

**Ventral-aspect radar cross sections and polarization patterns of insects at X band and their relation to size and form**

Journal:	<i>International Journal of Remote Sensing</i>
Manuscript ID	Draft
Manuscript Type:	IJRS Research Paper
Date Submitted by the Author:	n/a
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Keywords:	radar, animal tracking, ecology, polarization
Keywords (user defined):	insect, mass estimation, morphological form

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## Ventral-aspect radar cross sections and polarization patterns of insects at X band and their relation to size and form

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Funding bodies: JWC and KSL were supported by the Biotechnology and Biological Sciences Research Council (UK) under grant BBS/E/C/00005195 and the Science and Technology Facilities Council (UK) under Newton Fund grant ST/N006712/1.

Disclosure statement. The authors declare that they have no financial interest in the application of this research.

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7 Footnote

8 <sup>1</sup>Retired.

9  
10 [Note on supplemental files. These two files are Excel workbooks (.xlsx, 59 and 19 kB)  
11 each with a single sheet containing a table of data and associated notes. In the .pdf file  
12 they unfortunately extend over 27 poorly formatted pages. In the .html file they do not  
13 appear.]  
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## Ventral-aspect radar cross-sections and polarization patterns of insects at X band and their relation to size and form

### ABSTRACT

A dataset of ventral-aspect insect radar cross-sections (RCSs) and polarization patterns, measured at X band (9.4 GHz, linear polarization) in laboratory rigs, has been collated from a number of sources. The data have been analysed to identify relationships between RCS parameters (one representing size and two the polarization-pattern shape) and the insects' masses and morphological dimensions and forms. An improved mass-estimation relationship, with appropriate asymptotes for very small and very large insects, is presented. This relationship draws only on the RCS size parameter and it is shown that incorporating one or both of the RCS shape parameters provides little additional benefit. Small insects have polarization-pattern shapes that fall within a relatively limited region of the range of parameter values allowed by electromagnetic scattering theory. Larger insects have shapes that extend beyond this region, following a broad trajectory as size and mass increases; at masses above ~0.6 g the pattern becomes 'perpendicular', with maxima when the E-field is orthogonal to the body axis rather than parallel to it. RCS shape can be used to infer morphological form for small insects (<80 mg), but not for larger ones. These results are consistent with observations from X-band vertical-beam entomological radars and provide a basis for identification, at least to broad taxon classes, of the targets detected by such radars.

Keywords: insect; radar cross-section; polarization pattern; mass estimation; morphological form [Notes to editor: 1) if keywords not required, delete; 2) these keywords are preferred to those entered online, which were constrained by available choices.]

### 1. Introduction

A variety of radar types have proved to be effective at detecting insects in flight,

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2  
3 especially when the insects have risen above terrain features and vegetation (Drake and  
4  
5 Reynolds 2012). Flights at these higher altitudes usually constitute migrations (Dingle  
6  
7 2014) and may lead to invasions of growing crops and consequent economic losses  
8  
9 (Drake and Gatehouse 1995; Koul, Cuperus, and Elliott 2008). Radar provides the only  
10  
11 practical means of acquiring information about such flights (e.g. Chapman, Reynolds, et  
12  
13 al. 2002; Chapman et al. 2005, 2006; Drake and Reynolds 2012, chapters 12, 13; Drake  
14  
15 and Wang 2013). In addition, radar observation has proved critical to recent research  
16  
17 into the cues that insects use to determine their orientation (heading direction) while  
18  
19 flying hundreds of metres above the surface, often in darkness, and into the effects these  
20  
21 orientation behaviours have on the insects' flight trajectories (Chapman et al. 2010; Hu,  
22  
23 Lim, Reynolds, et al. 2016; Reynolds et al. 2016).

24  
25  
26  
27 A radar configuration that has proved particularly useful for observing insect  
28  
29 migrations employs a vertical beam that incorporates both rotating linear polarization  
30  
31 and a very narrow angle conical scan (Chapman, Smith, et al. 2002; Drake 2002). With  
32  
33 this 'ZLC configuration' (also known as a 'VLR' or *vertical-looking radar*), insects are  
34  
35 interrogated by the beam modulations during the few seconds that it takes for them to  
36  
37 complete a beam transit. Analysis of the rather complicated echo signal time series  
38  
39 allows retrieval of information not only about the individual insect's trajectory (its  
40  
41 height, its speed and direction of movement, and its heading direction) but also about its  
42  
43 identity. The latter takes the form of four parameters characterising the target: one  
44  
45 measure of size, two of shape, and the wing-beat frequency (though for some echoes no  
46  
47 wing-beating is detectable). Some or all of these parameters have been used to  
48  
49 discriminate target types and, in association with other data (e.g. trap catches), make  
50  
51 identifications of the species undertaking the migrations (e.g. Chapman, Reynolds, et al.  
52  
53 2002; Chapman et al., 2005, 2006, 2010; Drake and Wang 2013). A study of a large  
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3 sample of echoes for which all four parameters were retrieved, obtained over eight  
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5 months from a single site in inland eastern Australia using an X-band ZLC radar,  
6  
7 revealed several distinct target classes which occurred with varying frequency from  
8  
9 night to night and from month to month (Drake 2016).  
10

11  
12 From the viewpoint of a biologist user, mass is a much more readily  
13  
14 interpretable measure of target size than any directly radar-observable quantity. It is the  
15  
16 most obvious identification character to use when relating radar observations of  
17  
18 airborne insects to samples obtained from aerial or ground-level traps, in part because  
19  
20 the range of insect masses is very large (>4 orders of magnitude). Mass values also feed  
21  
22 directly into estimates of 'bioflow' and consideration of aero-ecological processes (Isard  
23  
24 and Gage 2001; Frick et al. 2013; Hu, Lim, Horvitz, et al. 2016), so their estimation has  
25  
26 intrinsic biological value. Methods for estimating the masses of insect targets from their  
27  
28 radar properties, especially the *radar cross section* (RCS, the radar measure of target  
29  
30 size), have been developed previously and are considered again here. It would  
31  
32 obviously be useful if further quantities could be identified that would allow  
33  
34 discrimination between targets with similar masses; these would constitute information  
35  
36 dimensions orthogonal to that provided by the measure of radar size. The obvious  
37  
38 candidates for such quantities are the wing-beat frequency (see below) and the two  
39  
40 shape parameters, either singly or in combination. Because the radar wavelength is  
41  
42 comparable to the size of the insect targets, the shape parameters can be expected to  
43  
44 provide information only about large-scale features. The obvious candidate is the  
45  
46 length:width ratio, termed here the 'form'  $f = l/w$ . The primary aim of this study has been  
47  
48 to identify relationships linking the three radar-target parameters to  $m$  and  $f$ , and if these  
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50 are informative to develop equations for routine estimation of these two characters from  
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52 ZLC-radar observation data.  
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3 Association of target properties with RCS size and shape values can be achieved  
4 through calculation using electromagnetics theory or by measurement. Application of  
5 theory to biological targets presents many challenges and so far has been confined to a  
6 single example (a bat; Mirkovic et al., 2016). Laboratory measurements of the RCSs of  
7 insects for which the species identification is known have been made on several  
8 occasions (summarized in Drake and Reynolds 2012, chapter 4). For this paper we have  
9 compiled a dataset containing all available vertical-incidence measurements made at X-  
10 band frequencies (~9.4 GHz) for which both size and shape parameters were obtained;  
11 we have then used this empirical data to examine the relationships between the masses  
12 and morphological properties of insects and their observable radar properties.  
13 Associations between radar parameters and taxonomic group will also be searched for.  
14 Some of the values in the dataset are from published research, some are from archived  
15 data for which only selected results had been published previously, and some are new  
16 measurements.

17  
18 The fourth identification parameter retrievable from ZLC echoes, the wing-beat  
19 frequency, may also have utility both for inferring target mass (as larger insects  
20 generally have lower wing-beat frequencies; Dudley 2000, chapter 3) and as an  
21 orthogonal dimension for discriminating between targets of similar masses (Drake  
22 2016). However, it was not determined for the specimens measured and is not  
23 considered further in this report.

## 2. Parameters, datasets, and measurements

### 2.1. Size, shape, and the polarization pattern

24 Both the ZLC observations and the laboratory measurements determine the  
25 backscattering RCS of a single insect oriented with its underside directed towards the  
26 beam ('ventral aspect'), and the variation of this with polarization angle (i.e. with the  
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3 direction of the electric field of a linear-polarized electromagnetic wave). The variation  
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5 of the RCS with polarization angle is termed the 'copolar linear polarization pattern'  
6  
7 (CLPP). In the case of the laboratory measurements, the specimen was mounted  
8  
9 horizontally and upright with the underside down, in the expectation that this  
10  
11 approximates a normal flight attitude, and the beam was directed vertically. The zero  
12  
13 angle of the CLPP is defined to be aligned with the main axis of the insect's body. For  
14  
15 the radar observations, it is not certain that the targets have adopted an upright and  
16  
17 horizontal attitude (see below), so it should only be said that the RCS values relate to  
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19 zenith incidence.  
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23 A generally steady flight is to be expected during migration, and an absence of  
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25 manoeuvring during the beam transit is assumed in the analysis of the echo-signal time  
26  
27 series. This assumption is essentially validated whenever a good quality fit to an echo  
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29 signal is obtained, as required for successful retrieval of the flight and target-  
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31 identification parameters (Drake and Reynolds 2012, pp. 156-159). A steady flight  
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33 suggests an upright stance (i.e. zero roll angle) but it does not require the insect's body  
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35 to be horizontal and there is now evidence that some migrating insects (particularly  
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37 small ones) fly with a non-zero (and positive, i.e. head above tail) pitch angle  
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39 (Melnikov, Istok, and Westbrook 2015). The effect of a pitched attitude cannot be  
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41 explored with the dataset available for this study and is not considered further, except to  
42  
43 note that: (1) consideration of electromagnetic scattering processes suggests pitch  
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45 effects will be slight if the pitch is only moderate, at least for targets that are not much  
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47 longer than a wavelength (32 mm for the X band radars of concern here); and (2) radar-  
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49 observed CLPPs (Dean and Drake 2005) appear compatible with the laboratory  
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51 measurements reported here.  
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3 For copolar-linear observations, the variation of the RCS  $\sigma$  with polarization  
4 angle  $\phi$  has the general form  
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$$\sigma(\phi) = a_0[1 + \alpha_2 \cos 2(\phi - \theta_2) + \alpha_4 \cos 4(\phi - \theta_4)], \quad (1)$$

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8  
9 where  $a_0$  is the zenith-incidence polarization-averaged RCS and  $\alpha_2$  and  $\alpha_4$  are  
10 dimensionless parameters with positive values (Aldhous 1989; Dean and Drake 2005).  
11  
12 The parameter  $a_0$  is a measure of the target's size, with dimensions  $L^2$  (i.e. area; units  $m^2$   
13 or, more commonly for insect targets,  $cm^2$ ; often expressed logarithmically as decibels  
14 relative to  $1 cm^2$ , denoted dBsc). In comparison with RCSs provided by other radar  
15 configurations,  $a_0$  has the considerable advantage of relating to a consistent aspect and  
16 of being independent of the insect's orientation. Relationships between  $a_0$  and mass  
17 have been developed previously (Aldhous 1989; Chapman, Smith, et al. 2002; Wang  
18 2008); an improved relationship incorporating the additional data available to this study  
19 is presented here.  
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32 The expression in square brackets in Equation (1) is the CLPP. For a bilaterally  
33 symmetric target, which an insect in unbanked flight will constitute to a good  
34 approximation, the CLPP must also exhibit bilateral symmetry and therefore  $\theta_2$  and  $\theta_4$   
35 must be equal. Symmetry considerations also require that the common value, denoted  
36  $\theta_0$ , must represent either the target's body axis or the perpendicular to it. Both radar  
37 observations (e.g. Dean and Drake 2005) and laboratory measurements (Hobbs and  
38 Aldhous 2006) are generally consistent with a common value for  $\theta_2$  and  $\theta_4$ , and this  
39 simpler CLPP form has been used in the analyses presented here. The  $\alpha_2$  term in the  
40 CLPP produces elongation (of a basic circular form) and  $\alpha_4$  contributes a cruciform  
41 element. Consideration of electromagnetic scattering mechanisms indicates that for  
42 insects that are small relative to a wavelength the elongation direction of the CLPP will  
43 coincide with the body axis. Previous analyses of measurements at X band have  
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confirmed this and have also demonstrated that for very large insects (e.g. female migratory locusts *Locusta migratoria*, typical mass ~3 g) CLPP elongation occurs at right angles to the body axis (Riley 1985). Following Dean and Drake (2005), these two CLPP types will be referred to as 'parallel' and 'perpendicular' respectively. For the measurements, the insects were oriented in the rig with their heads towards  $\theta_0 = 0$ . For observations made with a radar, determining whether  $\theta_0$  represents the body axis or the normal to it requires additional, *a priori*, information (such as that the observations are being made in a region where the aerial fauna includes very few large insects). Even if the  $90^\circ$  uncertainty is resolved, ambiguity about whether the heading direction is  $\theta_0$  or  $\theta_0 + 180^\circ$  (for the parallel case) will remain.

According to electromagnetic theory, the parameters  $\alpha_2$  and  $\alpha_4$  are positive and are constrained by

$$\alpha_4 \leq \left(1 \pm \sqrt{1 - \alpha_2^2/2}\right)/2 \quad (2)$$

(Dean and Drake 2005). This equation defines a semi-elliptical boundary with  $0 \leq \alpha_2 \leq \sqrt{2}$  and  $0 \leq \alpha_4 \leq 1$ , the ellipse centre being at  $(\alpha_2, \alpha_4) = (0, 1/2)$ . In the measurement data, the angle  $\theta_0$  for targets with perpendicular CLPPs will be retrieved as  $\sim 90^\circ$ . An alternative scheme for representing perpendicular targets is to retain  $\theta_0$  as representing the body axis (i.e.  $\theta_0 = 0$ ), but to make  $\alpha_2$  negative (Dean 2007); this moves these shapes into the left-hand half of the constraint ellipse so that they are clearly separated from similarly-shaped CLPPs with parallel alignment. This reset is straightforward for the laboratory measurements, for which the true alignment is known, and is adopted in this work. It is of course problematic for observation data unless some means of distinguishing the parallel and perpendicular cases is available.

