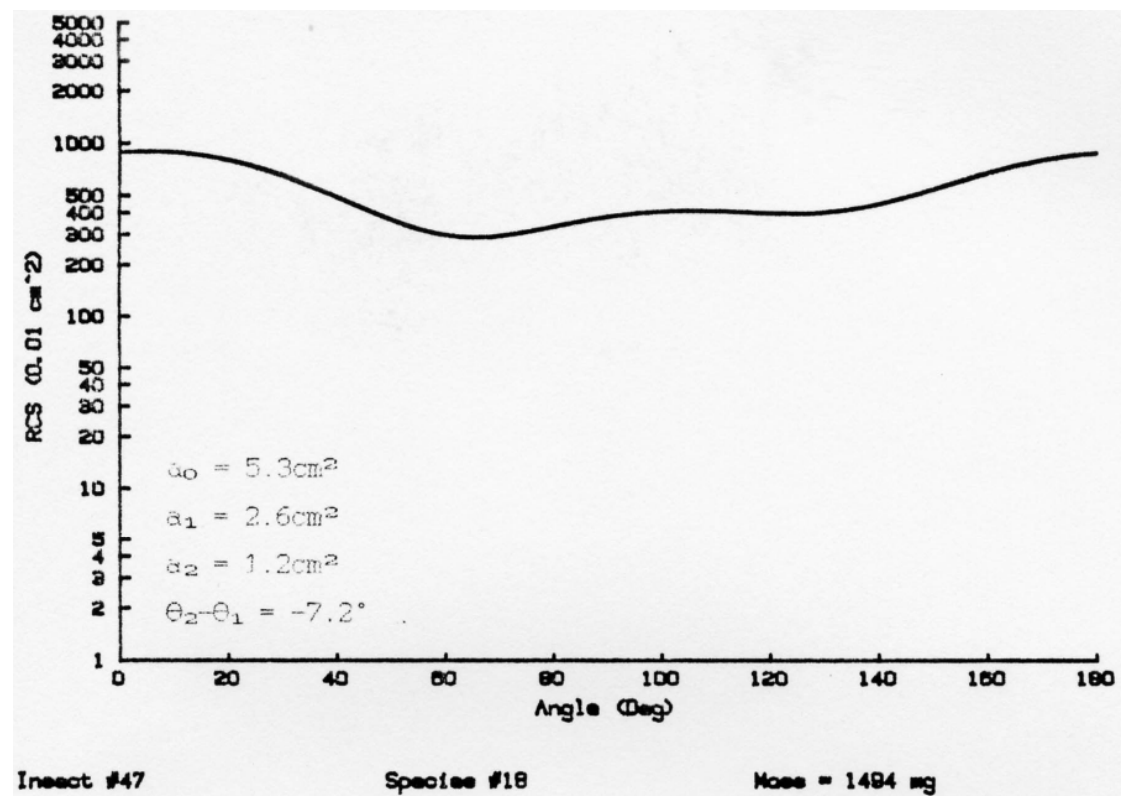


Figure 7.11 Graph of (a_1 / a_2) Against Mass

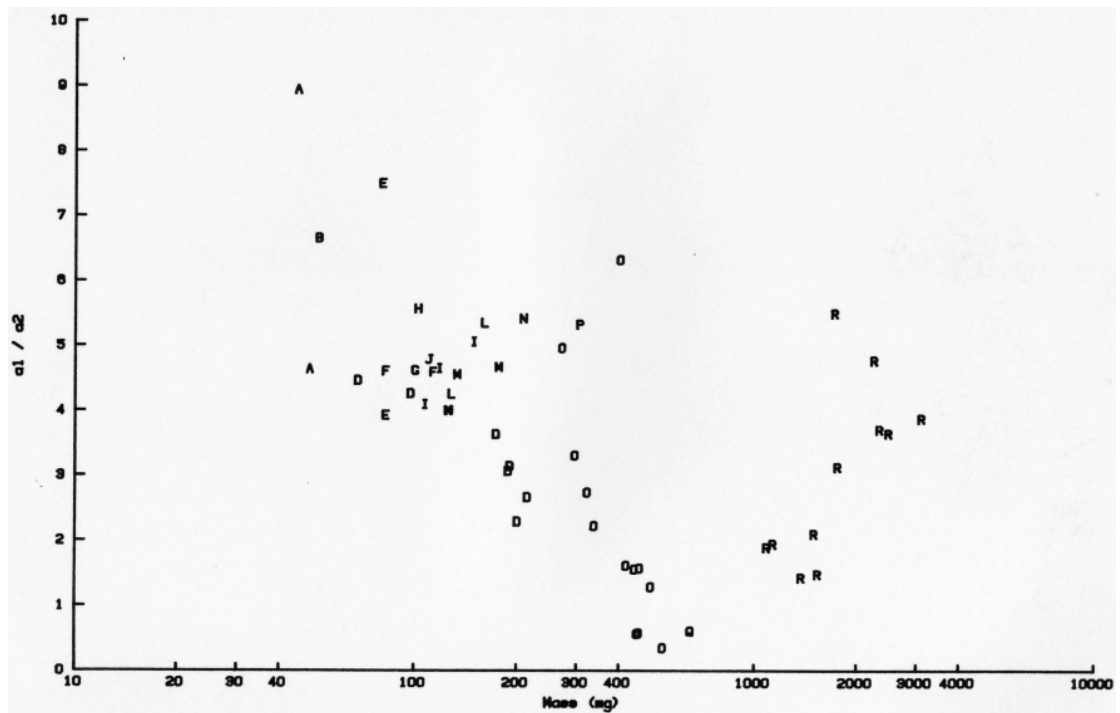


Figure 7.12 Graph of S_{xx} Against Mass

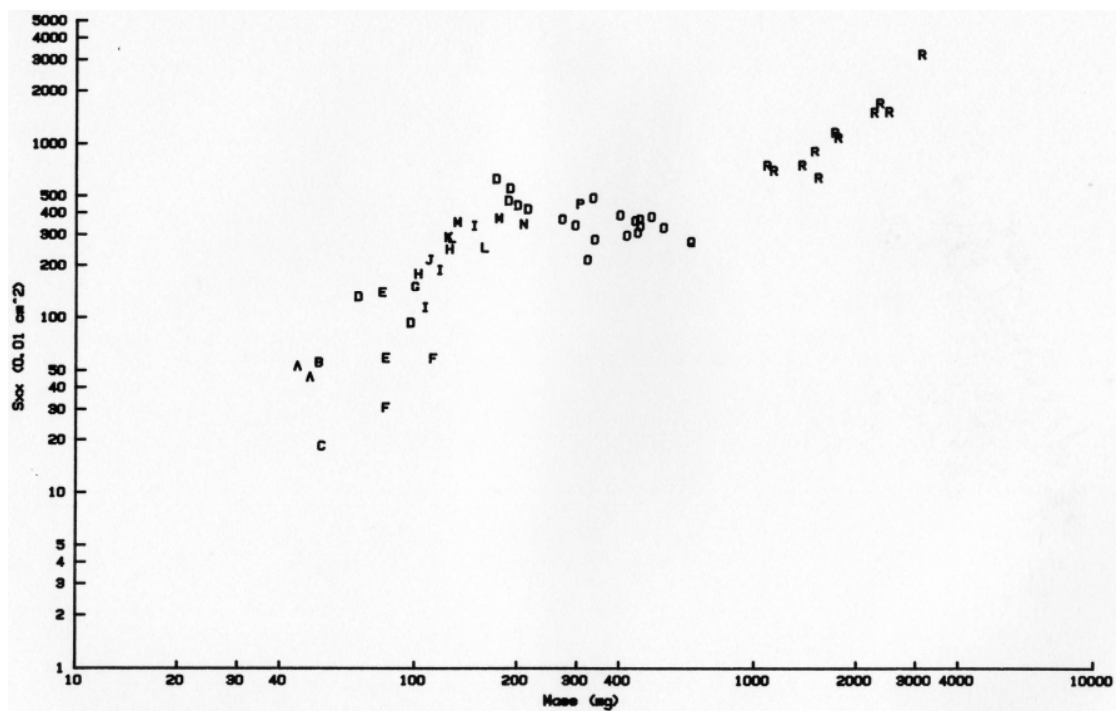


Figure 7.13 Graph of S_{yy} Against Mass

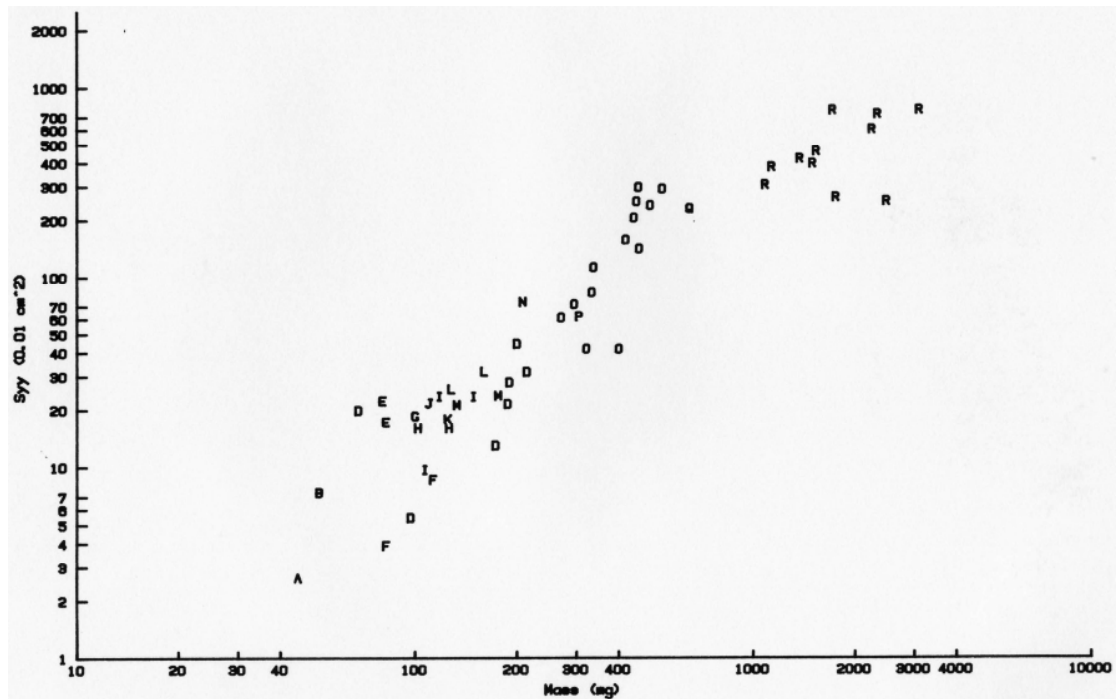


Figure 7.14 Graph of S_d Against Mass

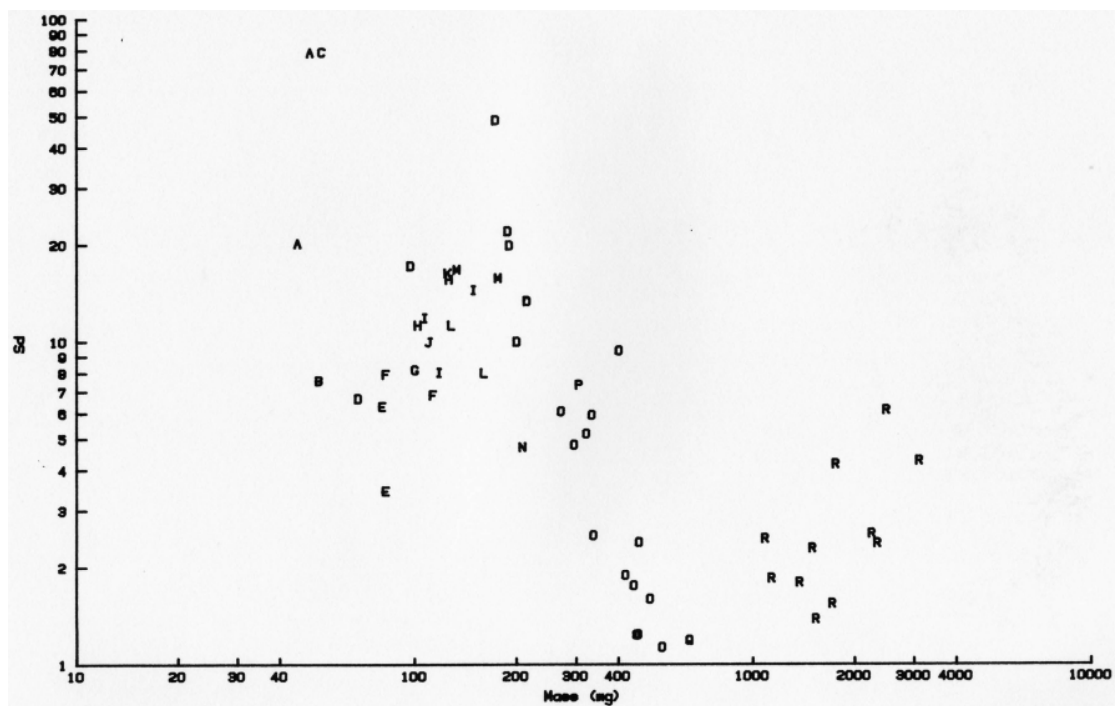


