Radar Cross Section of Insects

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X-band measurements of radar cross section as a function of the angle between insect body axis and the plane of polarization are presented. A finding of particular interest is that in larger insects, maximum cross section occurs when the E-vector is perpendicular to the body axis. A new range of measurements on small insects (aphids and planthoppers) is also described, and a comprehensive summary of insect cross-section data at X-band is given.

INTRODUCTION

Radar has been increasingly used over the past 10 years to observe insects in flight and it is now well established as a technique for studying their aerial migration [1], [2]. A knowledge of insect radar cross sections is a prerequisite of quantitative studies [3], [4] and a number of measurements of this property have been reported from time to time in the literature. The purpose of this paper is to present a range of new findings on the dependence of cross section on radar polarization together with some recent measurements of the very small cross sections of small insects. We also bring these findings together with previously published cross-section data in a compact and accessible form.

POLARIZATION SENSITIVITY MEASUREMENTS

We have previously described a vertically looking radar which uses rotating, linear polarization to measure individual insect alignment and parameters related to body shape [5]. Interpretation of the data from this radar requires a knowledge of how the insect's underside radar cross section varies with the angle between body axis and the radar polarization, and this requirement prompted the design of the experiment illustrated in Fig. 1. In this experiment, 3-cm TEM radiation propagates down the absorptive horn producing an approximately plane wave at the aperture [6] and reflections and leakage to the receiver are carefully canceled by 3-stub tuners. Insects and calibration spheres are separately placed in the 0.015-mm Mylar cradle supported by 0.1-mm nylon threads, and the receiver output is recorded as the target rotates.

The receiver was calibrated by plotting the computed cross sections of differently sized steel spheres [7] against the output they produced when placed in the cradle. Repeated calibration runs indicated that cross sections down to $\ll 10^{-1}$ cm^2 could be reliably measured. Very good agreement was found between the measured angular dependence of the radar cross section of a thin wire and the $\cos^4$ relation expected from theory [8].

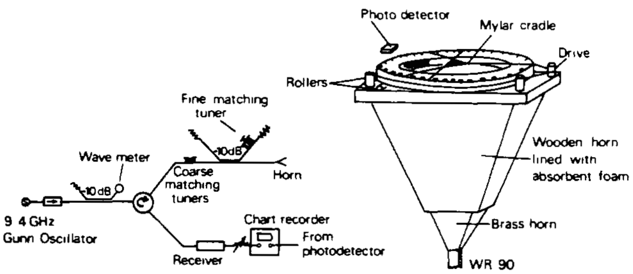

Fig. 1. Experimental system used to measure radar cross section as a function of the angle between *E*-vector and target body axis. The photodetector records angular position marks at 10° intervals around the rotating polystyrene former.

A selection of results for different species and sizes of insects is shown in Fig. 2. One feature of particular interest is the development in the larger insects of a subsidiary peak (Fig. 2(b)) at right angles to the principle maximum produced when *E*-vector and body axes are parallel. This effect was most pronounced in insects whose largest circumference was comparable to half a radar wavelength, and was presumably caused by constructive interference of creeping waves passing round a body. Its practical significance is that in extreme cases where the "circumferential" maximum replaces the longitudinal one (Fig. 2(e)), radar measurements of alignment made on the assumption that maxima occur when body axis and electric vector are aligned would be 90° in error. Fortunately, these cases may be identified in practice because the rotational modulation is relatively shallow.

MEASUREMENTS ON SMALL INSECTS

Small insects have very tiny radar cross sections and in consequence conventional radar range methods are inadequate for their measurement. The transmission line technique is particularly well-suited to the measurement of