Various transformations or combinations of the variables  $a_0$ ,  $\alpha_2$ ,  $\alpha_4$  and  $\theta_0$  are available and some have interpretative value in particular circumstances (Aldhous 1989; Hobbs and Aldhous 2006; Dean 2007; Drake 2016). The 'harmonic model' (Hobbs and Aldhous 2006) of Equation (1) appears natural and straightforward and has been used in a previous investigation of insect target shapes (Dean and Drake 2005); it will form the basis for the present analysis. There will however be some discussion of the parallel  $\sigma_{xx} = \sigma(\phi - \theta_0 = 0)$  and transverse  $\sigma_{yy} = \sigma(\phi - \theta_0 = 90^\circ)$  RCS values, which can be obtained from the transformations (Aldhous 1989, p. 21)

$$\sigma_{xx} = a_0(1 + \alpha_2 + \alpha_4) \quad (3a)$$

$$\sigma_{yy} = a_0(1 - \alpha_2 + \alpha_4) . \quad (3b)$$

The ratio of these two RCSs,  $r_{sh} = \sigma_{xx}/\sigma_{yy}$ , contours of which form straight lines in the  $(\alpha_2, \alpha_4)$  plane, will receive particular attention. Use will also be made of the orthogonal variables  $(p, q)$  introduced by Drake (2016). Contours of  $p$  are concentric ellipses, with  $p = 1$  defining the constraint boundary of Equation (2) and  $p = 0$  the central point at  $(\alpha_2, \alpha_4) = (0, 0.5)$ . Contours of  $q$  are orthogonal to these and form curves that run from the centre to the periphery, with  $q = 0$  coincident with the  $\alpha_4$  axis,  $q = 1$  intersecting the boundary at  $\alpha_2 \approx 0.9$ , and  $q = 2$  intersecting at  $\alpha_2 \approx 1.4$ , just below the boundary's right-hand maximum. The  $(p, q)$  system becomes unsatisfactory for  $\alpha_4 \geq 0.5$ , but such targets occur infrequently and there is only one example in the measurement dataset.

## 2.2. The dataset and data sources

The CLPP data used in this analysis comprise 156 specimens of 40 species (Table 1). They originate from four sources: (1) measurements made in 1979 by JRR and associates at the Centre for Overseas Pest Research, U.K., denoted here by C; (2) measurements by Aldhous (1989), denoted A; (3) measurements by Wolf et al. (1993),

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3 denoted W; and (4) measurements made in 2006 by ADS and DRR at Rothamsted  
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5 Research, U.K., denoted S. The species included are mainly grasshoppers and locusts  
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7 (Orthoptera) and moths and butterflies (Lepidoptera), two groups that include numerous  
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9 migratory species (Johnson 1969); a few beetles (Coleoptera), bees and wasps  
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11 (Hymenoptera), and crane flies (Diptera) are also present. All specimens occur once only  
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13 in the dataset. There are five species for which measurements are available from two  
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15 sources and 11 species for which measurements of five or more specimens are  
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17 available; however, intra-specific variation is not considered in this paper.  
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21 The specimens derive from Europe (southern England, C, A, S) and North  
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23 America (USA, W), or from laboratory cultures of African and North American species  
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25 (C, A, and probably W). Many of the species measured are known migrants and some  
26  
27 have been the subject of entomological radar observations (Drake and Reynolds 2012,  
28  
29 chapters 10-13). A few probably non-migratory species appear to have been included  
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31 because of their ready availability when measurements were being made; these add  
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33 diversity to the sample and in some cases provide examples of particular body forms  
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35 and sizes. Most of the species represented occur only in one continent and the dataset  
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37 will therefore not be representative of the migrating insect fauna at any actual ZLC-  
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39 radar observing site. This is especially the case for the orthopteran subsample, which  
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41 comprises only six species of which four, with 33 specimens (69% of the subsample),  
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43 are of unusually large types (locusts, all with  $m > 1$  g and all but one, an outlier, with  
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45 perpendicular CLPPs). Because such large insects are not found in the migrant faunas at  
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47 the two localities (in England and Australia) where most ZLC-radar observations have  
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49 been made, some of the analyses reported here have been repeated with these specimens  
50  
51 excluded. The lepidopteran specimens comprise 28 species, many known to be  
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53 migratory; the mass range  $100 < m \leq 300$  mg, with 54 specimens (57% of the  
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3 lepidopteran subsample), is perhaps disproportionately represented. Masses (for all  
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5 taxa) range from 9 mg to 4.1 g, the latter probably close to the upper limit for migrant  
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7 species; the range 550-1050 mg is unfortunately represented by only a single specimen.  
8

9  
10 *Insert Table 1 near here*

11  
12 Selected results from C appeared in Riley (1985), but the values used here have  
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14 been recalculated from the original data and for  $\alpha_2$  and  $\alpha_4$  are mostly new, as are all the  
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16 S data. For A and W, the values used here are those recalculated by Hobbs and Aldhous  
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18 (2006), with  $\alpha_2$  reset negative for targets with  $\theta_0 \approx 90^\circ$  from the body axis (i.e. the  
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20 largest targets); further, because these authors used a different convention, the  $\sigma_{xx}$  and  
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22  $\sigma_{yy}$  values for these large targets have been exchanged.  
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26 The values used in this analysis were obtained by the SM3 method of Hobbs and  
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28 Aldhous (2006), which ensures that  $\alpha_2$  and  $\alpha_4$  fall within (or on) the constraint  
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30 boundary of Equation (2). This in turn ensures that the RCS remains  $\geq 0$  at all  
31  
32 polarization angles, as required by definition. For C and S, SM3 estimates were  
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34 obtained with the *nlm* (Non-Linear Minimization) facility of the R data analysis system  
35  
36 (R Development Core Team 2008); the quantity minimized was the sum of squares of  
37  
38 the differences between the measured and fitted RCSs, over the full  $360^\circ$  range of  
39  
40 polarization angles  $\phi$ . The fitted RCSs were calculated from the SM3 formula with fit  
41  
42 variables  $\sigma_{xx}$ ,  $\varepsilon$ ,  $\beta$  and  $\theta_0$  (Hobbs and Aldhous 2006, their equation 4;  $\varepsilon^2 = \sigma_{yy}/\sigma_{xx}$  and  $\beta$   
43  
44 is a phase). Values of the parameters  $a_0$ ,  $\alpha_2$  and  $\alpha_4$  of Equation (1) were recovered as  
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47

$$48 \quad a_0 = \sigma_{xx}(3 + 2\varepsilon \cos \beta + 3\varepsilon^2)/8 \quad (4a)$$

$$49 \quad \alpha_2 = \sigma_{xx}(1 - \varepsilon^2)/2 a_0 \quad (4b)$$

$$50 \quad \alpha_4 = \sigma_{xx}(1 - 2\varepsilon \cos \beta + \varepsilon^2)/8 a_0 \quad (4c)$$

51  
52  
53 (Aldhous 1989, p. 21). Note that Equation (4b) automatically delivers the negative  
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55 values of  $\alpha_2$  discussed above for the targets for which  $\sigma_{yy} > \sigma_{xx}$ . Solutions were also  
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3 obtained via Equation (1) for verification purposes. They were mostly within 1% of the  
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5 SM3 values for  $a_0$  and  $\alpha_2$  and often also for  $\alpha_4$ , although there were some large  
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7 differences for this last parameter, usually when its value was  $<0.1$ . These 'harmonic'  
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9 solutions also helped to identify false minima in a small number of the SM3 fits, which  
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11 were then recalculated satisfactorily using different starting values. Some statistics for  
12  
13 the parameter values are provided in Table 2.  
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17 *Insert Table 2 near here*  
18

19 In addition to these CLPP measurements, in order to extend the analysis of the  
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21 mass vs RCS relationship to low masses, limited use has been made of available values  
22  
23 of  $\sigma_{xx}$  and  $\sigma_{yy}$  for smaller insects, denoted L. Measurements ( $\sigma_{xx}$  only) of planthoppers  
24  
25 and aphids (both Hemiptera) made by JRR and G. A. Bent respectively were recovered  
26  
27 by digitising a graphic in Riley (1985). Measurements of ladybirds and other beetles,  
28  
29 lacewings (Neuroptera), moths, and hoverflies (Diptera) were made between 2000 and  
30  
31 2009 by JWC and ADS, working at Rothamsted Research; statistics or example values  
32  
33 for some of these have appeared previously (Chapman, Reynolds, et al. 2002; Chapman  
34  
35 et al. 2005, 2006). After exclusion of two large specimens that fall well within the range  
36  
37 for which CLPP measurements are available, L comprises 77 specimens of 15 species  
38  
39 and covers a mass range of 0.2–65 mg; there are mass values for all of these, but only  
40  
41 37 (48%) also have lengths and widths.  
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### 45 46 **2.3. Measurements** 47

48  
49 All CLPP measurements were made in laboratory rigs with the target at a distance of  
50  
51  $\sim 1$  m from the antenna, which had a small aperture so that the target was in the far field.  
52  
53 For W a pulse-chirp radar system was used and only echo from the target's range was  
54  
55 recorded; the radar operated over frequencies ranging from 8 to 12 GHz and the results  
56  
57 are averages thought to represent a frequency of  $\sim 10$  GHz. The other measurement  
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3 systems used continuous transmission at 9.4 GHz, the frequency used by almost all X-  
4  
5 band entomological radars; they relied on absorptive materials, and for A a sky  
6  
7 background, plus cancellation of non-target echo by passively returning an anti-phase  
8  
9 signal via a directional coupler. Calibration was with metal spheres with RCSs  
10  
11 extending over the range of RCSs being measured and placed at the target position; a  
12  
13 calibration curve was fitted and its parameters used to convert measured echo intensities  
14  
15 (recorded as a voltage) to RCSs. Measurements were made at  $\phi$  intervals of  $10^\circ$  in C,  
16  
17  $15^\circ$  in W, and  $<1^\circ$  in A and S. The S data subset includes repeated measurements of a  
18  
19 small metal rod (length 16 mm, i.e.  $\sim\lambda/2$ , and diameter  $\sim 1$  mm) or 'dipole' that served to  
20  
21 verify that the system performance had not altered. Further details for A, C, and W are  
22  
23 available in the original publications (Aldhous 1989; Riley 1985; Wolf et al. 1993;  
24  
25 Hobbs and Aldhous 2006); for S, the rig used was an upgraded version of that for C,  
26  
27 with automated data acquisition at fine angular resolution.  
28  
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31

32 The smaller insects in the L data subset were measured with a transmission-line  
33  
34 (or 'rail-line') rig (Riley 1985). It was not practicable to measure the insect's angular  
35  
36 position, and the  $\sigma_{xx}$  and  $\sigma_{yy}$  values were obtained by gluing the insect first vertically  
37  
38 ( $\sigma_{yy}$  measurement) and then horizontally ( $\sigma_{xx}$  measurement) to a taut attachment line  
39  
40 passing between the rails, with the insect oriented perpendicular to the rails (and parallel  
41  
42 to the E-field) in the latter case.  
43  
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45

46 Measurements were made with specimens that were either anaesthetized (A, W),  
47  
48 freshly dead (some S, probably C), or freshly thawed after having been frozen (some S).  
49  
50 As water is the main radio-reflective component of an insect it is important to measure  
51  
52 both mass and the RCS properties before dehydration occurs; it appears that this was  
53  
54 generally achieved. The legs of some of the large locusts in C drooped when the insect  
55  
56 was mounted in the measuring rig, and for some of these the measurements were made  
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3 with the hind legs tied up with light thread to approximate the posture adopted by  
4 locusts in 'cruising flight'. An investigation of a small sample indicated that specimens  
5 with their legs drooping had CLPPs that were parallel, and thus very different from the  
6 perpendicular patterns obtained from the same specimens with their legs tied up.  
7  
8 Measurements made with the legs down, or with one or both legs missing, have not  
9  
10 been used. Masses and body lengths were measured for all 156 specimens and abdomen  
11  
12 widths for all but one.  
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### 20 **3. Results**

21  
22 The RCS parameters for each specimen, along with specimen identifications, masses,  
23 and dimensions, are provided in a supplementary spreadsheet file (Excel 2007,  
24 Microsoft Corporation, Redmond, WA, USA; available via Figshare [Note to Editor:  
25 please insert appropriate citation and link.]) containing two tables: the first with the  
26 CLPP parameters (C, A, S, and W data) and the second with  $\sigma_{xx}$  and  $\sigma_{yy}$  values (L). The  
27  
28 following sections present analyses and interpretations of this ensemble of results.  
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#### 36 **3.1. Estimation of target mass**

37  
38 With more measurements now available, it is appropriate to re-examine the relationship  
39 of target mass to ZLC-observable size and shape parameters. As the parameter  $a_0$  is a  
40 measure of target size, it is the obvious quantity on which to base an estimate of mass  
41 and a method depending on it alone is developed first. The possibility that improved  
42 mass estimates can be obtained by additionally incorporating the shape parameters  $\alpha_2$   
43 and  $\alpha_4$  is also explored.  
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##### 53 **3.1.1. Polarization-averaged RCS and mass**

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55 For a particular radar frequency and a particular target shape, the variation of the  
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3 target's RCS with its size passes through three regimes (Knott, Shaeffer, and Tuley  
4  
5 2004). In the 'Rayleigh region', where the target's longest dimension  $l$  is much smaller  
6  
7 than the radio wavelength  $\lambda$ , the RCS  $\sigma$  increases with the sixth power of  $l$ , i.e.  $\sigma \propto l^6$ .  
8  
9 At the opposite extreme, in the 'optical region',  $\sigma \propto l^2$ . Between these two is the  
10  
11 transitional 'Mie region', in which the RCS passes through a small number of maxima  
12  
13 and minima; these oscillations continue, with diminishing intensity, in the initial part of  
14  
15 the optical region. This variation is well documented for water spheres (e.g. Drake &  
16  
17 Reynolds 2012, pp. 51-54), for which the transition region is approximately  
18  
19  $\lambda/5 \leq l \leq 5\lambda$ . If this applies also to insects, then the two smallest specimens in the CLPP  
20  
21 dataset ( $l = 5$  mm, supplementary file) and about half of those in L just fall into the  
22  
23 Rayleigh region and the remainder ( $8 \leq l \leq 65$  mm) are Mie targets. The volume  $V$  of a  
24  
25 target will vary as  $l^3$  (again assuming a particular target shape). If migratory insects all  
26  
27 have approximately the same density, so that their mass  $m \propto V$ , then  $a_0 \propto m^2$  in the  
28  
29 Rayleigh region; for (hypothetical) optical-region mega-insects,  $a_0 \propto m^{2/3}$ .  
30  
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35 The variation of mass  $m$  with  $a_0$  for the combined datasets is shown in Figure 1  
36  
37 using logarithmic scales for both variables. For the L data points, the  $\sigma_{xx}$  values were  
38  
39 divided by a factor of 2.19, the average ratio of  $\sigma_{xx}/a_0$  for the targets in the main dataset  
40  
41 with  $a_0 < 0.25$  cm<sup>2</sup> ( $n = 18$ , s. d. 0.24). It is apparent that there is a broad spread, with a  
42  
43 range in  $\log_{10}m$  of  $\sim 0.5$  at most  $a_0$  values. For a 1-cm<sup>2</sup> target, for example, this  
44  
45 corresponds to a mass range of  $60 \leq m \leq 180$  mg. This can be attributed to variations in  
46  
47 shape and density between species, with a contribution also from experimental error.  
48  
49 There is no evidence of maxima and minima, except perhaps in the extent of the spread  
50  
51 which could originate from maxima and minima occurring at different  $a_0$  values for  
52  
53 insects with different morphological forms.  
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58 *Insert Figure 1 near here*  
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3 In order to estimate the masses of the targets detected by a ZLC radar, it is  
4 necessary to develop a mathematical relationship between  $m$  and  $a_0$ . From Figure 1, it is  
5 evident that a relatively simple, smooth, curve will suffice, and indeed is all that the  
6 data warrant. At low RCS values, the curve should exhibit the asymptotic Rayleigh  $m^2$   
7 dependence (i.e.  $m \propto a_0^{1/2}$ ) and at high values it should approach  $m \propto a_0^{3/2}$ . It therefore  
8 can appropriately be represented by a spline, with two linear regions (on a log-log plot)  
9 joined by a curved form. For the latter, a simple polynomial may be sufficient. At the  
10 two transition points, the values of both functions and both first derivatives should be  
11 equal. (If they are not, discontinuities or obvious distortions will appear in distributions  
12 of mass values estimated from the relationship.) These requirements place constraints  
13 on the curve parameters, two of which, the slopes of the linear sections, are already  
14 known. The result is that if a second-order polynomial is employed to describe the link  
15 section, only two parameters plus the two transition points are free variables. Choice of  
16 transition points is not entirely free as they should conform approximately with the  
17 limits of the Rayleigh and optical regions.