Figure 7.15 Graph of S_D Against Mass

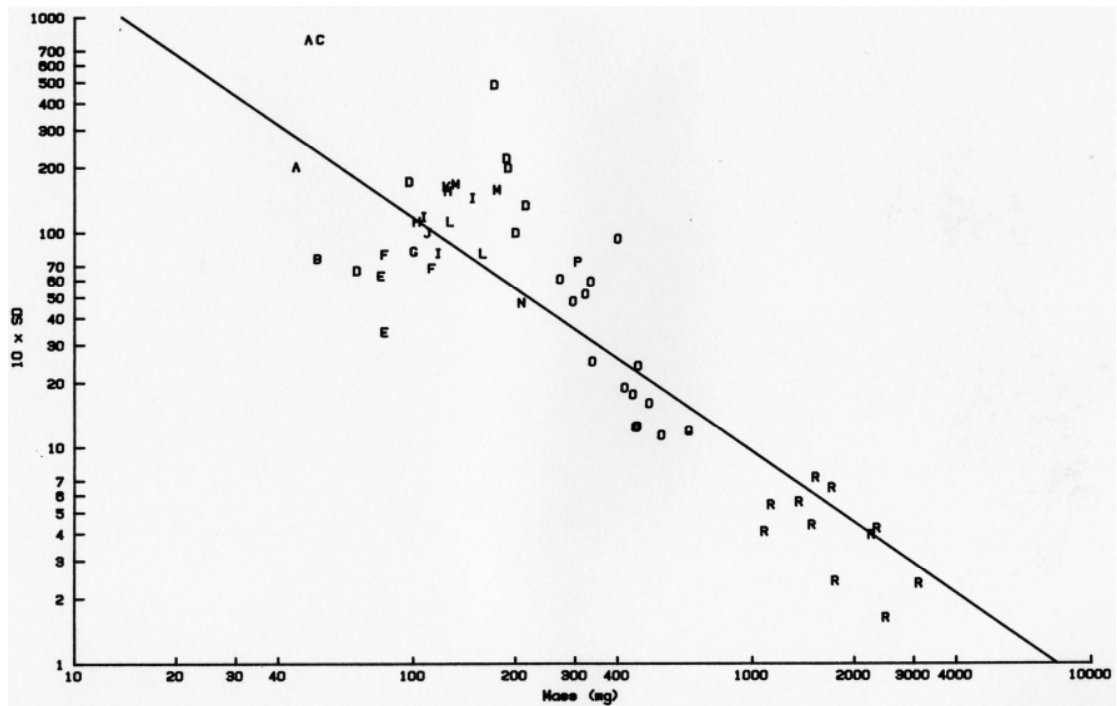


Figure 7.16 Graph of S_d Against Axial Ratio

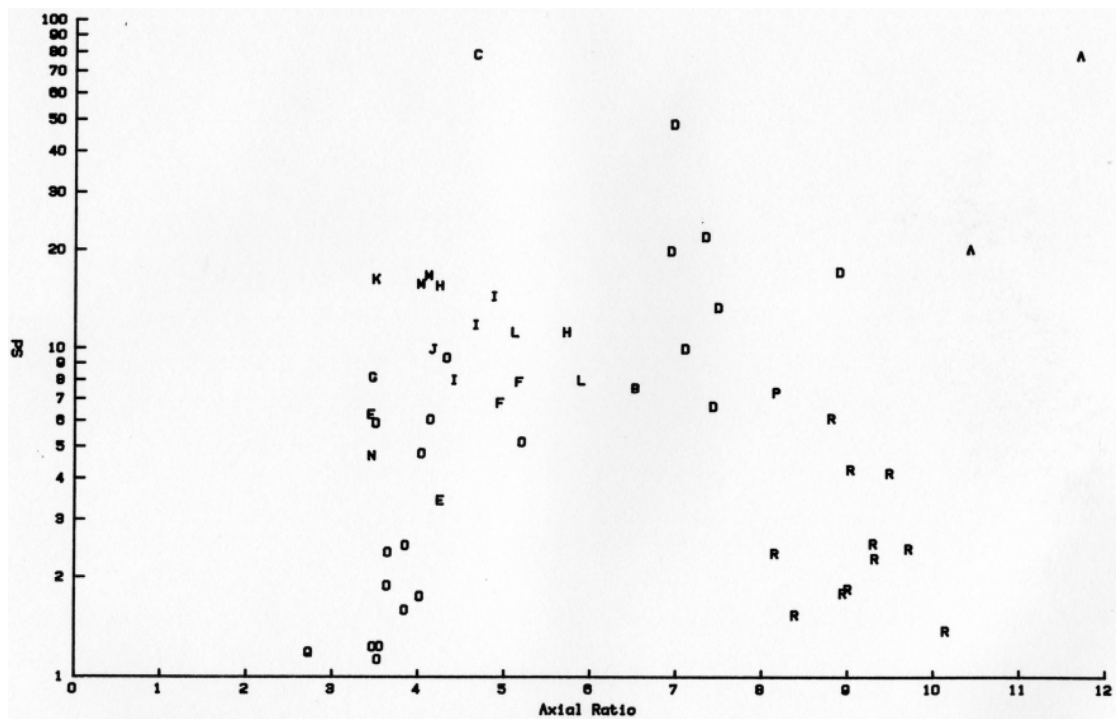


Figure 7.17 Graph of S_D ' Against Axial Ratio

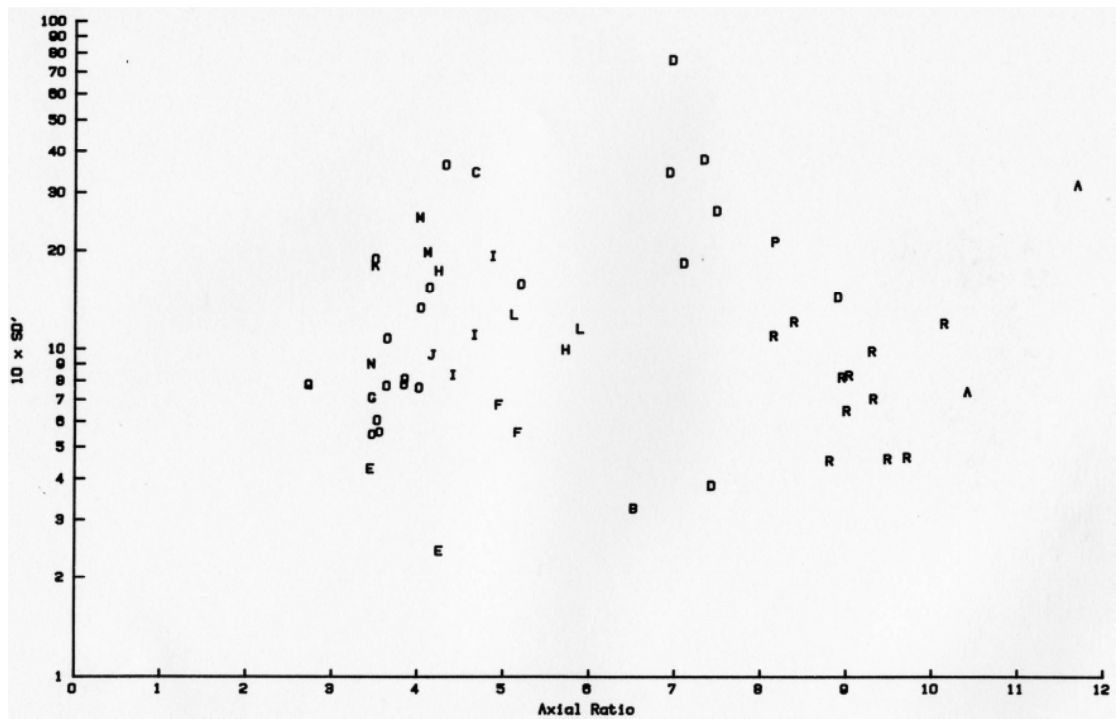


Figure 7.18 Parabola Fitted to a_0 Against Mass

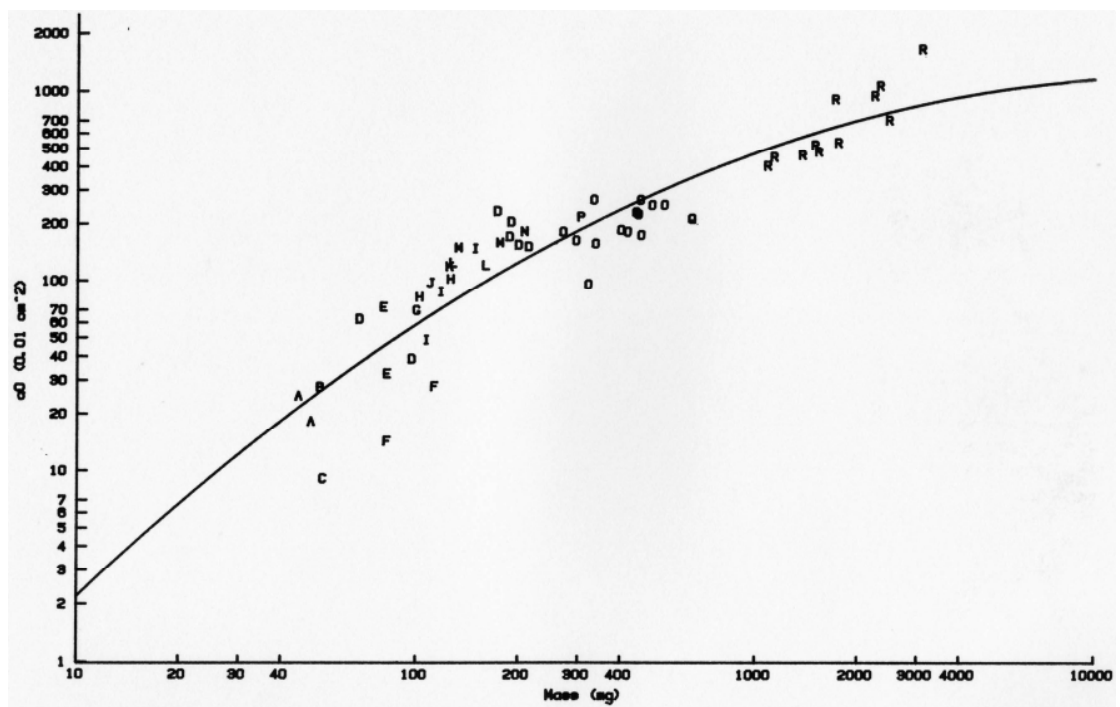