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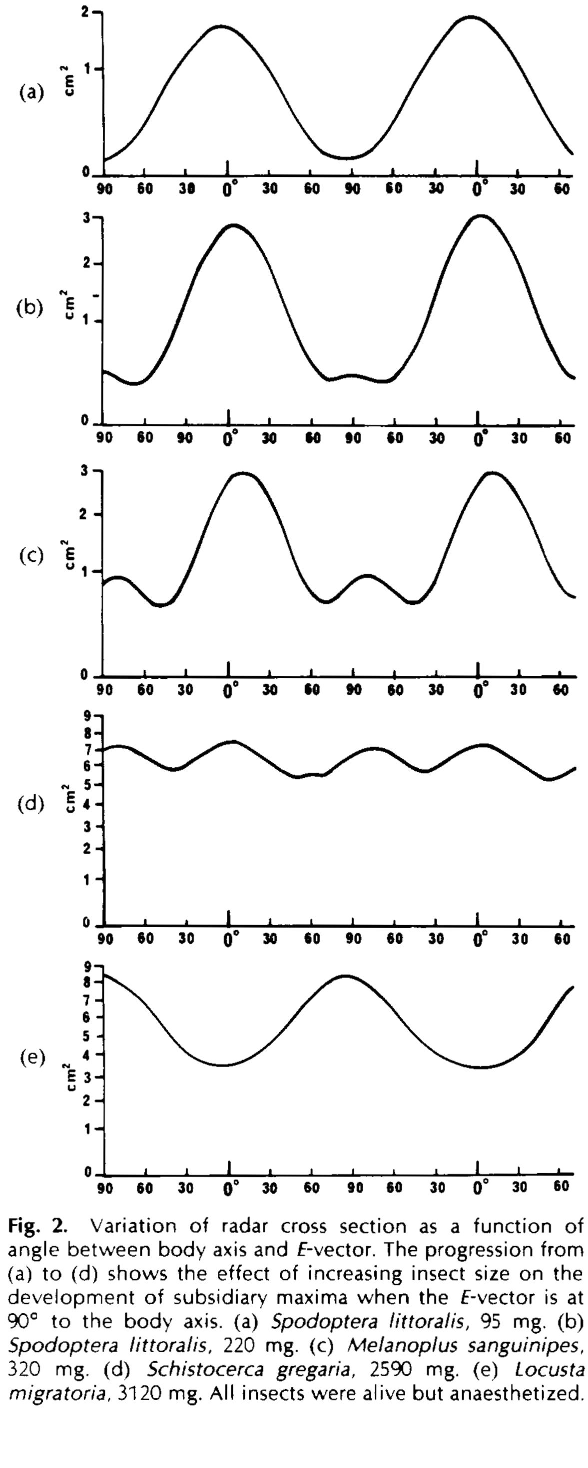

Fig. 2. Variation of radar cross section as a function of angle between body axis and *E*-vector. The progression from (a) to (d) shows the effect of increasing insect size on the development of subsidiary maxima when the *E*-vector is at 90° to the body axis. (a) *Spodoptera littoralis*, 95 mg. (b) *Spodoptera littoralis*, 220 mg. (c) *Melanoplus sanguinipes*, 320 mg. (d) *Schistocerca gregaria*, 2590 mg. (e) *Locusta migratoria*, 3120 mg. All insects were alive but anaesthetized.

small targets because it avoids the r^4 loss of signal power while preserving the free space, transverse nature of the electromagnetic field in the vicinity of the target [9]. In addition, the localized nature of the sensitive volume minimizes interfering returns from target supports. We have therefore adopted this technique to measure the cross sections of aphids and leafhoppers.

The apparatus is shown in Fig. 3 and is similar to that described by Neureuther *et al.* [10] except that an additional matching section was added to the end of the line so that standing waves within the measuring section could be tuned out. The receiver was calibrated by attaching small

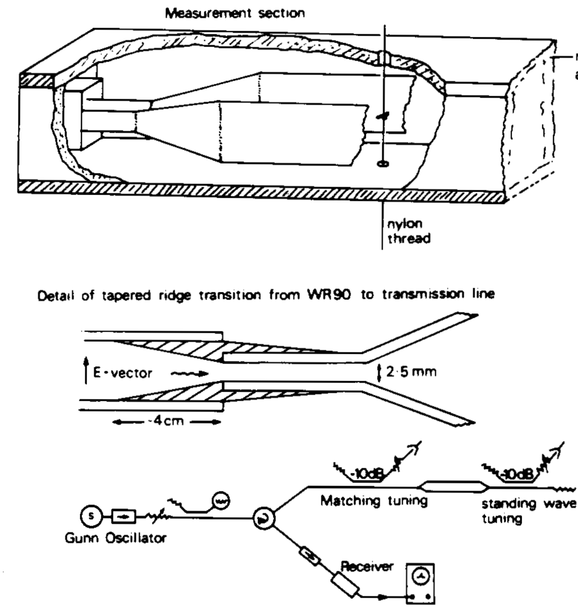

Fig. 3. Parallel-plate transmission line for cross-section measurements of small targets. The enclosure of microwave absorbing material reduces the sensitivity of the line to perturbations due to proximity of the operator.

steel spheres to the end of 0.1-mm-diameter nylon threads with very small spots of "super glue" and dangling them in the center of the measurement section. Very careful attention to the mechanical and thermal stability of the apparatus allowed repeatable measurements to be made down to 10^{-6} cm^2.