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36 Chapman, Smith, et al. (2002) have previously proposed an  $m$  vs  $a_0$  relationship  
37 (Table 3), with parameters estimated from analyses of the C, A, and W data subsets, that  
38 conforms with these requirements to a good approximation. It uses a second-order curve  
39 in the Mie region, and while it does not employ an optical-region asymptote explicitly,  
40 the slope at the position of the largest target ( $\log_{10}a_0 \approx 1.2$ ) is  $\sim 1.6$ , which is not much  
41 different from the asymptotic value of 1.5, so it is broadly consistent with this  
42 requirement. To determine the free Rayleigh-region parameter, they took account also  
43 of those elements of the L data subset that were then available. For the study dataset, the  
44 transition to the Rayleigh-region was fixed at  $a_0 = 0.25 \text{ cm}^2$ , the value used by  
45 Chapman, Smith, et al. (2002), as this appears consistent with both theory and the data  
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3 (Figure 1), and the theoretical slope values for both asymptotic regions were adopted as  
4 constants. The spline parameters were then obtained by treating the  $\log_{10}a_0$  values as  
5 independent variables and minimising the square of the residual between the  $\log_{10}$ -  
6 transformed estimated and measured masses (Table 3, Figure 1). The constant,  
7 quadratic, and (for the third-order case) cubic coefficients in the linking polynomial  
8 were free and the remaining coefficients and the upper transition point determined from  
9 their values. Minimization was carried out using the Solver function in Excel 2007,  
10 using the default options; for the third-order case, it was necessary to identify the  
11 appropriate solution of a quadratic equation for the upper transition point. The  
12 minimizations converged without difficulty.

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*Insert Table 3 near here*

The new relationship with a second-order linking section differs from that of Chapman, Smith, et al. (2002) mainly by an offset in the estimated  $\log_{10}m$  of from 0.11 to 0.17. The two curves run almost parallel to each other, crossing only at  $a_0 \approx 15$  dBsc ( $m \approx 20$  g), which is larger than any of the measured values (or any likely migrant species). The effect is to increase the estimates of  $m$  by 25% for small insects and up to 39% for the largest species. The root-mean-square deviation for  $\log_{10}m$  falls from 0.23 to 0.20, which is comparable with the range of variation apparent in Figure 1 (see above) and corresponds to an uncertainty in mass of around  $\pm 50\%$ . Introducing a third order term to the polynomial reduces the r.m.s. deviation to 0.19; as the course of the curve (not shown) changes only slightly and a slight sinuosity introduced in it appears spurious, and as the upper transition point becomes unreasonably low, this more complicated formula has not been adopted.

### 3.1.2. Mass estimation incorporating shape parameters

To explore whether the shape parameters  $\alpha_2$  and  $\alpha_4$  can contribute to the estimation of mass, we have undertaken a multiple-regression analysis with  $\log_{10}m$  as the dependent variable and  $\log_{10}a_0$ ,  $\alpha_2$  and  $\alpha_4$  as independent variables. This is of course possible only for targets for which the full CLPP was measured, i.e. for the C, A, S, and W data. No attempt has been made to merge the estimation relationship into the expected asymptotic forms in the Rayleigh and optical regions. However, the dataset includes some of the largest insects known to migrate and extends down to an  $a_0$  value of  $0.005 \text{ cm}^2$  ( $-23 \text{ dBsc}$ , mass  $9 \text{ mg}$ ; Table 2), which corresponds quite closely to the lower limit of target sizes that are detectable (Chapman, Smith, et al. 2002) or commonly detected (Drake 2013, 2016) with ZLC radars, so this is not a major defect.

A sequence of multiple linear regressions was undertaken, starting with a constant term plus a term linear in  $\log_{10}a_0$  and then adding terms in  $(\log_{10}a_0)^2$ ,  $\alpha_2$ , and  $\alpha_4$ . The quadratic term was included because the  $\log_{10}m$  vs  $\log_{10}a_0$  relationship must change slope over the  $a_0$  range encompassed by the dataset (as discussed in the previous subsection where a quadratic relationship was also employed). Regressions were carried out using the *lm* (Linear Models) facility of R (R Development Core Team 2008) and assessed using analysis of variance (with R's *anova* facility). The results are summarized in Table 4. They show that a linear term in  $\log_{10}a_0$  has the greatest explanatory power, and an  $\alpha_2$  term is more effective than a quadratic term in  $\log_{10}a_0$  at further reducing the residual sum of squares and increasing the  $R^2$ . Adding either a quadratic term in  $\log_{10}a_0$  or an  $\alpha_4$  term to the combination of  $\log_{10}a_0$  (linear) and  $\alpha_2$  provides no significant further improvement. A scatterplot of  $\alpha_2$  vs  $a_0$  (not shown) reveals that  $\alpha_2 > 0.5$  for  $a_0 < 0 \text{ dBsc}$  but it decreases steadily above this point and is negative for  $a_0 > 3 \text{ dBsc}$ , so the value of this parameter provides information on the

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3 higher masses that occur above the Rayleigh region (i.e. the upturn in slope in Figure 1  
4  
5 at  $a_0 \approx 0$  dBsc). A linear term in  $\alpha_2$  apparently does this more effectively than a  
6  
7 quadratic term in  $\log_{10}a_0$ , with the former giving an uncertainty on the mass estimates of  
8  
9  $\pm 40\%$  (residual standard error on  $\log_{10}m$  of 0.16) and the latter  $\pm 60\%$  (0.24). The  $\alpha_4$  vs  
10  
11  $a_0$  plot (also not shown) exhibits a less clear and more scattered dependence of  $\alpha_4$  on  $a_0$ ,  
12  
13 so it is unsurprising that this parameter makes almost no additional contribution.  
14  
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16  
17 *Insert Table 4 near here*  
18

19 Aldhous (1989), using only the A data subset, explored how mass varied with  
20  
21 several RCS quantities and found approximately linear relationships for  $\log_{10}m$  vs  
22  
23  $\log_{10}\sigma_{le}$ , where  $\sigma_{le}$  is the lesser of  $\sigma_{xx}$  and  $\sigma_{yy}$ , and for  $\log_{10}m$  vs  $\log_{10}(\sigma_{xx}/\sigma_{yy})$ . (These  
24  
25  $\sigma_{xx}$  and  $\sigma_{yy}$  are as defined here rather than in the original publication; see section 2.2.)  
26  
27 Scatterplots (not shown) demonstrate that these relationships retain their quasi-linear  
28  
29 form with the full CLPP dataset. We have therefore explored including these terms in  
30  
31 the regression as an alternative to  $\alpha_2$  (Table 4). It was found that  $\log_{10}\sigma_{le}$  provides only  
32  
33 modest additional explanatory power but  $\log_{10}(\sigma_{xx}/\sigma_{yy})$  performs almost as well as  $\alpha_2$ .  
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### 38 **3.2. Shape as an identification character**

#### 39 **3.2.1. Radar shape and taxonomic group**

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41 The distribution of the shape parameter pairs ( $\alpha_2$ ,  $\alpha_4$ ) over the allowed region of the  
42  
43 ( $\alpha_2$ ,  $\alpha_4$ ) plane is shown for the full CLPP dataset in Figure 2(a). It can be seen that  
44  
45  $\alpha_4 < 0.5$  for all but one specimen and that pairs are found across much of the right-hand  
46  
47 half ( $\alpha_2 > 0$ ) of the  $\alpha_4 < 0.5$  part of the allowed area but are confined to a more  
48  
49 restricted region ( $\alpha_4 < 0.3$ ) of the left-hand half. There is a concentration of targets on or  
50  
51 close to the boundary where  $\alpha_2 \approx 1.0$ , a region corresponding approximately to the  
52  
53 'main cluster' identified in analyses of ZLC-radar observations of target shape (Dean  
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3 and Drake 2005, Drake 2016). There are relatively few targets in the region  $0 < \alpha_2 \leq 0.5$   
4  
5 and only one of these has  $\alpha_4 < 0.2$ ; the equivalent region of the left-hand half, however,  
6  
7 is crowded.  
8

9  
10 *Insert Figure 2 near here*  
11

12 Lepidopteran specimens extend throughout the right-hand half of the figure but  
13 are most numerous in or close to the main-cluster region; there is only one specimen  
14 with  $\alpha_2 < 0$ . Orthopterans occur in both halves but only two fall into the main cluster;  
15  
16 orthopterans in the right-hand half mostly have  $\alpha_4 > 0.2$ . The specimens from other  
17  
18 orders all fall into the right-hand half, some in the main cluster but others well away  
19  
20 from the boundary; this is a morphologically mixed group so a variety of  $(\alpha_2, \alpha_4)$   
21  
22 combinations is to be expected. The figure also shows the results for the dipole; they  
23  
24 fall along the boundary where  $\alpha_2$  is approaching its maximum possible value and,  
25  
26 reassuringly, show little spread.  
27  
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32 In order to explore these patterns more precisely, a main-cluster region (MCR)  
33 will be defined in terms of the orthogonal variables  $(p, q)$  as these delineate it very  
34 nicely (Figure 2(b)). There are 79 specimens in the MCR, of which 2 are Orthoptera, 68  
35  
36 are Lepidoptera, and 9 are other taxa; of the 77 specimens falling outside the MCR, 46  
37  
38 are Orthoptera, 26 Lepidoptera, and 5 other. The uneven distribution of orthopterans  
39  
40 and lepidopterans is significant (G-test for a model-I  $2 \times 2$  contingency table with Yates  
41  
42 correction,  $G = 69.3$ , 1 d.f.,  $P < 0.001$ ; Sokal and Rolf 1995, ch. 17); it remains  
43  
44 significant, though at a lower level, if the specimens with perpendicular CLPPs (32  
45  
46 locusts, 1 moth) are excluded ( $G = 21.8$ ,  $P < 0.001$ ).  
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### 52 53 54 3.2.2. *Relation of radar shape to mass and morphology* 55

56 The location of a specimen on the  $(\alpha_2, \alpha_4)$  plane will be determined by its size and  
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3 general morphology, with these represented by the parameters  $m$ ,  $l$ ,  $w$ , and  $f$ . A  
4  
5 relatively clear pattern emerges when the symbols for the points on the  $(\alpha_2, \alpha_4)$  plane  
6  
7 indicate the specimen's mass (Figure 2(b)). All specimens in the left-hand half of the  
8  
9 allowed region have  $m > 600$  mg and only one specimen (an outlier – see below) in the  
10  
11 right-hand half exceeds this mass. All but two of the lightest specimens ( $m \leq 100$  mg,  
12  
13  $n = 29$ ) occur in the MCR, as do 49 (73%) of the intermediate-mass insects  
14  
15 ( $100 < m \leq 300$  mg,  $n = 67$ ). The remaining population of the MCR comprises 3 insects  
16  
17 with  $300 < m \leq 400$  mg, which constitutes 5% of the heaviest specimens ( $m > 300$  mg,  
18  
19  $n = 60$ ). The mass difference between specimens in the MCR and those falling outside it  
20  
21 is significant (Wilcoxon rank sum test, two-sided,  $n_1 = 79$ ,  $n_2 = 77$ ,  $W = 333$ ,  $P$   
22  
23  $< 0.001$ ). Inspection of Figure 2(b) suggests that in the MCR and further inwards, in the  
24  
25 adjoining 'MCR Extension' (MCRE; Figure 2(b)), there is a general increase of target  
26  
27 mass with distance from the boundary. Further, for specimens outside the MCR, there  
28  
29 appears to be a trend of mass increasing from top-right ( $\alpha_2 \approx 1.4$ ,  $\alpha_4 \approx 0.5$ ) to bottom-  
30  
31 mid-left ( $\alpha_2 \approx -0.7$ ,  $\alpha_4 \approx 0.05$ ). The latter phenomenon is the same as that noted in  
32  
33 section 3.1 where  $\alpha_2$  (if signed as here) was found to be a useful predictor of mass. As is  
34  
35 to be expected from the analysis of section 3.1, there is also a significant difference in  
36  
37  $a_0$  values between the specimens in the MCR and outside it ( $W = 705$ ,  $P < 0.001$ ). The  
38  
39 pattern of  $a_0$  values across the  $(\alpha_2, \alpha_4)$  plane (not shown) is similar to that for mass,  
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41 though the variance appears greater and this makes the trends somewhat less evident.  
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49 Regression analyses (Table 5) show that the trends are significant. However, the  
50  
51 decrease of mass with increasing  $p$  within the combined MCR and MCRE regions has a  
52  
53 modest adjusted  $r^2$  and accounts for only 29% of the sum of squares. Four points with  
54  
55 very low mass ( $9 \leq m \leq 14$  mg) appear as outliers, but this is essentially an artefact of  
56  
57 the measurement sample in which low masses are under-represented: it appears likely  
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3 that inclusion of more insects with  $m < 40$  mg would further reduce the  $r^2$  and the sum  
4  
5 of squares accounted for. Adding a  $q$  term into the regression produces negligible  
6  
7 improvement. For the non-MCR specimens, the adjusted  $r^2$  indicates a strong  
8  
9 dependence of mass on  $\alpha_2$ , with this parameter accounting for 86% of the sum of  
10  
11 squares; two outlier points here are due to specimens that arguably belong in the MCR  
12  
13 as they have masses (49, 82 mg) lower than the rest ( $\geq 173$  mg) and  $q$  values that only  
14  
15 just fall outside the nominal MCR limits. An added  $\alpha_4$  term is marginally significant but  
16  
17 accounts for only a further 1% of the sum of squares. When  $\log_{10}a_0$  rather than  $\log_{10}m$  is  
18  
19 made the dependent variable, the results (Table 5) are similar, though the adjusted  $r^2$   
20  
21 values are lower and smaller proportions of the sum of squares are accounted for. These  
22  
23 weaker statistics reflect the less strong trends and greater variance discerned through  
24  
25 inspection of the plots (previous paragraph). The trend statistics for the non-MCR  
26  
27 specimens are obviously strengthened by the large number of  $m > 1$  g specimens (all  
28  
29 locusts) with their extreme values of both  $\alpha_2$  and the response variables  $m$  and  $a_0$ .  
30  
31 Excluding these leaves a still significant relationship for  $\log_{10}m$  but not for  $\log_{10}a_0$   
32  
33 (Table 5). If the two low-mass specimens that arguably belong in the MCR are also  
34  
35 excluded, the adjusted  $r^2$  for  $\log_{10}m$  rises to 0.77 (though that for  $\log_{10}a_0$  is not  
36  
37 improved). Similar weak trends for  $\log_{10}a_0$  in these two regions were noted in an  
38  
39 analysis of a single night of ZLC-radar observations at an Australian site (Dean and  
40  
41 Drake 2005).  
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48 *Insert Table 5 near here*