Figure 7.19 Parabola Fitted to S_{yy} Against Mass

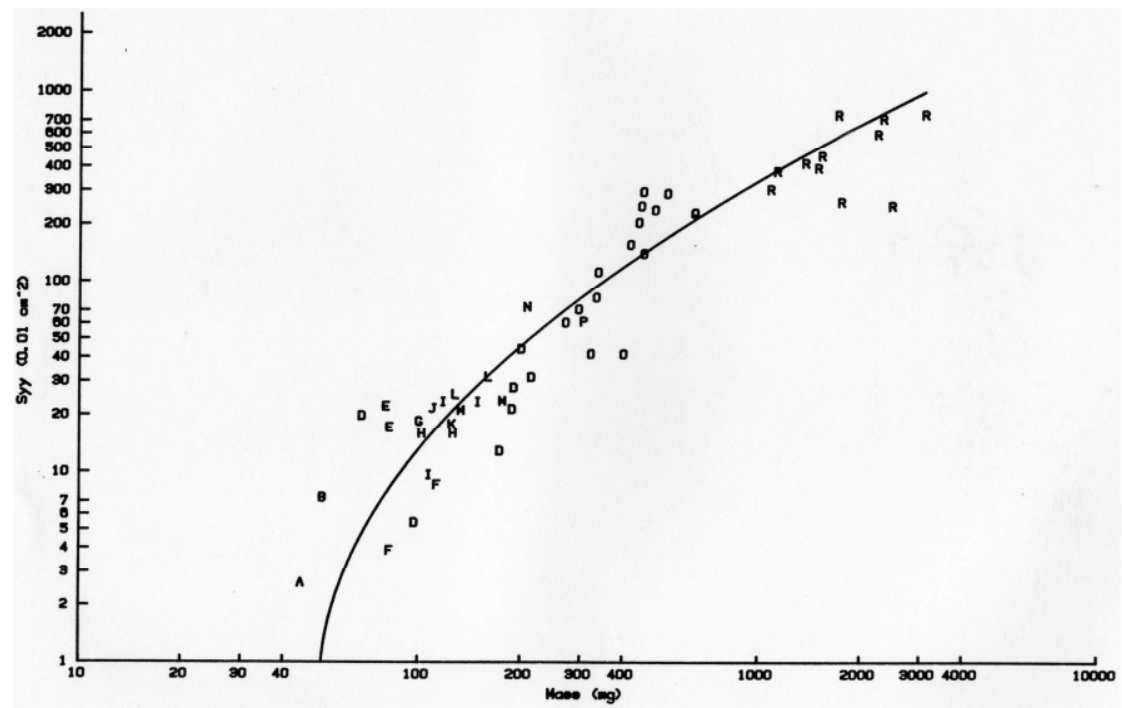


Figure 7.20 Variation of RCS with Aspect of a Range of Insects

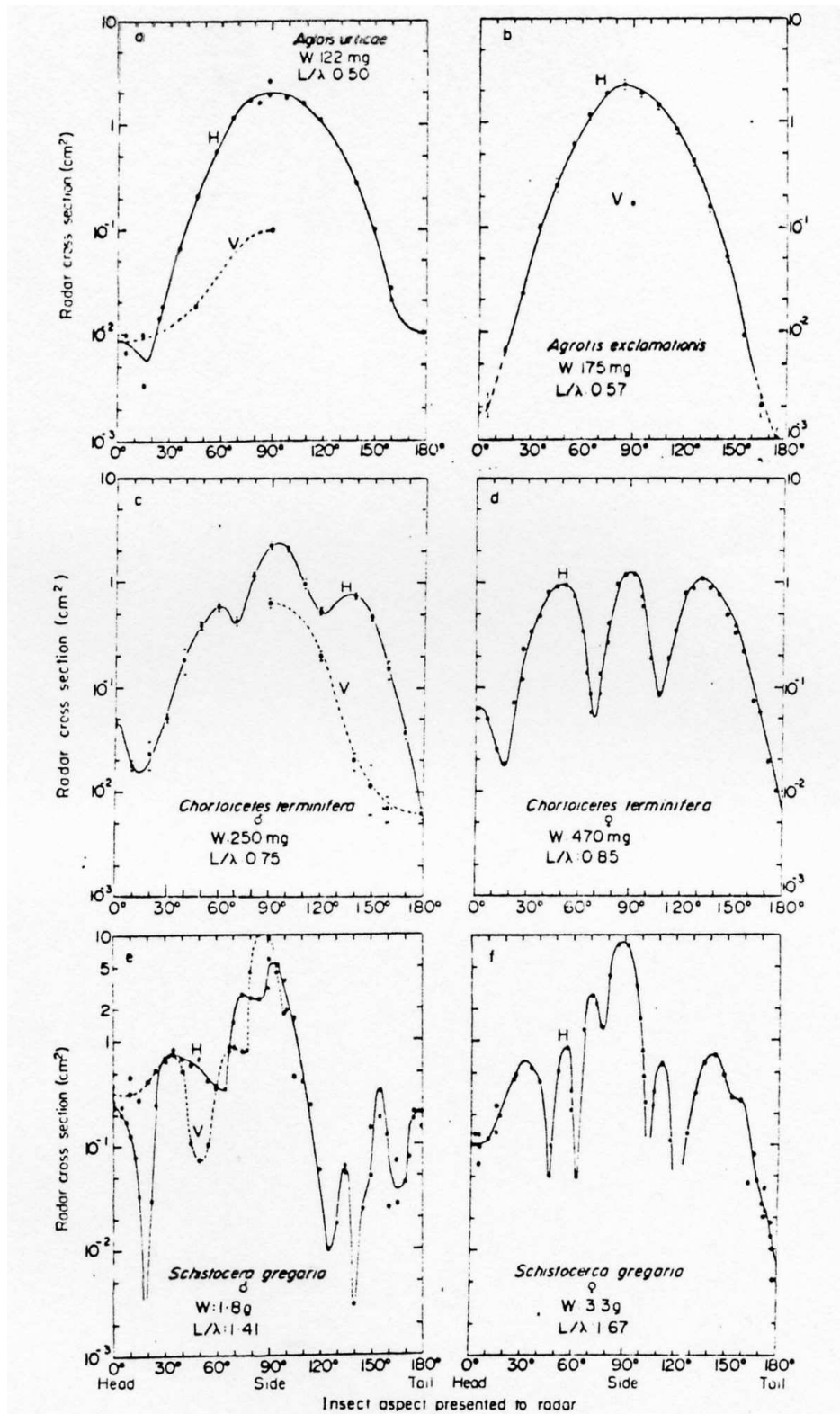


FIG. 8.54. Measured aspect-dependence of radar cross-sections of a range of insects. Length/width ratios 4-5; wavelength $\lambda = 3.18$ cm; polarization H and V; insect weight W; body-length L cm.