The anaesthetized insects were similarly glued with their body axis either vertical or horizontal, to the center of a nylon thread. This thread was passed vertically through the measurement section, so that it positioned the insect centrally. Twirling the thread caused the horizontally mounted insects to alternately present head-on and side-on aspects. Angular position was not accurately monitored but it could be seen that maxima in receiver output coincided with broadside aspect. Some results for insects of body weight between 10^{-4} and 10^{-6} g are shown in the lower range of Fig. 4.

Collation of Cross-Section Data

During the past 10 years we have accumulated a number of experimental measurements of insect radar cross section and it seems appropriate to present them here together with the results of the experiments described above. Perhaps the most instructive way to collate data from a variety of insects is to plot aspect averages of cross section against body weight. This is the method we have adopted in Fig. 4. For completeness we have also included all the *X*-band published data of which we are aware. In the cases where authors recorded dimensions rather than insect weight we have used these dimensions to estimate mass. The positions of the corresponding points on the graph are therefore of less significance than those for which the insect mass was known, and they are correspondingly plotted with broken lines. The continuous line in Fig. 4 shows the relationship

Table 1 Key to the Data Points of Figure 4

Plot No.	Insect Type	Author and Reference	Measurement Methods
1	*Culex pipiens* (mosquito)	Frost and Downing [12]	Scaled from $\lambda = 1.9$ cm, mass estimated from dimensions
2	*Timpula simplex* (range crane fly)	Hajovsky *et al.* [14]	Spot measurements with the electric vector along the body axis (L), and traverse to it (T), Mass estimated from dimensions.
3	*Lucilia caesar* (green bottle fly)		
4	*Apis mellifera* (honey bee)		
5	*Pogonomyrmex californicus* (California harvester ant)		
6	*Hippodamia convergens* (Convergent lady beetle)		
7	*Diabratica duodecimpunctata* (twelve spotted cucumber beetle)		
8	*Cirphis unipuncta* (army worm moth)		
9	*Colias eurytheme* (alfalfa caterpillar butterfly)		
10	*Trimeratropic dyanipennis* (blue winged locust)		
11	Spider unidentified		
12	*Schistocerca gregaria* ♂	Riley [15]	Averages over 360° in presented aspect with body axis and electric vector horizontal, elevation angle zero.
13	" ♀		
14	*Locusta migratoria* ♂		
15	" ♀		
16	*Spodoptera littoralis* ♀		
17	*Spodoptera exempta* ♂	Riley *et al.* [16]	
18	" ♀		
19	*Spodoptera littoralis* (moth) ♂	Riley (unpublished data)	Results obtained with the apparatus shown in Fig. 1, underside viewing, averages over a range of 180° between body axis and E-vector with body axis perpendicular to the (vertical) direction of propagation.
20	" ♀		
21	*Schistocerca gregaria* (desert locust) ♂		
22	" ♀		
23	*Locusta migratoria* (African migratory locust) ♂		
24	" ♀		
25	*Anacridium melanorhodon*		
26	*Locustana pardalina* ♂		
27	" ♀		
28	*Melanoplus sanguinipes* ♂		
29	" ♀		
30	*Aglais urticae*	Schaefer [17]	Averages over 360° in presented aspect with body axis and electric vector horizontal, elevation angle zero, except those marked with a V which are for vertical polarization.
31	*Agrotis exclamationis*		
32	*Chortoicetes terminifera* ♂		
33	" ♀		
34	*Schistocerca gregaria* ♂		
35	" ♀		
36	mosquito	Tarbell [18]	Mass estimated. Unspecified attitude producing the highest cross section (presumably broadside and parallel to the E-vector).
	Manduca sexta (tobacco hornworm)	Glover *et al.* [13]	Maximum values observed in free-flight observations.
	Apis mellifera (honey bee worker)		
	Nilaparvata lugens (Brown planthopper)	Riley (unpublished data)	These are new results obtained with the apparatus shown in Fig. 3.
39	" ♂		Head- or tail-on.
40	" ♀		"
41	" ♂		Broadside-on.
42	" ♀		"
43	Aphids	G. A. Bent (personal communication)	Broadside-on.
44	"		Body vertical.
45	"		Head- or tail-on.