49  
50 Differences between the MCR and non-MCR specimens are also evident when  
51  
52 the specimen character indicated is the length, width, or form (Figure 3; detailed results  
53  
54 not presented), and these are statistically significant (Wilcoxon test,  $n_2 = 77$  for  $l$  but 76  
55  
56 for  $w$  and  $f$ ,  $P < 0.001$ ). Regressions of  $l$ ,  $w$ , and  $f$  against  $p$  for the specimens in the  
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3 combined MCR and MCRE account respectively for 16, 5, and 1% of the sum of  
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5 squares, with the  $p$  coefficient significant at the  $P < 0.001$  level for  $l$ , at  $< 0.05$  for  $w$ , and  
6  
7 not significant ( $\sim 0.3$ ) for  $f$ . For the non-MCR specimens regressed against  $\alpha_2$ , the  
8  
9 proportions are 81, 10, and 37% respectively with  $P$  values  $< 0.001$ , 0.007, and  $< 0.001$ ;  
10  
11 with the  $m > 1$  g locusts excluded, the proportions are 36, 30, and 9% with  $P$  values  
12  
13  $< 0.001$ ,  $< 0.001$ , and 0.05. Thus the length shows differences and trends similar to those  
14  
15 for  $m$  and  $a_0$ , but for the width and form the trends are less clear.

16  
17  
18 *Insert Figure 3 near here*  
19

20  
21 Two additional regression analyses have been undertaken for the form  $f$  to  
22  
23 examine its potential for providing information orthogonal to that from  $a_0$ . For the  
24  
25 CLPP data, adding  $q$  into the regression of  $f$  against  $p$  in the combined MCR and MCRE  
26  
27 increases the sum of squares accounted for, but only to 2% and neither parameter is  
28  
29 significant. Adding  $\alpha_4$  into the regression of  $f$  against  $\alpha_2$  for all non-MCR specimens  
30  
31 provides negligible improvement; however, with the locusts excluded the proportion  
32  
33 accounted for increases to 20% and this is also achieved with  $\alpha_4$  alone.

34  
35  
36 For the small specimens in the L subsample, the available radar measure of  
37  
38 shape is the ratio  $r_{sh}$  (i.e.  $\sigma_{xx}/\sigma_{yy}$ ). The form  $f$  shows a significant relationship with  $r_{sh}$  for  
39  
40 these specimens (Figure 4(a);  $n = 39$ , coefficient  $0.224 \pm 0.028$ , intercept  $1.28 \pm 0.34$ ,  
41  
42 64% of variance accounted for,  $P < 0.001$ ). Two clusters apparent in this plot are due to  
43  
44 single-species groups, but other species show a broad spread of  $r_{sh}$  values (Figure 4(a)).  
45  
46 A similar analysis for the mostly larger CLPP specimens, with  $r_{sh}$  calculated from  $\alpha_2$   
47  
48 and  $\alpha_4$  via Equations 3 (and after excluding two specimens with  $r_{sh} > 50$ ), shows no  
49  
50 relationship (Figure 4(b);  $n = 121$ ,  $P \approx 0.8$ ). This is still the case if only specimens with  
51  
52  $m \leq 80$  mg, i.e. in the same mass range as those in the L subsample, are included  
53  
54 ( $n = 15$ ,  $P \approx 0.6$ ), and also if the range is extended slightly to  $m \leq 100$  mg in order to  
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2  
3 enlarge the sample ( $n = 27$ ,  $P \approx 0.6$ ). Thus for targets with  $a_0 \leq 0.25 \text{ cm}^2$  (which from  
4  
5 Table 3 corresponds to  $m \leq 80 \text{ mg}$ ),  $f$  can be estimated as

$$f = 0.224r_{\text{sh}} + 1.28 . \quad (5)$$

6  
7  
8  
9 Because of the uncertainties on these parameters, the 1-standard deviation uncertainty  
10  
11 on  $f$  will increase from  $\pm 0.3$  to  $\pm 0.9$  over the range  $0 < r_{\text{sh}} \leq 20$ . The data provide no  
12  
13 basis for estimating  $f$  for targets with  $a_0 > 0.25 \text{ cm}^2$ .  
14  
15

16  
17 *Insert Figure 4 near here*  
18  
19

### 20 3.2.3. Mass and morphology associated with different radar shapes

21  
22 An alternative way of representing these relationships is to determine where insects of  
23  
24 different sizes or shapes are located in the  $(\alpha_2, \alpha_4)$  plane. In the case of mass (Figure 5),  
25  
26 insects with  $m \leq 150 \text{ mg}$  are found entirely in the MCR; those with  $150 < m \leq 250 \text{ mg}$   
27  
28 occupy both the MCR and the MCRE and are also found in the adjacent area to the right  
29  
30 ( $q > 1.5$ ) of these; those with  $250 < m \leq 400 \text{ mg}$  are predominantly in the MCRE; those  
31  
32 with  $400 < m \leq 1000 \text{ mg}$  are in the area adjacent and to the left of the MCRE (with  
33  
34  $0 < q \leq 0.8$ ), and almost all of those with  $m > 1 \text{ g}$  fall into the left-hand half of the  
35  
36 diagram (where  $q$  is considered negative), with the largest ( $m > 2 \text{ g}$ ) slightly further to  
37  
38 the left. All but three of the 13 lightest insects ( $m \leq 70 \text{ mg}$ ) occur along the outer  
39  
40 periphery of the MCR, with  $p > 0.95$ . A trajectory traced through the plane by a  
41  
42 notional 'typical insect' as its mass increases can thus be identified, though it is broad in  
43  
44 extent (Figure 6). (It should be noted that variance in mass occurs along the trajectory,  
45  
46 on the scale indicated by the distance across the ellipses, as well as laterally.) The mass  
47  
48 ranges associated with the regions of Figure 6, and the number of specimens falling  
49  
50 within or near them, are presented in Table 6. Region C, which contains only a small  
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52 number of specimens, is tentatively identified as a spur off the main trajectory.  
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*Insert Figure 5 near here*

*Insert Figure 6 near here*

Similar trends are evident for RCS  $a_0$  and length  $l$  (Table 6), although these characters partition the specimens into the regions less precisely than does  $m$ . As specimens with similar widths  $w$  occur in both the left- and right-hand sides of the plane (not shown), there is no equivalent trend for this character. For the form  $f$ , specimens with  $f \leq 6$  ( $n = 102$ ) fall within regions A, B, D and E while those with  $f > 6$  fall predominantly ( $n = 31$ ) into the left-hand half of the plane with the remainder ( $n = 22$ ) scattered widely across the right hand half. The specimens in region C and close to the constraint boundary ( $n = 5$ ) had narrow bodies ( $2 < w \leq 3$  mm) and lengths in the range  $20 < l < 22$  mm (giving  $6 < f < 8$ ); all were *Chorthippus brunneus*, a grasshopper. Their location was the closest to that of the metal dipoles (Figure 2), which are also very narrow ( $\sim 1$  mm) and made to a length, 16 mm, that will produce resonance when aligned with the E field. The RCS values of the five *C. brunneus* specimens were  $\sim 1$  dB higher than predicted (from relationship of Table 5) for their  $\sim 200$  mg mass, so it is possible that they were at or near resonance too. Two smaller specimens of this species, with  $l \approx 16$  mm and  $f \approx 8$ , fell into region B. Several of the small L specimens have  $r_{sh} \geq 10$  (and  $f \geq 2.6$ , Figure 4), and from this it can be inferred that they lie in the right-hand parts of the A, B, or C regions (Figure 6, which shows contours of  $f$ ). The ladybird beetles, with  $f \approx 1.3$ , have  $r_{sh} \leq 4.3$  and therefore must fall to the left of A and B; their  $\alpha_4$  values are unknown but given their low masses ( $11 \leq m \leq 32$  mg), it seems likely (see Figure 5) that they lie close to the constraint boundary.

*Insert Table 6 near here*

### 3.2.4. Identification of perpendicular CLPPs

As noted above, when targets are observed with a ZLC-radar (as opposed to in a laboratory rig), there is a possibility of a 90° error in the retrieved alignment. The question of whether this can be resolved from the radar observations themselves is examined here by direct reference to the dataset. In this sample, and after eliminating one outlier point, the transition to perpendicular CLPPs occurs around  $m \approx 600$  mg (Figure 2b) and in the zone  $3 < a_0 \leq 4$  dBsc. Unfortunately the dataset includes only one specimen in the  $500 < m < 1000$  mg transition region, so the transition behaviour cannot be discerned in any detail.

## 4. Discussion

The measure of size provided by a ZLC radar is the polarization-averaged RCS  $a_0$  and an established monotonic relationship between this and mass has been verified, and its parameters refined, in this work. Masses estimated from  $a_0$  have an uncertainty of  $\sim \pm 60\%$ , but given the wide range of insect sizes this still provides useful discrimination. If the shape parameter  $\alpha_2$  is incorporated into the mass-estimation procedure the uncertainty can be reduced to  $\sim \pm 40\%$ , but seamless linking into the lower and upper asymptotic regions will then be lost so this is feasible only when small or very large insects are absent or of no interest. Use of a spline quadratic in  $\log_{10} a_0$  to link appropriate linear asymptotic slopes (Table 3, line 2) appears adequate and robust and leaves the shape parameters as independent identification variables; this relationship is therefore recommended for general use.

An important finding from this research is that the values of  $\alpha_2$  and  $\alpha_4$ , the primary shape parameters, are determined mainly by the size of the insect, as represented either by its mass or its length. Small and medium-sized insects, with

1  
2  
3  $m \leq 150$  mg and  $l \leq \sim 20$  mm, are almost completely confined to regions A and B of the  
4  
5  $(\alpha_2, \alpha_4)$  plane (Figure 6), an area also known as the MCR and identified previously  
6  
7 from ZLC observations of nocturnal insect migration. As insect size increases beyond  
8  
9 150 mg the CLPP parameters follow a broad trajectory, moving initially away from the  
10  
11 constraint boundary (i.e.  $\alpha_4$  increasing) into region D and then leftwards ( $\alpha_2$   
12  
13 decreasing) into E, passing into the left-hand half of the plane ( $\alpha_2$  negative, CLPP  
14  
15 perpendicular) at a mass of around 600 mg (region F) and getting close to the lower left-  
16  
17 hand boundary ( $\alpha_2$  and  $\alpha_4$  both decreasing, region E) at  $\sim 4$  g. Narrow ( $w \leq 3$  mm)  
18  
19 insects with  $m \approx 200$  mg and  $l \approx 20$  mm may be found off this main trajectory in region  
20  
21 C.  
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25  
26 These major variations of  $\alpha_2$  and  $\alpha_4$  with  $m$ , and hence also with  $a_0$ , mean that  
27  
28 these parameters do not form a naturally orthogonal system with  $a_0$ . The trajectory is  
29  
30 broad, and the obvious candidate for orthogonality is the transverse direction. This  
31  
32 changes as  $m$  increases, meaning that different relationships would have to be sought in  
33  
34 different regions. Symmetry considerations require that a perfectly round insect will  
35  
36 have a circular CLPP, i.e. one with  $\alpha_2 = \alpha_4 = 0$ , and basic consideration of  
37  
38 electromagnetic scattering leads to the expectation that the CLPPs of elongated insects  
39  
40 are unlikely to be circular, and that the patterns for insects of the same mass but  
41  
42 differing degrees of elongation (i.e. different forms) will not be the same, so some  
43  
44 degree of orthogonality seems assured. The obvious relation to test, therefore, is one  
45  
46 between form and a quantity representing the transverse direction; the latter could be  $\alpha_2$   
47  
48 or  $q$  in regions A, B and D and  $\alpha_4$  in regions C-G. Regression analyses found no  
49  
50 contribution from  $q$  in the former region and only a moderate one from  $\alpha_4$  in the latter.  
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55  
56 In contrast to these results which suggest there is little prospect of estimating  $f$   
57  
58 from the radar data for the larger insects ( $m > \sim 80$  mg) predominating the CLPP sample,  
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1  
2  
3 Chapman, Reynolds, et al. (2002) and Chapman et al. (2005, 2006) were able to use  
4  
5 shape to discriminate between targets when observing very small ( $m \leq 13$  mg) species.  
6  
7 They used the ratio  $r_{sh} = \sigma_{xx}/\sigma_{yy}$  as their identification parameter, with values  
8  
9 determined by laboratory measurements (and included here in L) of around 10, 10, and  
10  
11 20 for diamondback moths, carabid beetles, and lacewings respectively. In this study, a  
12  
13 linear relationship between  $r_{sh}$  and  $f$  was found for the full L sample ( $m \leq 81$  mg), but  
14  
15 not for a smaller sample of the specimens of similar size in the CLPP sample. That a  
16  
17 relationship between radar shape and morphological form should be more apparent for  
18  
19 small insects (targets falling into the Rayleigh region, or close to it) than for larger ones  
20  
21 (Mie region) is not altogether unexpected given the more complicated radio-wave  
22  
23 scattering processes involved with the latter which lead, at higher masses, to the  
24  
25 transition to perpendicular CLPPs. Given that  $r_{sh}$  broadly increases with  $\alpha_2$  (Figure 6),  
26  
27 there is no reason to expect it to have any advantage as a discriminating variable for  
28  
29 specimens larger than those in L.  
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34  
35 The majority of targets detected so far with ZLC-radars have  $a_0 < 3$  dBsc (e.g.  
36  
37 Drake 2016), which the results presented here indicate is in the range where CLPPs are  
38  
39 parallel rather than perpendicular. Thus target alignments can confidently be attributed  
40  
41 to the direction of the maximum axis of the CLPP. An attempt to detect this transition in  
42  
43 a single night's observations at an Australian site was unsuccessful, even though the  
44  
45 radar seemed to indicate that a small number of sufficiently large targets were present  
46  
47 (Dean and Drake 2005). Operation of a unit in a region where large locusts, or other  
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49 species of similar size, are known to be present in the aerial fauna may be necessary to  
50  
51 verify that orientations of such targets are at right angles to the observed CLPP axis, and  
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53 to better determine the  $a_0$  value at which the transition occurs.  
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3 The measurement sample analyzed in this work includes many migrant species,  
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5 but it is not representative of the migrant fauna at any particular location. However, a  
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7 study of radar characters of insects detected at the Australian site over an eight-month  
8  
9 period identified peaks in the A, B, D and E regions of the  $(\alpha_2, \alpha_4)$  plane, but not in C  
10  
11 or the region to the left of A and B (Drake 2016). Moreover, the peaks found by that  
12  
13 study in regions A and B (the MCR) were almost all centred at  $a_0 \leq -5$  dBsc, with  
14  
15 some extending up to 0 dBsc (masses of  $\sim 90$  and  $\sim 200$  mg respectively, Figure 1),  
16  
17 which agrees reasonably with the  $m \leq 150$  mg range determined here (Table 6). Peaks in  
18  
19 the D and E regions in the Australian study almost all had  $0 < a_0 \leq 5$  dBsc (i.e.  
20  
21  $200 < m < 850$  mg), which again is consistent with this work. The Australian data  
22  
23 suggest that the possibly resonant behaviour of the *C. brunneus* specimens in the  
24  
25 measurement dataset may be relatively unusual. They also indicate that the  
26  
27 measurement sample, with the large locusts ( $m > 1$  g) excluded, is reasonably  
28  
29 representative of the Australian migrant fauna (even though the great majority of the  
30  
31 species measured do not occur in Australia). Perhaps migrant insect faunas do not differ  
32  
33 morphologically very much from one continent to another: while the species differ, at  
34  
35 higher taxonomic levels there is much commonality (e.g. Johnson 1969) and as the  
36  
37 phenomena of nocturnal migration are broadly similar from region to region (e.g. Drake  
38  
39 & Gatehouse 1996, Drake & Reynolds 2012) it can be expected that the adaptations  
40  
41 leading to them will be too. The results from this study should therefore have wide  
42  
43 applicability.  
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## 50 51 52 **Acknowledgments**