Figure 7.21 SM Parameters for Prolate Spheroids

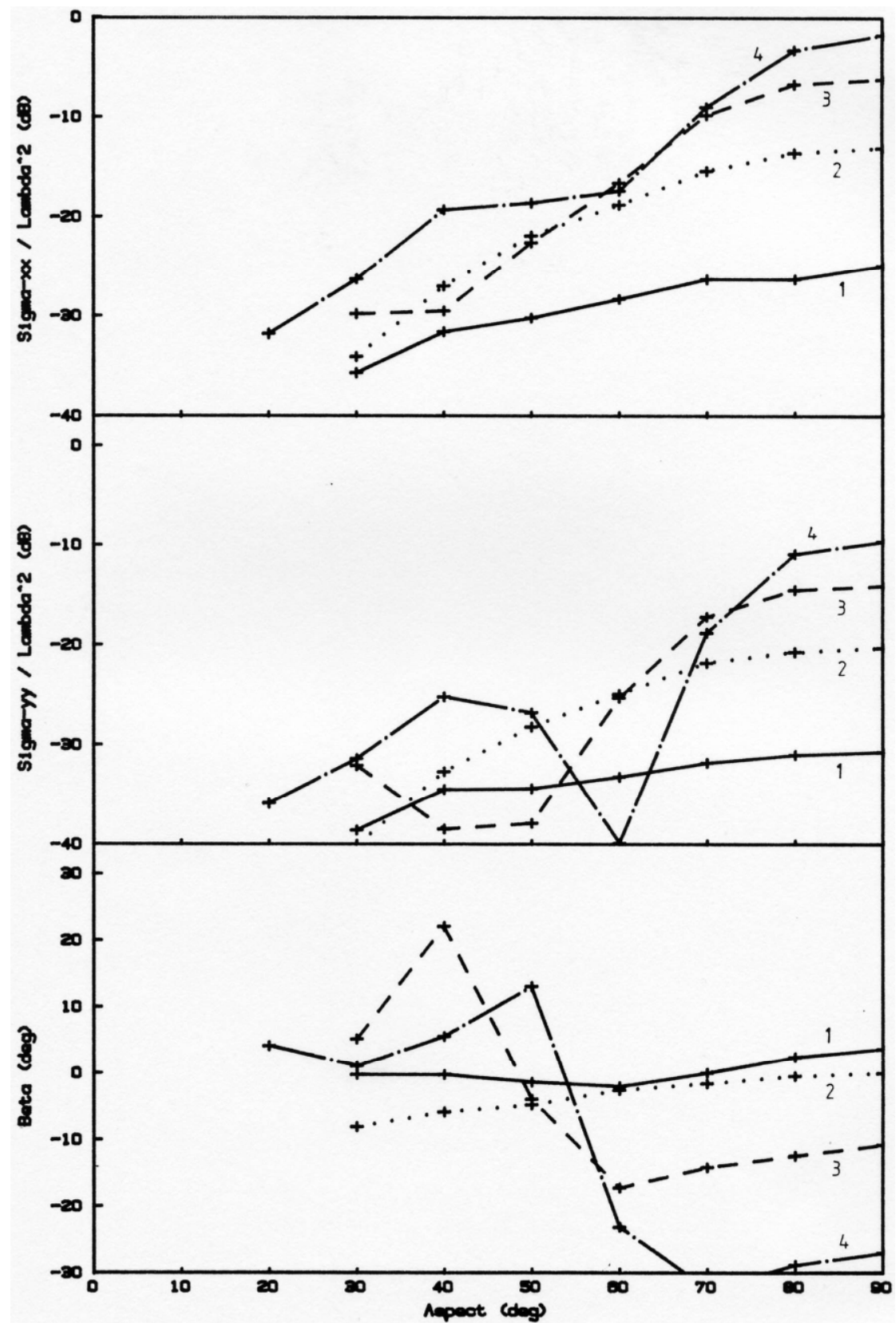


Table 7.1 Sample Data for Figure 7.21

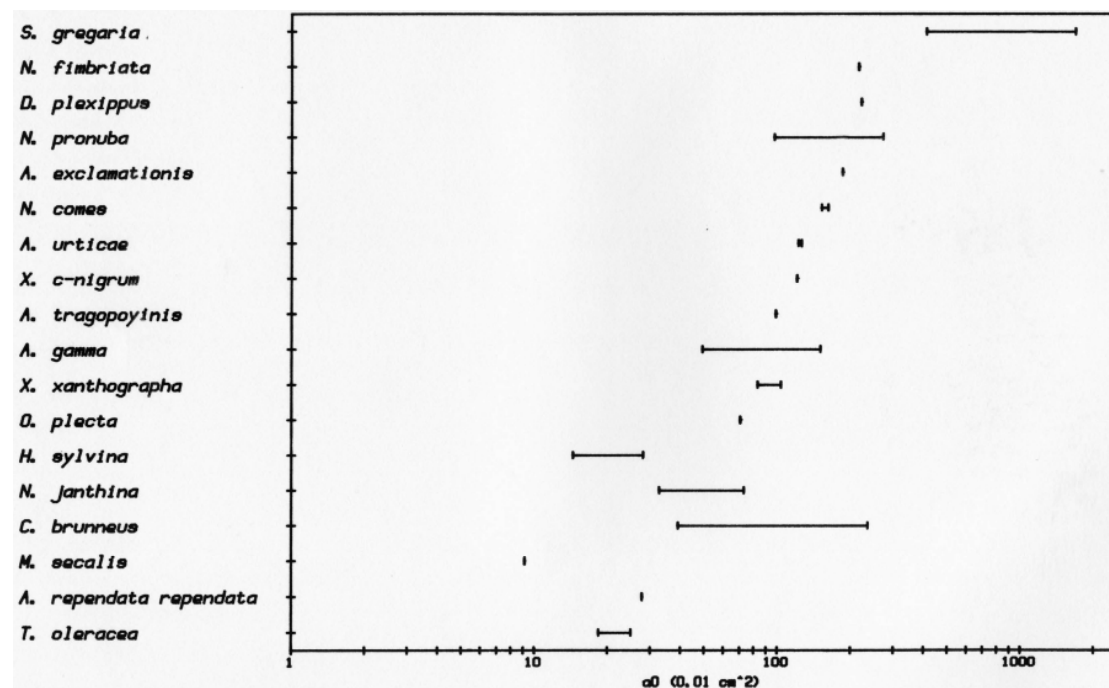
Sample No.	1	2	3	4
Ka	0.305	0.459	0.609	0.759
c/a	4.96	4.99	5.00	5.01
Re(ε)	3.20	3.20	3.14	3.14

In this table, the equation of the prolate spheroid is

$$x^2/a + y^2/a + z^2/c = 1$$

where $k = 2\pi / \lambda$, $a < c$ and ϵ is the dielectric constant of the body. The data was derived from Figure 2 of [Allan and McCormick].

Figure 7.21 SM Parameters for Prolate Spheroids



Chapter 8

Summary and Further Work

A summary of the work described in this thesis is given in section 8.1. Much work remains to be done and the following sections suggest an approach. Section 8.2 discusses theoretical research and section 8.3 looks at experimental research.

8.1 Summary

- 1) There have been few experimental or theoretical investigations of insect radar cross-section (RCS).
- 2) Modern entomological radars now obtain more information about insect RCS's using vertically pointing, linearly polarised radars with rotation planes of polarisation.
- 3) Experimental measurements of insect RCS's measured using this type of system are required to interpret the new information.
- 4) A five-parameter mathematical model was derived from the scattering matrix that describes the relationship of RCS with the orientation of the plane of polarisation at constant aspect.
- 5) Brief numerical experiments with the model suggest that current radar systems may not be sensitive to the cross-polarisation terms of the scattering matrix.
- 6) The model indicated that curve the of RCS against orientation of the plane of polarisation could display either a single maximum and minimum or dual maxima and minima, depending on the components of the scattering matrix.
- 7) An experimental system was developed to measure the RCS model parameters of an insect target viewed at constant vertical aspect.
- 8) The hardware was designed to operate in the open air to reduce background reflections and consisted of a continuous wave microwave circuit operating at 9.4GHz, a receiving system, a target support and rotation mechanism and a microcomputer to collect data.
- 9) A standard target was measured before each target and the software used the data to construct a calibration curve for the target data.