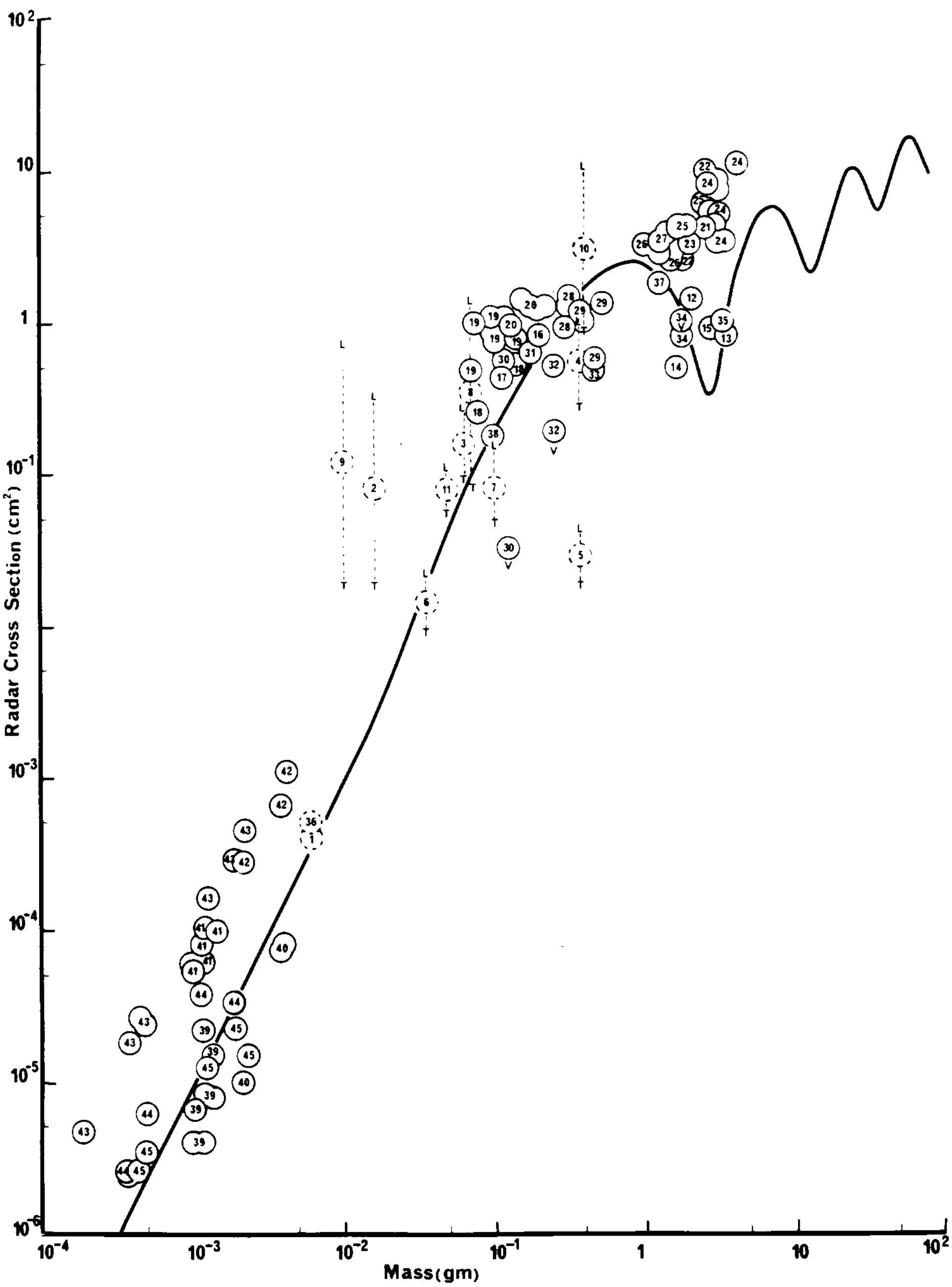

Fig. 4. Insect radar cross sections as a function of their mass. With the exception of point 1 (which was scaled from λ = 1.9 cm) all the results are for λ = 3.2 cm. Linear polarization was used in all cases. The insect mass for some measurements was not given by the author and so has been estimated from body dimensions—their positions on the graph are thus of lower significance than those of other points, and they are correspondingly plotted with dotted lines. The curve for water spheres is from the data of Herman *et al.* [11]. A key to data points is given in Table 1.

between the mass and radar cross section of spherical water droplets [11], and a key to the insect data sources is given in Table 1.

Discussion

It would appear from the data shown in Fig. 4 that the radar cross section of an insect may be very approximately represented by that of a spherical water droplet of the same mass, and that this representation holds true over a mass range of 10 000 : 1. It must be remembered however that the aspect dependence of radar cross section affects insect detectability. This is particularly the case where an aerial population has a measure of collective orientation and which may, in consequence, be detectable only in the "side-on" quadrants of a scanning radar [20]. Polarized displays of this sort are superficially similar to the sector patterns sometimes produced by birds on MTI radars (and with which they have apparently been confused [21]) but which, in fact, correspond to front-back rather than side-on quadrants.

It may be noted in conclusion that apart from their use in entomological studies, insect radar cross sections are of increasing relevance in the design of sensitive, short-range battlefield radars [22].

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