53  
54 A. S. Edwards assisted with the 1979 measurements (subset C) and performed initial analyses  
55  
56 that were helpful to this study. Rothamsted Research is a national institute of bioscience  
57  
58 strategically funded by the UK Biotechnology and Biological Sciences Research Council  
59  
60



(BBSRC). [Note to editor: funding information (provided at start of MS) has been omitted here on the assumption it will appear elsewhere; if not it should be inserted here.]

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Table 1. Composition and sources of the CLPP dataset<sup>a</sup>.

Taxonomic group	Source				
	C	A	W	S	All
Orthoptera	5, 30	2, 18	0, 0	0, 0	6, 48
Lepidoptera	1, 13	15, 34	3, 5	13, 42	28, 94
others <sup>b</sup>	1, 1	1, 2	3, 9	1, 2	6, 14
All	7, 44	18, 54	6, 14	14, 44	40, 156

<sup>a</sup>Number of species, number of specimens. See text (section 2.2) for details of sources C, A, W and S.

<sup>b</sup>Bees and wasps (Hymenoptera) (2, 7), beetles (Coleoptera) (2, 3), crane flies (Diptera) (2, 4).

Table 2. Summary of masses and RCS parameter values for the CLPP dataset.

Taxonomic group	Mass	RCS parameter		
	$m$ (mg)	$a_0$ (dBsc)	$\alpha_2$	$\alpha_4$
Orthoptera	1597 (68, 4120)	4.6 (0.39, 16.8)	-0.03 (-0.90, 1.31)	0.20 (0.01, 0.56)
Lepidoptera	194 (9, 648)	0.98 (0.013, 2.72)	0.91 (-0.10, 1.22)	0.23 (0.08, 0.43)
others <sup>b</sup>	114 (10, 220)	0.51 (0.005, 1.48)	0.94 (0.62, 1.27)	0.22 (0.09, 0.48)
All taxa	618 (9, 4120)	2.04 (0.005, 16.8)	0.62 (-0.90, 1.31)	0.22 (0.01, 0.56)

<sup>a</sup>Average (minimum, maximum).

<sup>b</sup>As in Table 1.

Table 3. Parameters of mass vs RCS relationships<sup>a</sup>

Origin ( $\log_{10}m$ r.m.s.)	Region			
	Lower <sup>b</sup>	Linking	Upper	Upper transition <sup>c</sup>
Chapman et al. (2002) (0.23)	2.097 0.5	2.205 0.8729 0.3323	–	–
This study, second order. (0.20)	2.207 0.5 (81 mg)	2.331 0.9124 0.3425	2.079 1.5	0.8580 (7.21 cm <sup>2</sup> 2.32 g)
This study, third order. (0.19)	2.243 0.5 (88 mg)	2.249 0.8028 0.9583 0.7826	2.1459 1.5	0.2605 (1.87 cm <sup>2</sup> , 359 mg)

<sup>a</sup>Parameters are for the relationship of  $\log_{10}m$  to  $\log_{10}a_0$ . (Note  $a_0$  (dBsc) is  $10\log_{10}a_0$ .)

The first value in each list is the constant term, the second the coefficient of  $\log_{10}a_0$ , and so on for higher powers of  $\log_{10}a_0$  if these are present.

<sup>b</sup>Transition from the lower to the linking curve was fixed at  $\log_{10}a_0 = -0.60206$  (i.e.  $a_0 = 0.25$  cm<sup>2</sup>) for all curves. Value in parenthesis is the corresponding mass  $m$ .

<sup>c</sup>First value is  $\log_{10}a_0$ ; values in parenthesis are  $a_0$  and the corresponding mass  $m$ .

Table 4. Results of multiple linear regression analyses of  $m$  vs ( $a_0$ ,  $\alpha_2$ ,  $\alpha_4$ ) relationships

Model <sup>a</sup> (note)	Coefficients	ANOVA sum of squares, ( $P$ ), [residual].	Adjusted $R^2$ , residual standard error.	Degrees of freedom, $F$ , ( $P$ ).
Constant	2.418	–	0.759	1, 154
$\log_{10}a_0$	0.829	35.93 (<0.001) [11.29]	0.271	490 (<0.001)
Constant	2.345	–	0.813	2, 153
$\log_{10}a_0$	0.9378	35.93 (<0.001)	0.239	338 (<0.001)
$(\log_{10}a_0)^2$	0.2156	2.578 (<0.001) [8.709]		
Constant	2.712	–	0.915	2, 153
$\log_{10}a_0$	0.5068	35.93 (<0.001)	0.161	837 (<0.001)
$\alpha_2$	–0.4655	7.334 (<0.001) [3.953]		
(See note b)				
Constant	2.645	–	0.819	2, 153
$\log_{10}a_0$	0.2591	35.93 (<0.001)	0.235	351 (<0.001)
$\log_{10}\sigma_e$	0.4343	2.831 (<0.001) [8.457]		
Constant	2.705	–	0.908	2, 153
$\log_{10}a_0$	0.5106	35.93 (<0.001)	0.167	768 (<0.001)
$\log_{10}(\sigma_{xx}/\sigma_{yy})$	–0.4315	7.009 (<0.001) [4.278]		

<sup>a</sup>Dependent variable is  $\log_{10}m$ .

<sup>b</sup>Adding  $(\log_{10}a_0)^2$  reduces sum of squares by 0.07 (0.2%), coefficient not significant ( $P \sim 0.09$ ). Adding  $\alpha_4$  reduces sum of squares by 0.04 (0.1%), coefficient not significant ( $P \sim 0.2$ ).

Table 5. Results of regression analyses of  $m$  and  $a_0$  vs  $(p, q)$  and  $(\alpha_2, \alpha_4)$ .

Region and dependent variable <sup>a</sup>	Model [2nd model] <sup>b</sup>	Coefficients	Sum of squares, ( $P$ ) <sup>c</sup> , [residual].	Adjusted $r^2$ , residual standard error.	Degrees of freedom, $F$ , ( $P$ ).
MCR and MCRE $\log_{10}m$	Constant $p$ [ $q$ , 0.9, 0.02%]	3.35 -1.39	- 2.88 (<0.001) [6.95]	0.29 0.27	1, 98 41 (<0.001)
MCR and MCRE $\log_{10}a_0$	Constant $p$ [ $q$ , 0.2, 1%]	1.07 -1.50	- 3.36 (<0.001) [21.34]	0.13 0.47	1, 98 15 (<0.001)
All except MCR $\log_{10}m$	Constant $\alpha_2$ [ $\alpha_4$ , 0.02, 1%]	2.97 -0.66	- 14.57 (<0.001) [2.39]	0.86 0.18	1, 75 456 (<0.001)
All except MCR $\log_{10}a_0$	Constant $\alpha_2$ [ $\alpha_4$ , 0.2, 0.9%]	0.47 -0.46	- 7.02 (<0.001) [4.41]	0.61 0.24	1, 75 120 (<0.001)
All except MCR ( $m > 1$ g excluded) $\log_{10}m$	Constant $\alpha_2$ [ $\alpha_4$ , 0.003, 9%]	2.74 -0.41	- 0.99 (<0.001) [0.89]	0.52 0.15	1, 42 47 (<0.001)
All except MCR ( $m > 1$ g excluded) $\log_{10}a_0$	Constant $\alpha_2$ [ $\alpha_4$ , 0.6, 0.6%]	0.22 -0.18	- 0.19 (0.07) [2.22]	0.06 0.23	1, 42 3.6 (0.07)

<sup>a</sup>MCR, MCRE – Main Cluster Region, MCR Extension (see sections 3.2.1, 3.2.2).

<sup>b</sup>The second model incorporates an additional independent variable; this variable, its  $P$  value, and the additional reduction in the sum of squares it produces (expressed as a proportion), are provided.

<sup>c</sup>From ANOVA; sum of squares accounted for by the variable, and  $P$  value for that variable.



Table 6. Predominant regions of the  $(\alpha_2, \alpha_4)$  plane for different insect characters

Mass $m$ (mg)			RCS $a_0$ (dBsc)			Length $l$ (mm)		
Range	Number <sup>a</sup>	Region <sup>b</sup>	Range	Number	Region	Range	Number	Region
<70	13	A				<12	6	A
70-150	46	A, B	<-2 <sup>c</sup>	45	A, B			
150-250 <sup>x</sup>	32	B, C	-2-0	25	B, D	12-22	87	A, B, C
250-400	22	D	0-4 <sup>d</sup>	50	B, C, D, E	22-25	17	D
400-1000	10	E				25-30	12	E
1000- 2000	15	F	>4	35	F, G	>30	33	F, G
>2000	17	G						

<sup>a</sup>Total 155 as specimen with no width measurement excluded from analysis.

<sup>b</sup>See Figure 6, but note that the ellipses there are schematic and indicate a general area.

*Figure captions*

Figure 1. Relation of measured insect masses  $m$  (mg) to polarization-averaged RCSs  $a_0$  (dBsc) for the study dataset. Key: • – CLPP averages; + – estimated from  $\sigma_{xx}$ ; × – water-filled capillary tube, estimated from  $\sigma_{xx}$ ; main curve – fitted spline (Table 3), with linear sections dashed and the second-order section continuous; short-dashed lines – Chapman, Smith, et al. (2002) fit, of which for clarity only the ends are shown.

Figure 2. (a) Positions of the CLPP dataset specimens on the  $(\alpha_2, \alpha_4)$  plane;  $n = 156$ . The solid line indicates the constraint boundary (Equation (2)). The area within the dashed rectangle is shown enlarged at right. Key: ○ Orthoptera ( $n = 48$ ), + Lepidoptera ( $n = 94$ ), Δ other orders ( $n = 14$ ), □ dipole ( $n = 7$ ). (b) As (a) but with the dipoles omitted and symbols representing the specimen's mass (see key on plot) and the MCR (Main Cluster Region,  $0.8 < p \leq 1$ ,  $0.7 < q \leq 1.5$ ) and MCRE (MCR Extension,  $0.5 < p \leq 0.8$ , same  $q$  range) indicated.

Figure 3. As Figure 2b but with size of symbol indicating the specimen's (a) length, (b) width, and (c) form. For (b) and (c),  $n = 155$ .

Figure 4. Scatterplots of the form  $f$  against the ratio  $r_{sh} = \sigma_{xx}/\sigma_{yy}$  for (a) the L subsample (with regression line shown) and (b) the combined C, A, W, and S subsamples (less two specimens with  $r_{sh} > 50$ ). Clusters A and B in (a) are of ladybirds and lacewings respectively; regions C, D, and E are occupied by carabid beetles, hoverflies, and moths respectively. Specimens with  $m \leq 80$  mg in (b) are marked with a +.

Figure 5. Positions on the  $(\alpha_2, \alpha_4)$  plane of CLPP dataset specimens in different mass ranges. The symbols indicate the specimens' forms  $f$  (see key at top left).

Figure 6. Schematic trajectory on the  $(\alpha_2, \alpha_4)$  plane traced by a notional 'typical insect' as its mass increases (grey line). The ellipses show the approximate area of the plane occupied by CLPP specimens for each of the mass ranges of Figure 5 (with the two similar distributions for  $70 < m < 100$  mg and  $100 < m < 150$  mg combined, and see Table 6); they provide an indication of the lateral spread of points from the notional trajectory line. The dashed lines are contours of  $r_{sh} = \sigma_{xx}/\sigma_{yy}$  with values 2, 5, 10, and 20.