- 10) Software was developed that performed a least squares fit of the RCS model to the calibrated target data, using Givens reduction and singular value decomposition.
- 11) The system could measure RCS with an absolute accuracy of $\pm 25\%$; performance could not be improved due to limited finance.
- 12) Measurements are presented of 54 insect specimens representing 18 species, the majority of which were Noctuid moths or Orthopterians.
- 13) As has been found by other workers, the RCS averaged over all orientations of the plane of polarisation were approximately that of an equivalent mass water sphere.
- 14) As suggested by previous work, the RCS patterns were divided into three classes depending on the mass, m , of the insect:
 - a) $M < 250 \text{ mg}$ – there was a maximum and minimum when the plane of polarisation was parallel and perpendicular to the body axis respectively;
 - b) $250\text{mg} < m < 1000\text{mg}$ – the pattern displayed a maximum when the plane of polarisation was parallel to the body axis, a subsidiary maximum when the plane of polarisation was perpendicular to the body axis and minima at orientations between;
 - c) $m > 1000\text{mg}$ – the pattern was similar to that of b), except that the main maximum occurred when the plane of polarisation was perpendicular to the body axis.
- 15) Most of the RCS patterns were approximately symmetrical except for those from the heaviest targets (*S. gregaria*), which were often asymmetrical.
- 16) The RCS pattern can be used to measure the orientation of a flying insect to within $\pm 8^\circ$, although care must be taken in interpreting the orientation of angle of large insects since the angle may not correspond to the orientation of the insect's body axis.
- 17) A *differential RCS*, corresponding to the ratio of maximum RCS to the RCS when the plane of polarisation was orientated at 90° to that required for maximum RCS was defined, since this is clearly related to the ratio of length to width of a target and so may serve as a measure of this ratio.
- 18) The data indicated that the differential RCS was not simply related to the ratio of body length to body width for targets in the mass range measured, probably because the effect of different body masses dominated.

- 19) The differential RCS was slightly dependent on the target mass.
- 20) The average RCS could be used to provide an estimate of mass to within a factor of three, and hence differentiate between insect species with masses differing by a factor of five or more.
- 21) Although the system could not measure aspect dependence of RCS, previously published data of the aspect dependence of a few targets, and theoretical data from prolate ice spheroids was used to suggest that the RCS is not strongly dependent on aspect for aspects around 90° to the body axis for targets small compared to the wavelength of the radar, but can change dramatically for small changes in aspect for targets if the same order of size as the wavelength.
- 22) It is suggested that improved target identification and discrimination could be achieved using a discriminant function constructed from scattering matrix measurements of many specimens of common entomological radar targets.

8.2 Further Theoretical Research

This thesis has not addressed the theoretical aspects of insect RCSs. Although a general model of an insect would be incredibly complex, simplifying assumptions can be made. For example, the data has suggested that insects generally appear as rotationally symmetric targets, except for locusts whose large rear legs have a significant effect.

Many numerical models of homogeneous targets with rotational symmetry are available [Holt, 1982]. A shape that has been used by Schaefer [1976] and for which a good numerical model is available is the homogeneous prolate spheroid [Holt et al, 1978]. By approximating an insect as a prolate spheroid with an equivalent mass and axial ratio, this model could be used to investigate the dependence of the diagonal scattering matrix elements on mass and axial ratio in all scattering regions at relatively low cost.

This model could be used to determine how effective any radar is likely to be in discriminating between targets of different shapes and sizes and therefore differentiation between different insect targets.

8.3 Further Experimental Research

The data presented in this thesis suggests that simple linear polarisation and parallel reception measurements of insect RCSs do not provide enough information for reliable classification of the target to species level. As more information is contained in the scattering matrix, further work should move towards measuring all the scattering matrix elements, both in the field and in the laboratory. This may enable better identification of insect targets, perhaps based on discriminant analysis.

8.3.1 Laboratory Experiments

Further measurements of insect RCS's of the type described in this thesis would not provide the more detailed information required. A laboratory system for measuring the scattering matrix would enable a library of typical values of the matrix elements for the species commonly detected by entomological radars to be built up. This library could then be used to aid in identifying targets detected by field entomological radars (perhaps via a discriminant function). It seems unlikely that identification to species would be possible (especially with very similar species) but it may be possible to determine which family the target species is most likely to belong to. Species identification may be possible when only a few species with different typical scattering matrices are flying.

The present system could be rebuilt, retaining the linear polarisation and target rotation techniques but using a source/receiver system that was capable of measuring complex voltage at the antenna terminals (i.e. the phase and amplitude of the returned wave). This would furnish sufficient information to obtain all the scattering matrix elements [Copeland, 1960]. The system should also be constructed to operate indoors as weather conditions severely limits the available data collection periods on an outdoor system. However, because the target must be rotated at constant aspect, it would be difficult for such a system to measure the aspect dependence of the scattering matrix.

Alternatively, a more complex system, such as that used by Allan et al [1986], could be built that measures all elements of the scattering matrix directly. Although the more expensive option, this method enables the dependence of the matrix elements on target aspect to be determined without rotating the target. The viewing

aspect of the target could easily be changed to measure the aspect dependence of the scattering matrix, providing further information about insect scattering matrices.

8.3.2 Field Entomological Radar

To obtain further information in the field, radars capable of measuring the scattering matrix should be used. However, entomological radars often operate in difficult environments and need to be reliable and easy to maintain. An increase in complexity would be unwelcome.

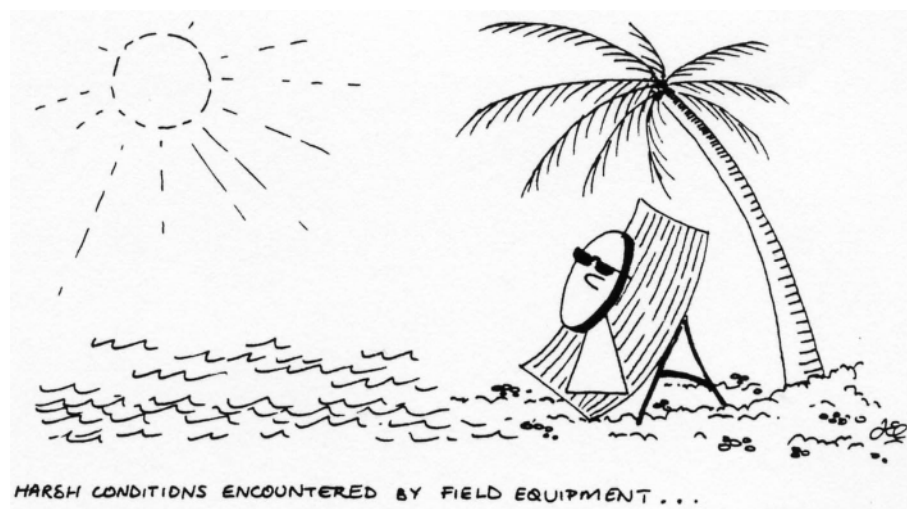
The scanning radars used to observe large scale insect movements view from an indeterminate aspect and, due to beam shape, cannot make reliable absolute measurements of RCS. These radars provide mainly positional information (although density can be estimated from the PPI screen [Drake, 1981] and sometimes wing beat frequencies can be derived from individual targets). It would serve no purpose to make these radars capable of measuring the complete scattering matrix because of the high degree of uncertainty in the viewing aspect.

Vertically pointing radars are used to determine the orientation, wing beat frequency and vertical density profile of the insects. The viewing aspect is relatively well defined as from below, at 90° to the longitudinal body axis. If this is all that is required, then there is no reason for an increase in radar complexity. However, if further information is required, this radar could be modified so that it was capable of measuring the scattering matrix.

If only element values relative to each other are required, then the beam shape need not be considered. Otherwise some method of correcting for the beam shape, such as a nutating beam, [Bent, 1984] would be required, but the increased complexity would tend to reduce any advantage gained.

As with the laboratory system, two options are available. The cheapest would be to use the existing rotating dipole antenna with a radar capable of measuring the amplitude and phase of the echo signal. Relative scattering matrix values could be derived from the signal by microcomputer using suitable software. The other option would be to use a dual polarisation system, capable of measuring the relative scattering matrix elements directly. However, this system would necessarily be much more complex and expensive and may not be reliable when used in the harsh conditions encountered by field equipment.

The work described in this thesis demonstrates the complexity of insect RCS's and hopefully will stimulate further work in this field. Greater understanding of insect RCS's will enhance the utility of entomological radar, already a unique and powerful tool for the study of the distribution and movements of insects over large distances in the atmosphere.



Appendix A

Mathematical Details

Mathematical details are briefly discussed in this appendix. Section A.1 derives three results concerning the scattering matrix that were stated in chapter. 2. Section A.2 is a short introduction to B-splines, including the algorithm for their evaluation. The theory of the least-squares solution of an inconsistent set of linear simultaneous equations is outlined in A.3. The algorithm used to compute such solutions is briefly described in A.4. Algorithms are described in a Pascal like language.

A.1 Scattering Matrix Derivations

Three results that were stated in chapter 2 are derived here. First there is a brief explanation of how one matrix transformation affects another since this is used in all three derivations. Then follows proofs of the following statements:

- 1) the scattering matrix of a body that is mirror symmetric about the x - z or y - z plane is diagonal (section 2.2);
- 2) the scattering matrix of a body with rotational symmetry about the z -axis is a multiple of the unit matrix (section 2.3);
- and 3) if the scattering matrix of a body is diagonalisable by a rotation of the coordinate axes, then the required rotation angle is the RCS model parameter θ_l (section 2.4).

A.1.1 Matrix Transformations

Let M be a matrix and $\mathbf{u}, \mathbf{v}$ be two vectors such that

$$\mathbf{v} = M\mathbf{u}.$$

Consider another matrix transform L and its inverse L^{-1} such that

$$\mathbf{u}' = L\mathbf{u}, \mathbf{v}' = L\mathbf{v},$$

$$\mathbf{u} = L^{-1}\mathbf{u}', \mathbf{v} = L^{-1}\mathbf{v}',$$

Then $\mathbf{u}'$ and $\mathbf{v}'$ are related by the matrix

$$M' = LML^{-1}$$

since

$$\mathbf{v}' = L\mathbf{v} = LM\mathbf{u} = LML^{-1}\mathbf{u}' = M'\mathbf{u}'.$$

The matrix M is transformed to the matrix M' by the operation represented by L . The following three derivations depend upon this type of matrix operation.