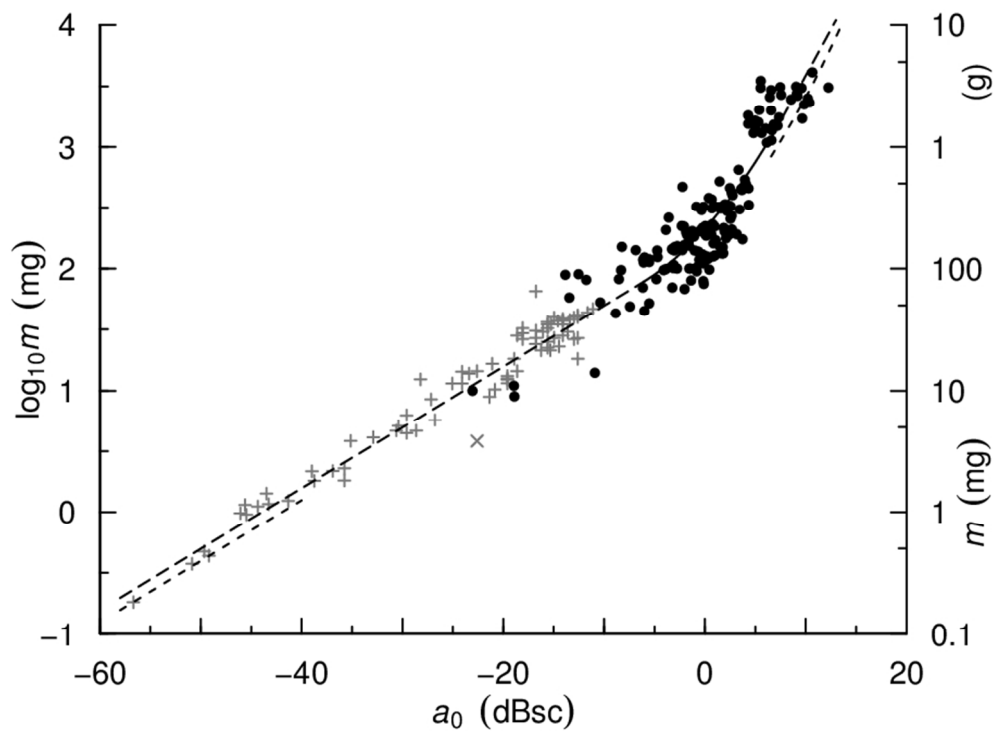


Figure 1  
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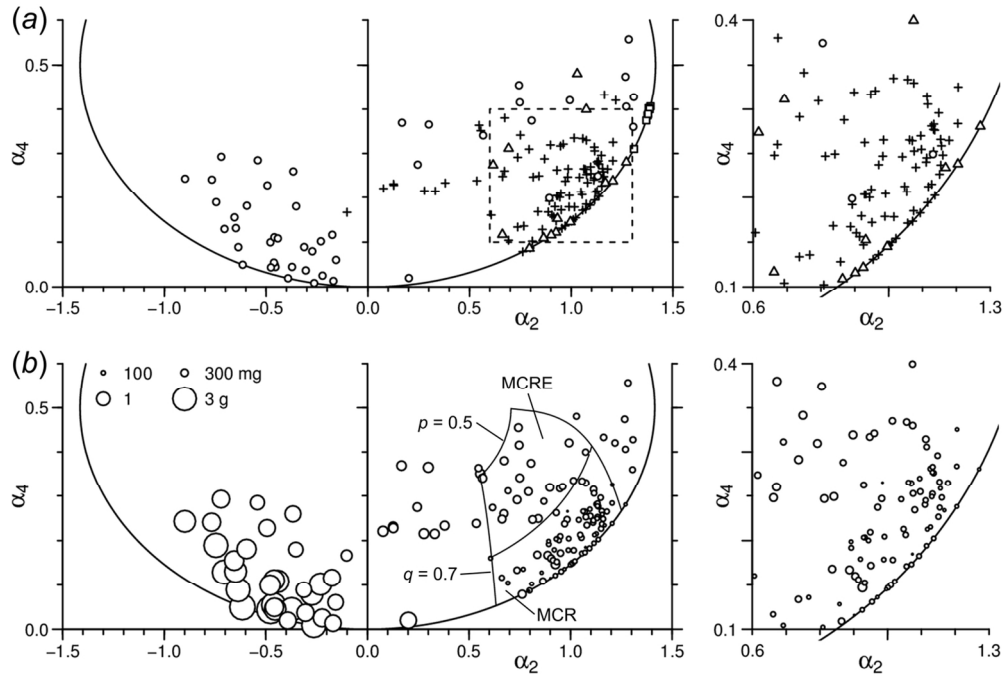


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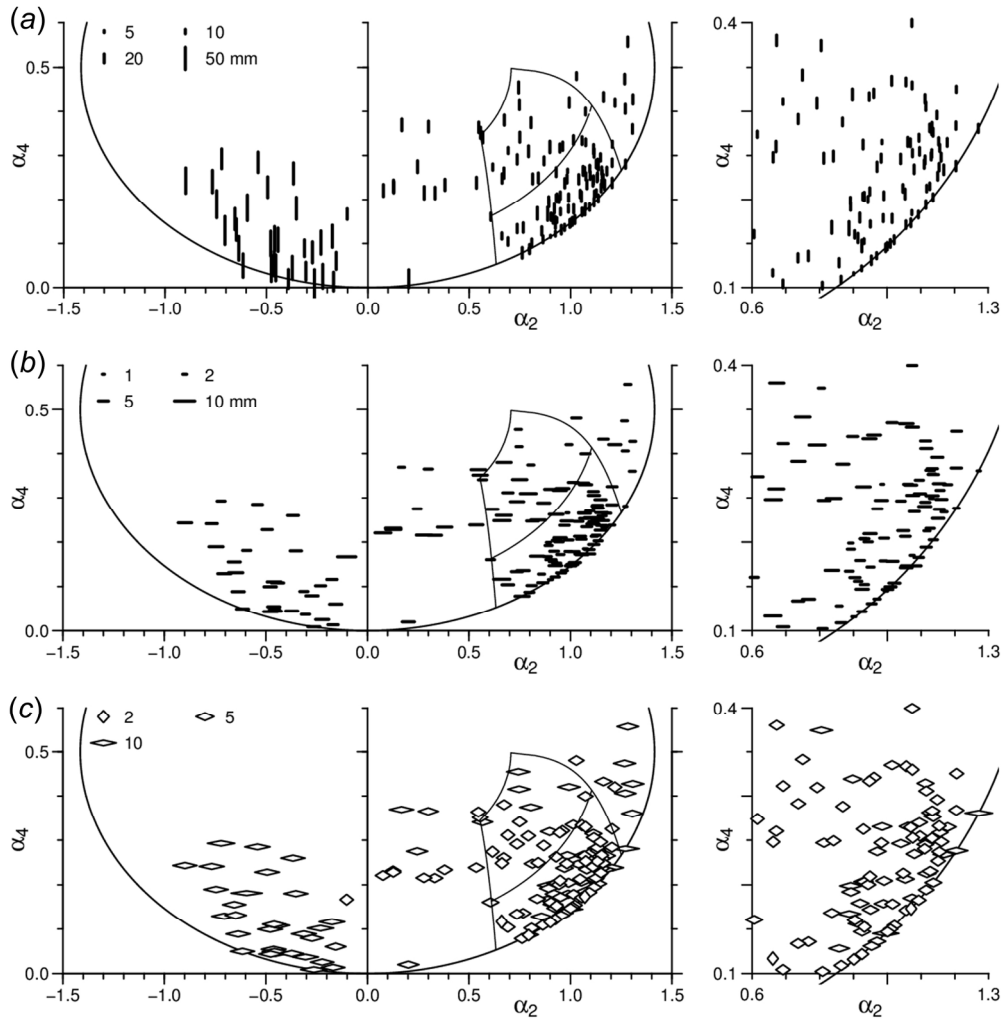


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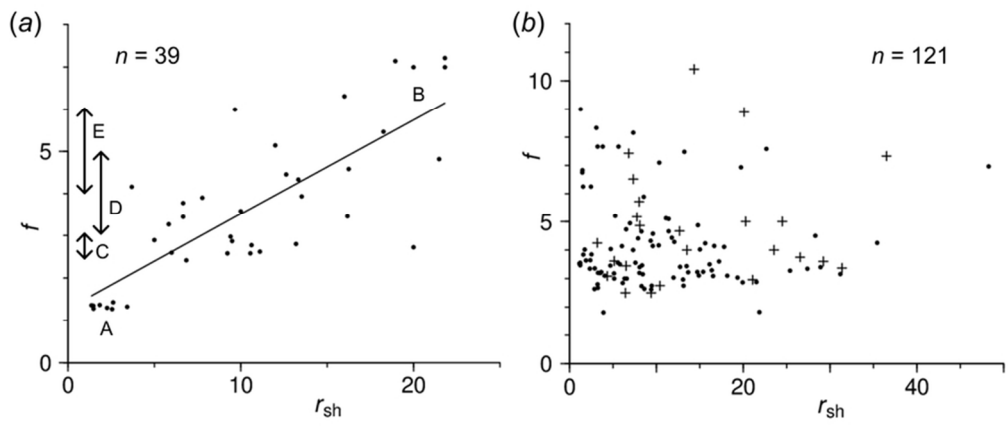


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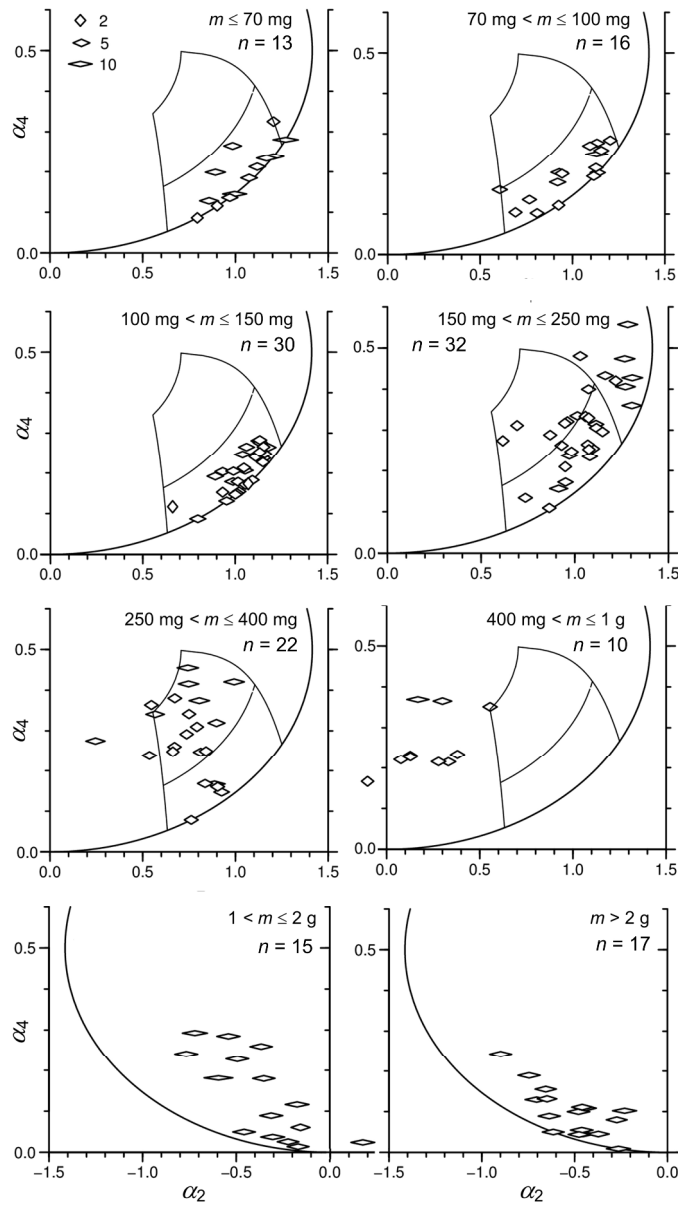


Figure 5  
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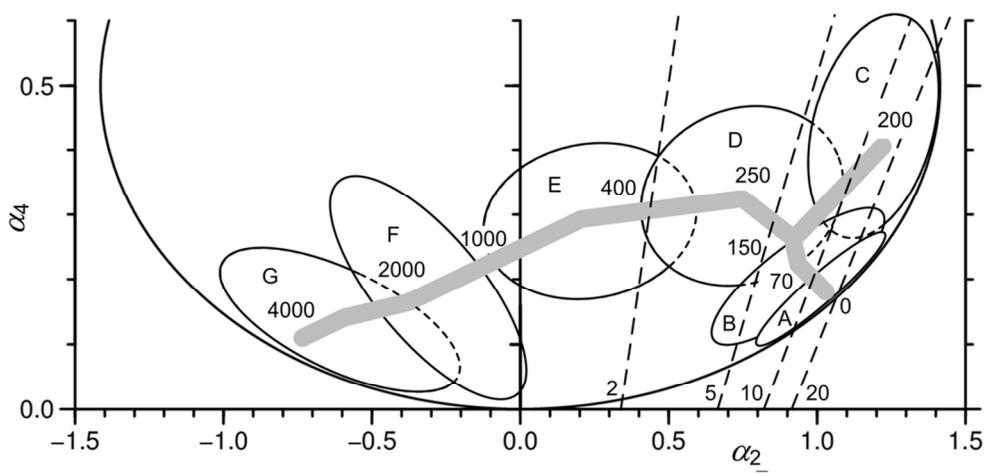


Figure 6  
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**Supplementary file 1 of 2 for:-**

"Ventral-aspect radar cross sections and polarization patterns of insects at X band and their relation to size and form" (V. A. Drake, J. W. Chapman, K Dataset compiler/contact: V. A. Drake (ORCID 0000-0001-9031-7906, a.drake@adfa.edu.au). Dataset released (date, TBA).

This Excel workbook contains a single sheet that is 'protected' (locked) to safeguard data integrity. Users needing to make modifications can copy the

**Ventral-aspect Radar Cross Sections of Insects (X band)**

Note 1

Species (Scientific name) (Also sex if available)	Species (Common name)
<i>Tipula oleracea</i>	Cranefly (T. o.)
<i>Tipula oleracea</i>	Cranefly (T. o.)
<i>Alcis repandata</i>	Mottled Beauty
<i>Mesapamea secalis</i>	Common Rustic
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Chorthippus brunneus</i>	Common Field Grasshopper
<i>Noctua janthina</i>	Langmaid's Yellow Underwing
<i>Noctua janthina</i>	Langmaid's Yellow Underwing
<i>Triodia (Hepialus) sylvina</i>	Orange Swift
<i>Triodia (Hepialus) sylvina</i>	Orange Swift
<i>Ochropleura plecta</i>	Flame Shoulder
<i>Xestia xanthographa</i>	Square-spot Rustic
<i>Xestia xanthographa</i>	Square-spot Rustic
<i>Autographa gamma</i>	Silver-Y
<i>Autographa gamma</i>	Silver-Y
<i>Autographa gamma</i>	Silver-Y
<i>Amphipyra tragopoginis</i>	Mouse Moth
<i>Xestia c-nigrum</i>	Setaceous Hebrew Character
<i>Aglais urticae</i>	Small Tortoiseshell

**Dataset 1: Copolar-Linear Polarization Patterns.**

Order - group within order	Species code	Species index	Group code
Note 2	Note 3		Note 4
Dip - cranefly (Tipulidae)	CfTo		1 O
Dip - cranefly (Tipulidae)	CfTo		1 O
Lep - geometrid moth	MgMB		2 Mo
Lep - noctuid moth	MnCR		3 Mn
Orth - acridid grasshopper	GaCb		4 GL
Orth - acridid grasshopper	GaCb		4 GL
Orth - acridid grasshopper	GaCb		4 GL
Orth - acridid grasshopper	GaCb		4 GL
Orth - acridid grasshopper	GaCb		4 GL
Orth - acridid grasshopper	GaCb		4 GL
Orth - acridid grasshopper	GaCb		4 GL
Lep - noctuid moth	MnLnYU		5 Mn
Lep - noctuid moth	MnLnYU		5 Mn
Lep - hepialid moth	MhOS		6 Mo
Lep - hepialid moth	MhOS		6 Mo
Lep - noctuid moth	MnFS		7 Mn
Lep - noctuid moth	MnSsR		8 Mn
Lep - noctuid moth	MnSsR		8 Mn
Lep - noctuid moth	MnSY		9 Mn
Lep - noctuid moth	MnSY		9 Mn
Lep - noctuid moth	MnSY		9 Mn
Lep - noctuid moth	MnMM		10 Mn
Lep - noctuid moth	MnSHC		11 Mn
Lep - nymphalid butterfly	BunST		12 Bu

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<i>Aglais urticae</i>	Small Tortoiseshell	Lep - nymphalid butterfly	BunST	12 Bu
<i>Noctua comes</i>	Lesser Yellow Underwing	Lep - noctuid moth	MnLeYU	13 Mn
<i>Noctua comes</i>	Lesser Yellow Underwing	Lep - noctuid moth	MnLeYU	13 Mn
<i>Agrotis exclamationis</i>	Hart and Dart	Lep - noctuid moth	MnHD	14 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
<i>Danaus plexippus</i>	Monarch Butterfly	Lep - nymphalid butterfly	BunMB	16 Bu
<i>Noctua fimbriata</i>	Broad-bordered Yellow Underwing	Lep - noctuid moth	MnBbYU	17 Mn
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Schistocerca gregaria</i>	Desert Locust	Orth - acridid locust	LaDL	18 GL
<i>Helicoverpa zea</i> ♀	Corn Earworm	Lep - noctuid moth	MnCE	19 Mn
<i>Helicoverpa zea</i> ♂	Corn Earworm	Lep - noctuid moth	MnCE	19 Mn
<i>Apis mellifera</i> M (drone)	European Honey Bee	Hym - honeybee	HyEHB	20 Hy
<i>Apis mellifera</i> M (drone)	European Honey Bee	Hym - honeybee	HyEHB	20 Hy
<i>Apis mellifera</i> F (queen)	European Honey Bee	Hym - honeybee	HyEHB	20 Hy
<i>Apis mellifera</i> F (queen)	European Honey Bee	Hym - honeybee	HyEHB	20 Hy
<i>Apis mellifera</i> F (worker)	European Honey Bee	Hym - honeybee	HyEHB	20 Hy
<i>Apis mellifera</i> F (worker)	European Honey Bee	Hym - honeybee	HyEHB	20 Hy

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4	<i>Nomius pygmaeus</i>	Stink Beetle	Col - carabid beetle	BecaSB	21 O
5	<i>Spodoptera frugiperda</i>	Fall Armyworm	Lep - noctuid moth	MnFA	22 Mn
6	<i>Elasmopalpus lignosellus</i>	Lesser Cornstalk Borer	Lep - pyralid moth	MpLCB	23 Mo
7	<i>Elasmopalpus lignosellus</i>	Lesser Cornstalk Borer	Lep - pyralid moth	MpLCB	23 Mo
8	<i>Anthonomus grandis</i>	Boll Weevil	Col - curculionid beetle	BecuBW	24 O
9	<i>Anthonomus grandis</i>	Boll Weevil	Col - curculionid beetle	BecuBW	24 O
10	<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
11	<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
12	<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
13	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
14	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
15	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
16	<i>Agrotis exclamationis</i>	Hart and Dart	Lep - noctuid moth	MnHD	14 Mn
17	<i>Agrotis exclamationis</i>	Hart and Dart	Lep - noctuid moth	MnHD	14 Mn
18	<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
19	<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
20	<i>Agrotis segetum</i>	Turnip Moth	Lep - noctuid moth	MnTM	25 Mn
21	<i>Agrotis segetum</i>	Turnip Moth	Lep - noctuid moth	MnTM	25 Mn
22	<i>Agrotis segetum</i>	Turnip Moth	Lep - noctuid moth	MnTM	25 Mn
23	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
24	<i>Helicoverpa armigera</i>	Cotton Bollworm	Lep - noctuid moth	MnCB	26 Mn
25	<i>Helicoverpa armigera</i>	Cotton Bollworm	Lep - noctuid moth	MnCB	26 Mn
26	<i>Helicoverpa armigera</i>	Cotton Bollworm	Lep - noctuid moth	MnCB	26 Mn
27	<i>Helicoverpa armigera</i>	Cotton Bollworm	Lep - noctuid moth	MnCB	26 Mn
28	<i>Vanessa cardui</i>	Painted Lady	Lep - nymphalid butterfly	BunPL	27 Bu
29	<i>Vanessa cardui</i>	Painted Lady	Lep - nymphalid butterfly	BunPL	27 Bu
30	<i>Vanessa cardui</i>	Painted Lady	Lep - nymphalid butterfly	BunPL	27 Bu
31	<i>Vanessa cardui</i>	Painted Lady	Lep - nymphalid butterfly	BunPL	27 Bu
32	<i>Vanessa cardui</i>	Painted Lady	Lep - nymphalid butterfly	BunPL	27 Bu
33	<i>Vanessa atalanta</i>	Red Admiral	Lep - nymphalid butterfly	BunRA	28 Bu
34	<i>Vanessa atalanta</i>	Red Admiral	Lep - nymphalid butterfly	BunRA	28 Bu
35	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
36	<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
37	<i>Noctua pronuba</i>	Large Yellow Underwing	Lep - noctuid moth	MnLaYU	15 Mn
38	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
39	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
40	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
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4	<i>Autographa gamma</i>	Silver-Y	Lep - noctuid moth	MnSY	9 Mn
5	<i>Agrotis segetum</i>	Turnip Moth	Lep - noctuid moth	MnTM	25 Mn
6	<i>Agrotis segetum</i>	Turnip Moth	Lep - noctuid moth	MnTM	25 Mn
7	<i>Mythimna vitellina</i>	Delicate	Lep - noctuid moth	MnDe	29 Mn
8	<i>Noctua comes</i>	Lesser Yellow Underwing	Lep - noctuid moth	MnLeYU	13 Mn
9	<i>Noctua comes</i>	Lesser Yellow Underwing	Lep - noctuid moth	MnLeYU	13 Mn
10	<i>Eupsilia transversa</i>	Satellite	Lep - noctuid moth	MnSa	30 Mn
11	<i>Asteroscopus sphinx</i>	Sprawler	Lep - noctuid moth	MnSp	31 Mn
12	<i>Dichonia aprilina</i>	Merveille du Jour	Lep - noctuid moth	MnMdJ	32 Mn
13	<i>Tipula paludosa</i>	Crane-fly (T. p.)	Dip - crane-fly (Tipulidae)	CfTp	39 O
14	<i>Tipula paludosa</i>	Crane-fly (T. p.)	Dip - crane-fly (Tipulidae)	CfTp	39 O
15	<i>Eurois occulta</i>	Great Brocade Moth	Lep - noctuid moth	MnGB	33 Mn
16	<i>Spodoptera littoralis</i> F	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
17	<i>Spodoptera littoralis</i> F	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
18	<i>Spodoptera littoralis</i> F	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
19	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
20	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
21	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
22	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
23	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
24	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
25	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
26	<i>Spodoptera littoralis</i> M	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
27	<i>Spodoptera littoralis</i> F	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
28	<i>Spodoptera littoralis</i> F	African Cotton Leafworm	Lep - noctuid moth	MnACL	34 Mn
29	<i>Melanoplus sanguinipes</i> F	Migratory Grasshopper	Orth - acridid grasshopper	GaMG	35 GL
30	<i>Melanoplus sanguinipes</i> M	Migratory Grasshopper	Orth - acridid grasshopper	GaMG	35 GL
31	<i>Melanoplus sanguinipes</i> M	Migratory Grasshopper	Orth - acridid grasshopper	GaMG	35 GL
32	<i>Melanoplus sanguinipes</i> M	Migratory grasshopper	Orth - acridid grasshopper	GaMG	35 GL
33	<i>Melanoplus sanguinipes</i> F	Migratory grasshopper	Orth - acridid grasshopper	GaMG	35 GL
34	<i>Melanoplus sanguinipes</i> F	Migratory grasshopper	Orth - acridid grasshopper	GaMG	35 GL
35	<i>Melanoplus sanguinipes</i> M	Migratory grasshopper	Orth - acridid grasshopper	GaMG	35 GL
36	<i>Melanoplus sanguinipes</i> F	Migratory grasshopper	Orth - acridid grasshopper	GaMG	35 GL
37	<i>Schistocerca gregaria</i> F	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL
38	<i>Schistocerca gregaria</i> F	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL
39	<i>Schistocerca gregaria</i> M	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL
40	<i>Schistocerca gregaria</i> F	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL
41	<i>Schistocerca gregaria</i> F	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL
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4	<i>Schistocerca gregaria</i>	F	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL	
5	<i>Schistocerca gregaria</i>	F	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL	
6	<i>Schistocerca gregaria</i>	F	Desert Locust	Orth - acridid grasshopper	LaDL	18 GL	
7	<i>Locusta migratoria</i>	M	Migratory Locust	Orth - acridid grasshopper	LaML	40 GL	
8	<i>Locusta migratoria</i>	F	Migratory Locust	Orth - acridid grasshopper	LaML	40 GL	
9	<i>Locusta migratoria</i>	F	Migratory Locust	Orth - acridid grasshopper	LaML	40 GL	
10	<i>Locusta migratoria</i>	F	Migratory Locust	Orth - acridid grasshopper	LaML	40 GL	
11	<i>Locusta migratoria</i>	F	Migratory Locust	Orth - acridid grasshopper	LaML	40 GL	
12	<i>Locusta migratoria</i>	F	Migratory Locust	Orth - acridid grasshopper	LaML	40 GL	
13	<i>Locustana pardalina</i>	F	Brown Locust	Orth - acridid grasshopper	LaBL	36 GL	
14	<i>Locustana pardalina</i>	F	Brown Locust	Orth - acridid grasshopper	LaBL	36 GL	
15	<i>Locustana pardalina</i>	F	Brown Locust	Orth - acridid grasshopper	LaBL	36 GL	
16	<i>Locustana pardalina</i>	M	Brown Locust	Orth - acridid grasshopper	LaBL	36 GL	
17	<i>Locustana pardalina</i>	M	Brown Locust	Orth - acridid grasshopper	LaBL	36 GL	
18	<i>Locustana pardalina</i>	M	Brown Locust	Orth - acridid grasshopper	LaBL	36 GL	
19	<i>Anacridium melanorhodon</i>	M	Tree locust	Orth - acridid grasshopper	LaTL	37 GL	
20	<i>Anacridium melanorhodon</i>	M	Tree locust	Orth - acridid grasshopper	LaTL	37 GL	
21	( <i>Vespula vulgaris</i> ?)		Common wasp?	Hym - wasp	HyW	38 Hy	
22							
23	Dipole			Cal - D	Dip	D	Di
24	Dipole			Cal - D	Dip	D	Di
25	Dipole			Cal - D	Dip	D	Di
26	Dipole			Cal - D	Dip	D	Di
27	Thin dipole			Cal - TD	TDip	TD	Di
28	Dipole			Cal - D	Dip	D	Di
29	Dipole			Cal - D	Dip	D	Di
30	Dipole			Cal - D	Dip	D	Di

31 Formulas (Note 10)

32 Notes

- 33
- 34
- 35 1 Measured at 9.4 GHz (A, C, S - see Note 6) or ~10 GHz (W); all with linea
- 36 anaesthetized, freshly dead, or freeze-killed and thawed specimens.
- 37 2 Col - Coleoptera, Dip - Diptera, Hym - Hymenoptera, Lep - Lepidoptera, C
- 38 3 Simple code for use if required in analysis software. Local to this dataset.
- 39 4 Bu - Butterfly, GL - Grasshopper/ Locust, Hy - bee/wasp, Mn - Moth (noct)
- 40 5 A - Hobbs and Aldhous (2006); C - Riley (1985) and unpublished; S - A.D
- 41 et al. (1993). See Drake et al. (submitted) for further information.
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6 Obtained from an SM3 fit (see Hobbs and Aldhous, 2006): for A and W, fr  
V.A.Drake using original measurement data. All other RCS quantities in tr  
7 Transformed into the range ( $\varepsilon \geq 0, 0 < \beta \leq 180^\circ$ ). (SM3 fitting sometimes  
8  $a_2$  and  $\alpha_2$  are -ve for perpendicular CLPPs. For A, original dataset had t  
9 ( $p, q$ ) are orthogonal parameters describing CLPP shape, an alternative s  
10 Formulas used to calculate the derived values. Data values are copied fro  
Not available  
Recorded that legs were tied up. Specimens for which it was recorded tha  
this dataset. For other specimens it has been presumed that legs were in  
Outlier. Omitted from later analyses in Drake et al. (submitted). Unrecorde

NA  
LTU  
OUT

Count (insects) 156 (including 1 outlier, 1 for which  $w$  is not ava

References

Drake, V. A., J. W. Chapman, K. S. Lim, D. R. Reynolds, J. R. Riley, and A. D. Smith. Submitted. "Ventral-aspect ra  
Hobbs, S. E., and A. C. Aldhous. 2006. "Insect Ventral Radar Cross-section Polarisation Dependence Measuremer  
Riley, J. R. 1985. "Radar Cross Section of Insects." *Proceedings of the IEEE* 73: 228-232. doi:10.1109/PROC.1985  
Wolf, W. W., C. R. Vaughn, R. Harris and G. M. Loper. 1993. "Insect Radar Cross-sections for Aerial Density Measr



(S Lim, D. R. Reynolds, J. R. Riley, and A. D. Smith.) *International Journal of Remote Sensing* (submitted 30 March 2017).

data to another workbook.