A.1.2 Scattering Matrix of a Mirror Symmetric Target

Consider a target that is mirror symmetric about the x - z plane. The target is invariant under inversion of the y coordinate ($y \rightarrow -y$) and therefore, so is the scattering matrix. The matrix operator representing this inversion is

$$V = V^{-1} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

Since the scattering matrix is invariant under inversion,

$$S = VSV^{-1},$$

so that

$$\begin{pmatrix} s_{xx} & s_{xy} \\ s_{xy} & s_{yy} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} s_{xx} & s_{xy} \\ s_{xy} & s_{yy} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = \begin{pmatrix} s_{xx} & -s_{xy} \\ -s_{xy} & s_{yy} \end{pmatrix}.$$

This implies that

$$s_{xy} = 0.$$

When the target is mirror symmetric about the y - z plane, a similar argument leads to the same conclusion. Therefore, if the target is mirror symmetric about the x - z or y - z planes, the scattering matrix is diagonal.

A.1.3 Scattering Matrix of a Rotationally Symmetric Target

Consider a target that can be rotated by an angle θ about the z axis so that it appears identical. The target is invariant under a rotation of θ and therefore so is the scattering matrix. Writing s for $\sin \theta$ and c for $\cos \theta$, the rotation matrix operator and its inverse are

$$R = \begin{pmatrix} c & -s \\ s & c \end{pmatrix},$$

$$R^{-1} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix}.$$

Then, since S is invariant under a rotation of θ ,

$$S = RSR^{-1},$$

so that

$$\begin{pmatrix} s_{xx} & s_{xy} \\ s_{xy} & s_{yy} \end{pmatrix} = \begin{pmatrix} c & -s \\ s & c \end{pmatrix} \begin{pmatrix} s_{xx} & s_{xy} \\ s_{xy} & s_{yy} \end{pmatrix} \begin{pmatrix} c & s \\ -s & c \end{pmatrix}.$$

Expanding this matrix equation gives three simultaneous, complex equations in three unknowns:

$$0 = -s_{xx}s^2 + 2s_{xy}sc + s_{yy}s^2,$$

$$0 = -s_{xx}sc + 2s_{xy}s^2 + s_{yy}sc,$$

$$0 = -s_{xx}s^2 + 2s_{xy}sc + s_{yy}s^2.$$

the last of which is degenerate with the first. If $s = 0$ ($\theta = 180^\circ$), all the equations degenerate; rotation by 180° leaves any scattering matrix unchanged, as expected since rotation the plane of polarisation by 180° leaves the system unchanged independently of the target (see section 2.4). Solving the equations for the elements of the scattering matrix, assuming that s is non-zero, gives

$$s_{xx} = s_{yy},$$

$$s_{xy} = 0.$$

There are no real solutions for θ , for arbitrary values of the scattering matrix elements. Therefore, if the target possesses rotational symmetry in the plane normal to the line of sight, the scattering matrix is a multiple of the unit matrix.

A.1.3 The RCS Model from a Diagonal Scattering Matrix

Consider a target with a diagonal scattering matrix in some coordinate axes:

$$S = \begin{pmatrix} s_{xx} & 0 \\ 0 & s_{yy} \end{pmatrix}.$$

Rotating the axes by an arbitrary angle, θ , transforms the matrix to:

$$S = RSR^{-1}$$

$$S = RSR^{-1}$$

$$= \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} s_{xx} & 0 \\ 0 & s_{yy} \end{pmatrix} \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}.$$

In the new coordinates, the RCS model from this matrix is:

$$\begin{aligned}
\sigma(\phi) &= \left| \begin{pmatrix} \cos \phi & \sin \phi \end{pmatrix} S' \begin{pmatrix} \cos \phi \\ \sin \phi \end{pmatrix} \right|^2 \\
&= \left| \begin{pmatrix} \cos \phi & \sin \phi \end{pmatrix} R S R^{-1} \begin{pmatrix} \cos \phi \\ \sin \phi \end{pmatrix} \right|^2 \\
&= \left| \begin{pmatrix} \cos \phi & \sin \phi \end{pmatrix} \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} s_{xx} & 0 \\ 0 & s_{yy} \end{pmatrix} \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \cos \phi \\ \sin \phi \end{pmatrix} \right|^2 \\
&= \left| \begin{pmatrix} \cos(\phi + \theta) & \sin(\phi + \theta) \end{pmatrix} \begin{pmatrix} s_{xx} & 0 \\ 0 & s_{yy} \end{pmatrix} \begin{pmatrix} \cos(\phi + \theta) \\ \sin(\phi + \theta) \end{pmatrix} \right|^2 \\
&= a_0 + a_1 \cos 2(\phi + \theta) + a_2 \cos 4(\phi + \theta),
\end{aligned}$$

where a_0 , a_1 and a_2 are the model parameters from the original, diagonal matrix, and

$$\theta_1 = -\theta,$$

the negative angle through which the original axes were rotated. It therefore follows that if a scattering matrix is diagonalisable by a rotation of the coordinate axes, the the required rotation angle is θ_1 .

A.2 B-Splines

It is often necessary to construct an empirical curve to approximate experimental data and B-splines are frequently used for this purpose because they are easily evaluated and numerically stable. They are used by the software to build the calibration curve for each target measurement (see section 4.2). B-splines are discussed in detail by C. de Boor [1978]. A brief introduction is given here.

The n independent k^{th} order splines, $B_{i,k}(x)$, $i = 1..n$ are constructed from a knot-sequence, t_i , $i = 1..n+k$, where $t_i \leq t_{i+1}$, using the recurrence relation

$$B_{i,1}(x) = 1, t_i < x \leq t_{i+1},$$

$$0 \text{ otherwise,}$$

$$B_{i,k}(x) = \frac{(x - t_i)}{(t_{i+k} - t_{i+1})} B_{i,k-1}(x) + \frac{(t_{i+k} - x)}{(t_{i+k} - t_{i+1})} B_{i+1,k-1}(x)$$

and are defined over the interval $t_k < x \leq t_n$. The values of the knots $t_1 .. t_{k-1}$ and $t_{n+1} .. t_{n+k}$ are arbitrary and are usually taken so that $t_1 = t_2 = .. = t_k$ and $t_n = t_{n+1} = .. = t_{n+k}$. at x , where $t_i < x \leq t_{i+1}$, only $B_{i-k+1,k} .. B_{i,k}$ are possibly non-zero.

A general curve $f(x)$ over the valid interval is a linear combination of the n splines $B_{i,k}(x)$:

$$f(x) = \sum a_i B_{i,k}(x), t_k < x \leq t_n.$$

By carefully choosing the knot positions and the values of the multiplying coefficients, $f(x)$ can be constructed to fit many empirical shapes.

A knot is said to be p -fold (where $p \leq k$) if

$$t_{i-1} < t_i = t_{i+1} = \dots = t_{i+p-1} < t_{i+p}.$$

The general curve is discontinuous in the $k - p^{\text{th}}$ derivative at a p -fold knot. For example, if $k = 4$ (cubic B-splines) and the knot sequence were (0, 0, 0, 0, 1, 2, 2, 3, 4, 4, 4, 4) then the general curve $f(x)$ would be discontinuous in the third derivative at $x = 1$ and $x = 3$ and discontinuous in the second derivative at $x = 2$.

B-splines can be easily evaluated in a numerically stable way using the recurrence relation above. The algorithm used by the software to evaluate B-splines is given below:

Algorithm BSPLVB

```
{  Evaluates the  $k$  possibly non-zero B-splines of order  $k$  defined on the knot
sequence contained in array  $t$ , at the point  $x$ , with  $t[i] < x \leq t[i+1]$  and
 $t[i] < t[i+1]$ . The values of the  $k$  B-splines  $B_{i-k+1,k} \dots B_{i,k}$  are returned in
 $b[1] \dots b[k]$ .}
```

```
b[1] := 1
```

```
FOR j := 1 TO k-1 DO
```

```
  dr[j] := t[i + j] - x
```

```
  dl[j] := x - t[i + 1 - j]
```

```
  saved := 0.0
```

```
  FOR r := 1 TO j DO
```

```
    term := b[r] / (dr[r] + dl[j + 1 - r])
```

```
    b[r] := saved + dr[r] * term
```

```
    saved := dl[j + 1 - r]
```

```
  END FOR r
```

```
  b[j + 1] := saved
```

```
END FOR j
```

A.3 Least Squares Solutions

Many problems involve the solution of a set of simultaneous linear equations of the form

$$l_{11} x_1 + l_{12} x_2 + \dots + l_{1n} x_n = y_1,$$

$$l_{21} x_1 + l_{22} x_2 + \dots + l_{2n} x_n = y_2,$$

....

$$l_{m1} x_1 + l_{m2} x_2 + \dots + l_{mn} x_n = y_m,$$

which can be written in matrix form as

$$L\mathbf{x} = \mathbf{y}$$

where $L = l_{ij}$, $i = 1 \dots m$, $j = 1 \dots n$ is an n by m matrix of the coefficients, $\mathbf{x} = x_i$, $i = 1 \dots n$ is a vector of the unknowns and $\mathbf{y} = y_i$, $i = 1 \dots m$ is a vector of the right-hand sides.

In general, if $m < n$ there are not sufficient equations to uniquely determine all the x 's; there are infinitely many solutions unless the equations are inconsistent, in which case there are no solutions. If $m \geq n$ then a solution may or may not exist and, if it does exist, may or may not be unique. If fewer than n equations are linearly independent then infinitely many solutions exist. If the equations are inconsistent, then no solution exists that can satisfy all equations simultaneously.

Often, due to experimental error or statistical variation, a set of equations is inconsistent. However, a 'best' solution can be found that comes closest, in some sense, to satisfying all the equations simultaneously. Several measures of closeness exist, the most useful being the residual sum of squares

$$S = \sum (y_i - \sum l_{ij} x_j)^2.$$

The least squares solution of an inconsistent set of linear equations is simply the set of x 's such that S is a minimum. The general solution of this problem is the solution of the *normal equations*:

$$L^T L \mathbf{x} = L^T \mathbf{y}$$

(where L^T denotes the transpose of matrix L). A full discussion is given in Davies, [1975]. The matrix $L^T L$ is a symmetric matrix and is often highly ill-conditioned. Therefore great care must be taken in solving the normal equations as the resulting numerical instabilities may generate meaningless results.

Two problems that require least squares solutions arose in this work. The first was to fit a cubic B-spline

$$f(x) = \sum a_i B_{i,4}(x)$$

with a given knot sequence to the calibration data (σ_i, x_i) (see section 4.2). (There is no known procedure for choosing an optimum knot sequence. The one used was found by trial and error.) The matrix elements were:

$$l_{ij} = B_{j,4}(x_i)$$

$$x_j = a_j$$

$$y_j = \sigma_i$$

The other problem was to fit the model

$$a_0 + a_{11} \cos 2\phi + a_{12} \sin 2\phi + a_{21} \cos 4\phi + a_{22} \sin 4\phi$$

to the target RCS data (σ_i, θ_i) (see section 4.3). In this case,

$$l_{i1} = 1$$

$$l_{i2} = \cos 2\phi_i$$

$$l_{i3} = \sin 2\phi_i$$

$$l_{i4} = \cos 4\phi_i$$

$$l_{i5} = \sin 4\phi_i$$

$$x_1 = a_0$$

$$x_2 = a_{11}$$

$$x_3 = a_{12}$$

$$x_4 = a_{21}$$

$$x_5 = a_{22}$$

$$y_j = \sigma_i$$

These problems were solved using the algorithm described in the following section.

A.4 Least Squares Solution Algorithm

The algorithm used by the software to calculate least-squares solutions was described by Nash [1979] and a full description is given there. It uses Givens reduction of L followed by singular-value decomposition.

The algorithm first decomposes the matrix L into an m by m orthogonal matrix Q (i.e. $Q^T Q = Q^T Q = \mathbf{1}_m$ where $\mathbf{1}_m$ is the m by m unit matrix) and an upper triangular n by m matrix R such that

$$L = QR$$

Then

$$L^T L x = R^T Q^T Q R x = R^T Q^T Q R x = R^T Q^T y = L^T y.$$

The matrix R is constructed by successive plane rotations of L , each of which sets an element of L to zero. The rotations are carefully ordered so as not to make non-zero an element already set to zero by a previous rotation. Each of these rotations is also applied to $\mathbf{y}$ to compute $\mathbf{d} = Q^T \mathbf{y}$ without the necessity of storing the large matrix Q . The rows of L are needed one at a time so the memory workspace needed by the algorithm is small. The residual sum of squares is computed concurrently in a stable manner.

A singular value decomposition of R is then constructed, such that

$$R = USV^T$$

Where U and V are orthogonal unit matrices and S is the diagonal matrix of singular values. (The diagonal elements of S are taken to be non-negative as only their square is defined.) If one or more of the singular values are zero, then R is singular. If all the values are not of the same order of magnitude, R is ill-conditioned and numerical instabilities in the results can be expected. Singular values can therefore be used to indicate the reliability of the results.

The least squares solution is then

$$\mathbf{x} = US^+U^T\mathbf{d},$$

where S^+ is the diagonal matrix with elements given by

$$S_{ii}^+ = \frac{1}{S_{ii}}, S_{ii} > 0$$

$$0, S_{ii} = 0$$

When R is singular (i.e. when one of the singular values is zero) this computes a minimum length solution such that the residual sum of squares and $\mathbf{x}^T \mathbf{x}$ are minimised. Since the calculated singular values are unlikely to be exactly zero due to rounding error, $ZTol$, a tolerance for zero, is used, so that

$$S_{ii}^+ = \frac{1}{S_{ii}}, S_{ii} > ZTol$$

$$0, S_{ii} \leq ZTol$$

The algorithm, computes the orthogonal matrix SV^T using an iterative process that sweeps through the matrix, performing plane rotations that orthogonalise pairs of rows in such a way the whole matrix approaches orthogonality. The rotations constitute U^T and are applied directly to the right hand side vector $\mathbf{d}$, forming the new vector $\mathbf{f}$; U^T is not stored. S is calculated by normalising the rows of SV^T . Finally, the least squares solution is calculated, taking into account the possibility of zero singular

values. If any singular values are zero, a correction is made to the residual sum of squares.

The algorithm is given below:

Algorithm Givens

```
{ Calculates the least –squares solution of  $Lx = y$  using Givens reduction and
singular value decomposition. The  $m$  rows of  $L[i, j]$  and  $y[j]$  are loaded one at
a time, The solutions are returned in  $x[1] .. x[n]$  and the residual sum of
squares in  $rss$ . }
```

```
{ Zero the work array. }
```

```
FOR i := 1 TO n DO
    FOR j := 1 TO n+1 DO
        W[i, j] := 0.0
    END FOR j
END FOR i
```

```
rss := 0.0 { Zero the residual sum of squares. }
```

```
FOR i := 1 TO m DO
    { Load  $i^{th}$  row of  $L$  and  $y_i$  into the work array. }
    FOR j := 1 TO n DO
        W[n + 1, j] := L[i, j]
    END FOR j
    W[n + 1, n+1] := y[i]
    { Set each element  $n + 1^{th}$  row to zero by plane rotations. }
    FOR j := 1 TO n DO
        { Calculate the sine and cosine of the rotation angle. }
        s := W[n + 1, j]
        c := W[j, j]
        b := ABS(c)
        IF ABS(s) > b THEN b := ABS(s) ENDIF
        IF b <> 0 THEN
            c := c / b
            s := s / b
            p := SQRT(c * c + s * s)
            s := s / p
```

```

    IF ABS(s) > ZTol THEN
        c := c / p
        { Rotate W. }
        FOR k := j TO n + 1 DO
            r := W[j, k]
            W[j, k] := r * c + s * W[n + 1, k]
            W[n + 1, k] := -r * s + c * W[n + 1, k]
        END FOR k
    END IF
END IF
END FOR j
{ Sum residual sum of squares. }
rss := rss + W[n + 1, n + 1] * W[n + 1, n + 1]
END FOR i
{ Givens reduction is now complete.  $R$  is stored in the upper  $n$  by  $n$  sub-matrix of
 $W$ .  $d$  is stored in the  $n + 1^{\text{th}}$  column of  $W$ . }
{ Singular Value Decomposition. }
REPEAT
    { Set convergence counter. }
    count := n * (n - 1) DIV 2
    FOR i := 1 to n - 1 DO
        FOR j := (i + 1) TO n DO
            { Calculate quantities used to find rotation angle. }
            p := 0.0
            q := 0.0
            r := 0.0
            FOR k := 1 TO n DO
                p := p + W[i, k] * W[k, k]
                q := q + W[i, k] * W[j, k]
                r := r + W[j, k] * W[k, k]
            END FOR k
            IF q < r THEN
                { The rows are approaching null vectors. Perform rotation that
                exchanges rows which are out of order. }

```

```

        FOR k := 1 TO n + 1 DO
            r := W[i, k]
            W[i, k] := W[j, k]
            W[j, k] := -r
        END FOR k
    ELSE IF ABS(q * r) < ZTol OR (p * p) / (q * r) < ZTol THEN
        { The rows are null or orthogonal so the rotation is not needed. }
        count := count + 1
    ELSE
        { Calculate sine and cosine of rotation angle. }
        q := q - r
        r := SQRT(4 * p * p + q * q)
        c := SQRT((r + q) / (2 * r))
        s := p / (r * c)
        { Rotate rows in ij plane. }
        FOR k := 1 TO n + 1 DO
            r := W[i, k]
            W[i, k] := r * c + s * W[j, k]
            W[j, k] := -r * s + c * W[j, k]
        END FOR k
    END ELSE
END FOR j
END FOR i
{ Count = 0 when no rotations were performed so matrix is orthogonal. }
UNTIL count <= 0
{ Normalise rows to get singular values. }
FOR i := 1 TO n DO
    s[i] := 0
    FOR j := 1 TO n DO
        s[i] := s[i] + W[i, j] / s[i]
    END FOR j
    s[i] := SQRT(s[i])
    IF s >= ZTol THEN
        FOR j := 1 TO n DO

```

```

        W[i, j] := W[i, j] / s[i]
    END FOR j
END IF
END FOR i
{ Singular value decomposition is complete.  $V^T$  is in the leading  $n$  by  $n$  sub-array
  and  $\mathbf{f}$  is in column  $n + 1$  of the work array. }
{ Least squares solution – form  $VS^+\mathbf{f}$ . }
FOR i := 1 TO n DO
    x[j] := 0
    FOR j := 1 TO n DO
        IF s[j] > ZTol THEN
            x[i] := x[i] + W[i, j] * W[j, n + 1] / s[j]
        END IF
    END FOR j
    { Adjust sum of squares in rank deficient case. }
    IF s[i] <= ZTol THEN
        Rss := rss + W[i, n + 1] * W[i, n + 1]
    END IF
END FOR i
END Givens

```

Appendix B

Original Data

Two tables listing the data collected are presented in this appendix. Table B.1 details the biometric data (mass, wing length, body length, abdomen width and, for *S. gregaria*, thorax width) for each specimen. Table B.2 details the model measured for each specimen.

Table B.1 Biometric Data for Each Insect Target Measured

Insect No.	Species	Mass (mg)	Wing Length (mm)	Body Length (mm)	Abdomen Width (mm)
1	<i>T. oleracea</i>	45	14.8	17.7	1.7
2	<i>T. oleracea</i>	49	17.2	18.7	1.6
3	<i>A. rependata rependata</i>	52	20.2	18.9	2.9
4	<i>M. secalis</i>	53	14.5	14.0	3.0
5	<i>C. brunneus</i>	68	13.8	15.6	2.1
6	<i>C. brunneus</i>	97	13.7	16.9	1.9
7	<i>C. brunneus</i>	173	11.5	20.2	2.9
8	<i>C. brunneus</i>	188	11.7	22.0	2.9
9	<i>C. brunneus</i>	190	12.0	20.8	3.0
10	<i>C. brunneus</i>	200	12.4	21.3	3.0
11	<i>C. brunneus</i>	214	15.4	21.7	2.9
12	<i>N. janthina</i>	80	16.5	15.5	4.5
13	<i>N. janthina</i>	82	17.0	17.0	4.0
14	<i>H. sylvina</i>	82	14.1	15.5	3.0
15	<i>H. sylvina</i>	113	15.4	17.3	3.5
16	<i>O. plecta</i>	100	13.2	14.2	4.1
17	<i>X. xanthographa</i>	102	16.8	16.3	3.2
18	<i>X. xanthographa</i>	126	16.9	17.8	4.2
19	<i>A. gamma</i>	107	20.0	20.5	4.4
20	<i>A. gamma</i>	118	20.2	19.4	4.4
21	<i>A. gamma</i>	149	20.6	22.9	4.7
22	<i>A. tragopyinis</i>	110	18.4	17.9	4.3
23	<i>X. c-nigrum</i>	125	17.7	17.5	5.0

Insect No.	Species	Mass (mg)	Wing Length (mm)	Body Length (mm)	Abdomen Width (mm)
24	<i>A. urticae</i>	128	25.4	21.5	4.2
25	<i>A. urticae</i>	160	25.8	21.2	3.6
26	<i>N. comes</i>	133	17.5	18.5	4.5
27	<i>N. comes</i>	176	18.6	19.7	4.9
28	<i>A. exclamationis</i>	208	17.5	19.0	5.5
29	<i>N. pronuba</i>	270	25.4	27.3	6.6
30	<i>N. pronuba</i>	295	23.5	23.0	5.7
31	<i>N. pronuba</i>	321	25.0	26.0	5.0
32	<i>N. pronuba</i>	333	24.5	24.5	7.0
33	<i>N. pronuba</i>	337	25.5	25.0	6.5
34	<i>N. pronuba</i>	400	26.5	26.8	6.2
35	<i>N. pronuba</i>	419	25.3	25.8	7.1
36	<i>N. pronuba</i>	443	27.7	26.9	6.7
37	<i>N. pronuba</i>	451	24.5	26.0	7.5
38	<i>N. pronuba</i>	457	26.1	27.0	7.6
39	<i>N. pronuba</i>	459	26.1	25.5	7.0
40	<i>N. pronuba</i>	495	25.0	28.8	7.5
41	<i>N. pronuba</i>	538	26.9	27.5	7.8
42	<i>D. plexippus</i>	305	39.5	30.2	3.7
43	<i>N. fimbriata</i>	648	24.5	24.5	9.0
44	<i>S. gregaria</i>	1084	45.7	46.6	4.8
45	<i>S. gregaria</i>	1133	48.9	50.4	5.6
46	<i>S. gregaria</i>	1371	45.2	48.3	5.4
47	<i>S. gregaria</i>	1494	45.3	47.5	5.1
48	<i>S. gregaria</i>	1532	46.6	50.7	5.0
49	<i>S. gregaria</i>	1713	56.1	54.5	6.5
50	<i>S. gregaria</i>	1751	47.0	51.2	5.4
51	<i>S. gregaria</i>	2241	51.9	56.7	6.1
52	<i>S. gregaria</i>	2326	54.7	55.4	6.8
53	<i>S. gregaria</i>	2474	53.3	58.1	6.6
54	<i>S. gregaria</i>	3094	50.3	62.3	6.9

Table B.2 RCS Model Data for Each Insect Target Measured

Insect No.	Species	a_0	a_1	a_2	θ_1	$\theta_2 - \theta_1$
		(cm ²)	(cm ²)	(cm ²)	(deg)	(deg)
1	<i>T. oleracea</i>	0.250	0.250	0.028	-21.9	4.2
2	<i>T. oleracea</i>	0.180	0.230	0.049	-2.4	1.0
3	<i>A. rependata rependata</i>	0.280	0.240	0.036	-26.1	-1.4
4	<i>M. secalis</i>	0.091	0.091	0.002	10.0	-13.4
5	<i>C. brunneus</i>	0.630	0.560	0.130	-14.3	-4.2
6	<i>C. brunneus</i>	0.390	0.440	0.100	-4.8	-3.6
7	<i>C. brunneus</i>	2.360	3.080	0.850	5.1	-0.2
8	<i>C. brunneus</i>	1.730	2.260	0.740	0.1	0.4
9	<i>C. brunneus</i>	2.070	2.630	0.840	3.3	0.0
10	<i>C. brunneus</i>	1.570	2.000	0.870	-2.6	1.3
11	<i>C. brunneus</i>	1.540	1.950	0.730	4.9	0.2
12	<i>N. janthina</i>	0.730	0.590	0.078	-2.7	-4.0
13	<i>N. janthina</i>	0.330	0.200	0.053	6.3	0.5
14	<i>H. sylvina</i>	0.140	0.130	0.029	2.0	2.8
15	<i>H. sylvina</i>	0.280	0.250	0.054	4.4	0.9
16	<i>O. plecta</i>	0.700	0.660	0.140	1.5	-0.2
17	<i>X. xanthographa</i>	0.830	0.820	0.150	-3.5	-2.1
18	<i>X. xanthographa</i>	1.030	1.160	0.290	-0.3	0.8
19	<i>A. gamma</i>	0.490	0.520	0.130	5.1	-0.2
20	<i>A. gamma</i>	0.880	0.820	0.180	-1.5	1.5
21	<i>A. gamma</i>	1.500	1.580	0.310	-6.6	-0.7
22	<i>A. tragopyinis</i>	0.980	0.970	0.200	-1.6	-0.2
23	<i>X. c-nigrum</i>	1.200	1.360	0.340	-5.0	0.4
24	<i>A. urticae</i>	1.260	1.310	0.310	8.2	0.3
25	<i>A. urticae</i>	1.220	1.110	0.210	-13.5	5.8
26	<i>N. comes</i>	1.510	1.670	0.370	1.2	-1.6
27	<i>N. comes</i>	1.620	1.750	0.380	-2.3	-0.6
28	<i>A. exclamationis</i>	1.850	1.360	0.250	0.7	-2.1
29	<i>N. pronuba</i>	1.840	1.540	0.310	0.4	-0.6
30	<i>N. pronuba</i>	1.660	1.350	0.410	-3.8	0.4

Insect No.	Species	a_0	a_1	a_2	θ_1	$\theta_2 - \theta_1$
		(cm ²)	(cm ²)	(cm ²)	(deg)	(deg)
31	<i>N. pronuba</i>	0.970	0.870	0.310	3.5	1.0
32	<i>N. pronuba</i>	2.720	2.030	0.140	-3.6	-8.3
33	<i>N. pronuba</i>	1.590	0.850	0.380	-4.8	2.3
34	<i>N. pronuba</i>	1.880	1.740	0.280	-0.5	-2.0
35	<i>N. pronuba</i>	1.840	0.700	0.430	-1.6	0.9
36	<i>N. pronuba</i>	2.330	0.770	0.500	-3.1	2.0
37	<i>N. pronuba</i>	2.280	0.290	0.520	-1.8	1.1
38	<i>N. pronuba</i>	2.710	0.360	0.620	-11.6	10.4
39	<i>N. pronuba</i>	1.770	0.980	0.620	-8.7	2.1
40	<i>N. pronuba</i>	2.550	0.710	0.550	4.0	0.9
41	<i>N. pronuba</i>	2.490	0.190	0.550	-46.6	-1.1
42	<i>D. plexippus</i>	2.210	1.960	0.370	4.9	-0.7
43	<i>N. fimbriata</i>	2.160	0.220	0.360	-89.4	-1.2
44	<i>S. gregaria</i>	4.110	2.220	1.170	-86.8	-1.8
45	<i>S. gregaria</i>	4.580	1.600	0.830	-80.8	-5.7
46	<i>S. gregaria</i>	4.690	1.670	1.170	-75.3	-11.5
47	<i>S. gregaria</i>	5.300	2.550	1.220	-78.5	-7.2
48	<i>S. gregaria</i>	4.880	0.880	0.600	-60.2	-20.1
49	<i>S. gregaria</i>	9.240	2.050	0.370	-75.9	-12.8
50	<i>S. gregaria</i>	5.440	4.150	1.320	-83.7	-2.4
51	<i>S. gregaria</i>	9.640	4.610	0.970	-89.5	-2.0
52	<i>S. gregaria</i>	10.900	4.960	1.340	-78.1	-7.1
53	<i>S. gregaria</i>	7.170	6.420	1.760	88.3	-2.2
54	<i>S. gregaria</i>	16.800	12.500	3.210	-89.0	-2.1

Note that insect numbers 1, 3 and 41 were known to be misaligned when measured on the system.

Since $-45^\circ < \theta_2 \leq 45^\circ$, the phase difference ($\theta_2 - \theta_1$) was also brought into the same range by addition or subtraction of a multiple of 90° .

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