Source	Mass	Wing length	Body length	Body width	$\sigma_{xx}$	$\varepsilon$ (-ve)	$\beta$ ( $\varepsilon$ -ve)	$\varepsilon$	$\beta$	$\theta_0$	$a_0$	$a_2$	$a_4$
Note 5	(mg)	(mm)	(mm)	(mm)	(cm <sup>2</sup> )	Note 6	Note 6	Note 7	Note 7	(deg)	(cm <sup>2</sup> )	(cm <sup>2</sup> )	(cm <sup>2</sup> )
						Note 6	Note 6	Note 7	Note 7	Note 6		Note 8	
A	45	14.8	17.7	1.7	0.537	0.264	0.0	0.264	0.00	-21.9	0.251	0.250	0.036
A	49	17.2	18.7	1.6	0.460	0.062	0.0	0.062	0.00	-2.3	0.180	0.229	0.051
A	52	20.2	18.9	2.9	0.556	0.369	32.9	0.369	32.90	-26.1	0.280	0.240	0.036
A	53	14.5	14	3	0.193	0.281	0.0	0.281	0.00	9.9	0.092	0.089	0.012
A	68	13.8	15.6	2.1	1.314	0.383	59.7	0.383	59.70	-14.4	0.629	0.561	0.125
A	97	13.7	16.9	1.9	0.927	0.223	61.6	0.223	61.60	-4.9	0.389	0.440	0.097
A	173	11.5	20.2	2.9	6.290	0.144	102.1	0.144	102.10	5.2	2.360	3.080	0.850
A	188	11.7	22	2.9	4.730	0.210	119.5	0.210	119.50	0.1	1.730	2.261	0.740
A	190	12	20.8	3	5.540	0.225	111.2	0.225	111.20	3.3	2.070	2.630	0.840
A	200	12.4	21.3	3	4.452	0.311	139.5	0.311	139.50	-2.2	1.568	2.011	0.874
A	214	15.4	21.7	2.9	4.220	0.275	124.0	0.275	124.00	4.9	1.540	1.950	0.730
A	80	16.5	15.5	4.5	1.394	0.392	22.3	0.392	22.30	-2.5	0.729	0.590	0.075
A	82	17	17	4	0.583	0.560	58.4	0.560	58.40	6.4	0.330	0.200	0.053
A	82	14.1	15.5	3	0.299	0.359	59.4	0.359	59.40	2.3	0.140	0.130	0.029
A	113	15.4	17.3	3.5	0.584	0.379	57.5	0.379	57.50	4.5	0.280	0.250	0.054
A	100	13.2	14.2	4.1	1.500	0.346	57.4	0.346	57.40	1.5	0.700	0.660	0.140
A	102	16.8	16.3	3.2	1.798	0.296	43.7	0.296	43.70	4.7	0.830	0.820	0.148
A	126	16.9	17.8	4.2	2.480	0.253	75.1	0.253	75.10	-0.4	1.030	1.161	0.290
A	107	20	20.5	4.4	1.140	0.296	72.8	0.296	72.80	5.1	0.490	0.520	0.130
A	118	20.2	19.4	4.4	1.879	0.356	59.2	0.356	59.20	-1.5	0.880	0.820	0.179
A	149	20.6	22.9	4.7	3.389	0.260	49.6	0.260	49.60	-6.5	1.500	1.580	0.309
A	110	18.4	17.9	4.3	2.151	0.312	55.6	0.312	55.60	-1.6	0.980	0.971	0.200
A	125	17.7	17.5	5	2.900	0.249	75.5	0.249	75.50	-5.0	1.200	1.360	0.340
A	128	25.4	21.5	4.2	2.880	0.300	67.6	0.300	67.60	8.2	1.260	1.310	0.310

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4	A	160	25.8	21.2	3.6	2.515	0.342	41.3	0.342	41.30	-14.1	1.215	1.110	0.190
5	A	133	17.5	18.5	4.5	3.587	0.237	61.7	0.237	61.70	1.4	1.521	1.693	0.373
6	A	176	18.6	19.7	4.9	3.750	0.258	60.2	0.258	60.20	-2.2	1.620	1.750	0.380
7	A	208	17.5	19	5.5	3.457	0.461	46.0	0.461	46.00	0.8	1.849	1.361	0.247
8	A	270	25.4	27.3	6.6	3.690	0.407	52.6	0.407	52.60	0.4	1.841	1.539	0.310
9	A	295	23.5	23	5.7	3.420	0.459	74.1	0.459	74.10	-3.8	1.660	1.350	0.410
10	A	321	25	26	5	2.150	0.436	87.5	0.436	87.50	3.7	0.970	0.871	0.310
11	A	333	24.5	24.5	7	5.012	0.415	0.0	0.415	0.00	-3.1	2.723	2.074	0.214
12	A	337	25.5	25	6.5	2.819	0.629	75.2	0.629	75.20	-3.9	1.589	0.852	0.379
13	A	400	26.5	26.8	6.2	3.895	0.327	34.5	0.327	34.50	-0.2	1.879	1.739	0.277
14	A	419	25.3	25.8	7.1	2.970	0.727	75.2	0.727	75.20	-1.1	1.840	0.700	0.430
15	A	443	27.7	26.9	6.7	3.599	0.756	72.3	0.756	72.30	-1.9	2.328	0.771	0.500
16	A	451	24.5	26	7.5	3.090	0.901	75.0	0.901	75.00	-0.8	2.280	0.291	0.520
17	A	457	26.1	27	7.6	3.672	0.902	75.5	0.902	75.50	-1.9	2.705	0.342	0.625
18	A	459	26.1	25.5	7	3.371	0.646	92.5	0.646	92.50	-7.4	1.768	0.982	0.621
19	A	495	25	28.8	7.5	3.810	0.792	72.6	0.792	72.60	4.6	2.551	0.710	0.549
20	A	538	26.9	27.5	7.8	3.230	0.939	73.9	0.939	73.90	132.3	2.490	0.191	0.549
21	A	305	39.5	30.2	3.7	4.539	0.369	48.9	0.369	48.90	5.0	2.209	1.960	0.369
22	A	648	24.5	24.5	9	2.740	0.916	64.5	0.916	64.50	89.5	2.160	-0.220	0.360
23	A	1084	45.7	46.6	4.8	7.501	0.638	82.8	0.638	82.80	92.3	4.108	-2.224	1.169
24	A	1133	48.9	50.4	5.6	6.998	0.735	65.9	0.735	65.90	96.4	4.567	-1.609	0.822
25	A	1371	45.2	48.3	5.4	7.513	0.741	79.4	0.741	79.40	96.9	4.620	-1.694	1.199
26	A	1494	45.3	47.5	5.1	9.055	0.653	73.7	0.653	73.70	98.6	5.258	-2.597	1.200
27	A	1532	46.6	50.7	5	6.238	0.854	53.8	0.854	53.80	106.9	4.832	-0.844	0.562
28	A	1713	56.1	54.5	6.5	11.519	0.802	22.7	0.802	22.70	104.0	9.229	-2.055	0.235
29	A	1751	47	51.2	5.4	10.901	0.486	73.5	0.486	73.50	96.2	5.430	-4.163	1.308
30	A	2241	51.9	56.7	6.1	15.210	0.627	44.9	0.627	44.90	90.5	9.635	-4.615	0.960
31	A	2326	54.7	55.4	6.8	17.053	0.644	48.7	0.644	48.70	101.5	10.859	-4.990	1.204
32	A	2474	53.3	58.1	6.6	15.330	0.401	71.6	0.401	71.60	88.6	7.158	-6.432	1.739
33	A	3094	50.3	62.3	6.9	32.472	0.479	62.2	0.479	62.20	91.2	16.784	-12.511	3.177
34	W	254 NA		17	5	3.697	0.352	44.4	0.352	44.40	-0.9	1.791	1.619	0.287
35	W	206 NA		14.5	3.5	0.871	0.323	45.1	0.323	45.10	0.7	0.410	0.390	0.071
36	W	182 NA		14	5	1.563	0.556	86.6	0.556	86.60	0.0	0.780	0.540	0.243
37	W	208 NA		14.5	5.5	1.964	0.590	80.8	0.590	80.80	0.3	1.039	0.640	0.285
38	W	185 NA		16	4.5	2.585	0.424	114.5	0.424	114.50	-0.2	1.030	1.060	0.495
39	W	196 NA		16	4.5	2.028	0.363	102.8	0.363	102.80	-0.1	0.820	0.880	0.328
40	W	150 NA		11	4	0.313	0.325	36.8	0.325	36.80	-0.5	0.150	0.140	0.023
41	W	99 NA		11	4	0.840	0.310	0.0	0.310	0.00	0.6	0.410	0.380	0.050
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4	W	132 NA	14.5	8	2.633	0.506	43.8	0.506	43.80	0.7	1.481	0.979	0.173
5	W	100 NA	14.5	3.5	1.277	0.245	73.4	0.245	73.40	0.9	0.530	0.600	0.147
6	W	14 NA	10	2	0.183	0.222	27.4	0.222	27.40	1.5	0.081	0.087	0.015
7	W	9 NA	8	1.4	0.029	0.353	75.1	0.353	75.10	-0.8	0.013	0.013	0.003
8	W	10 NA	5	2	0.010	0.326	7.1	0.326	7.10	-0.6	0.005	0.004	0.001
9	W	11 NA	5	2	0.024	0.394	0.0	0.394	0.00	-0.4	0.013	0.010	0.001
10	S	308 NA	24.5	7.9	3.0162	0.496	86.09	0.496	86.09	0.83	1.435	1.137	0.444
11	S	321 NA	21.4	8	2.4456	0.5535	75.99	0.554	75.99	-2.36	1.280	0.848	0.317
12	S	260 NA	24.1	7.2	0.8358	0.6539	94.17	0.654	94.17	0.65	0.438	0.239	0.159
13	S	97 NA	17.2	5.1	0.3669	0.1785	70.45	0.179	70.45	0.79	0.147	0.178	0.042
14	S	144 NA	17.8	5.5	1.018	0.2549	0.00	0.255	0.00	0.73	0.471	0.476	0.071
15	S	58 NA	14.2	4.8	0.1144	0.2177	87.52	0.218	87.52	-1.67	0.045	0.054	0.015
16	S	118 NA	15.4	4.7	0.5552	0.1985	0.00	0.199	0.00	-1.19	0.244	0.267	0.045
17	S	202 NA	17.8	6	1.9756	0.2765	110.94	0.277	110.94	-3.31	0.749	0.912	0.315
18	S	322 NA	23	7.2	1.7203	0.5319	91.24	0.532	91.24	-0.31	0.823	0.617	0.281
19	S	311 NA	22.9	7.2	3.2431	-0.4418	105.85	0.442	74.15	-0.19	1.551	1.305	0.387
20	S	140 NA	18	5.7	0.7997	0.1791	41.25	0.179	41.25	2.53	0.336	0.387	0.076
21	S	149 NA	18.6	6	1.174	0.2346	59.57	0.235	59.57	-0.67	0.499	0.555	0.120
22	S	140 NA	16.7	5.8	1.2085	0.2155	67.21	0.216	67.21	-1.18	0.499	0.576	0.133
23	S	119 NA	16.8	5.2	0.598	0.2606	0.00	0.261	0.00	-1.83	0.278	0.279	0.041
24	S	123 NA	17.6	5.8	0.5609	0.2273	16.10	0.227	16.10	1.09	0.252	0.266	0.043
25	S	197 NA	18.6	5.9	1.4518	0.3443	70.28	0.344	70.28	-1.46	0.651	0.640	0.161
26	S	90 NA	17.6	5.7	0.1002	0.4794	37.06	0.479	37.06	1.12	0.056	0.039	0.006
27	S	152 NA	17.6	5.8	1.2403	0.2889	72.14	0.289	72.14	0.96	0.531	0.568	0.141
28	S	89 NA	20.9	4.3	0.08656	0.35161	51.19	0.352	51.19	2.23	0.041	0.038	0.007
29	S	203 NA	21.5	4.7	2.3259	-0.3227	69.10	0.323	110.90	0.87	0.896	1.042	0.388
30	S	187 NA	21.4	4.6	1.4711	0.3475	67.96	0.348	67.96	-1.85	0.666	0.647	0.158
31	S	141 NA	20.8	4.4	0.3885	0.3917	0.00	0.392	0.00	-0.34	0.206	0.164	0.018
32	S	124 NA	19.5	4.4	0.7073	0.2913	0.00	0.291	0.00	-1.00	0.339	0.324	0.044
33	S	222 NA	21	4.9	1.4297	0.2879	85.33	0.288	85.33	1.12	0.589	0.656	0.185
34	S	214 NA	20	5	2.2217	0.3695	90.33	0.370	90.33	-1.38	0.946	0.959	0.317
35	S	172 NA	17.4	5.6	1.6426	0.2591	67.21	0.259	67.21	1.27	0.699	0.766	0.178
36	S	331 NA	23.5	7	3.1724	0.5869	96.71	0.587	96.71	-2.04	1.545	1.040	0.588
37	S	328 NA	23.7	7.4	3.338	0.552	78.13	0.552	78.13	1.17	1.728	1.160	0.450
38	S	156 NA	19.1	5.6	1.5336	0.2802	82.97	0.280	82.97	-2.92	0.633	0.707	0.194
39	S	143 NA	18.9	5.5	1.0472	0.2723	38.85	0.272	38.85	1.55	0.477	0.485	0.085
40	S	112 NA	17.9	9.8	0.5536	0.2139	0.00	0.214	0.00	1.87	0.247	0.264	0.043
41	S	141 NA	17.4	5.4	1.34701	0.27055	53.75	0.271	53.75	-0.06	0.596	0.624	0.127
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4	S	153 NA		17	5.5	1.6998	0.2459	79.19	0.246	79.19	0.74	0.696	0.799	0.206
5	S	210 NA		17.7	6.7	2.5755	-0.3406	89.93	0.341	90.07	-0.08	1.078	1.138	0.360
6	S	101 NA		18.1	5.5	1.055	0.2471	0.00	0.247	0.00	2.92	0.485	0.495	0.075
7	S	137 NA		18.4	5.5	2.0744	-0.1911	123.69	0.191	56.31	0.32	0.861	0.999	0.214
8	S	222 NA		18.9	6.3	2.3054	0.3973	87.67	0.397	87.67	2.08	1.010	0.971	0.324
9	S	324 NA		21.3	6.6	3.6435	0.5228	83.17	0.523	83.17	-3.01	1.796	1.324	0.523
10	S	152 NA		16.7	6.1	1.3137	0.3473	60.25	0.347	60.25	-0.11	0.609	0.578	0.127
11	S	190 NA		20.4	6.8	2.2013	0.3898	75.57	0.390	75.57	-1.71	1.004	0.933	0.264
12	S	230 NA		18.5	6.5	2.689	-0.404	93.09	0.404	86.91	-1.08	1.188	1.125	0.376
13	S	43 NA		22	3	0.3129	0.1655	41.35	0.166	41.35	-1.90	0.130	0.152	0.030
14	S	70 NA		21.6	2.7	0.5919	0.117	0.00	0.117	0.00	-2.02	0.242	0.292	0.058
15	S	81 NA		21.7	6	0.1267	0.4404	45.02	0.440	45.02	-5.45	0.067	0.051	0.009
16	C	220	15.5	15.7	6	2.998	0.326	89.22	0.326	89.22	5.12	1.247	1.340	0.411
17	C	150	15	17.2	6	3.373	-0.224	117.05	0.224	62.95	-5.76	1.414	1.602	0.357
18	C	170	15.5	16.5	6	2.978	-0.276	112.11	0.276	67.90	-15.35	1.279	1.376	0.323
19	C	95	16	18	5	1.915	0.185	12.38	0.185	12.38	-2.63	0.829	0.925	0.161
20	C	100	15	17	4	1.671	0.168	0.00	0.168	0.00	2.95	0.714	0.812	0.145
21	C	120	15	17	5	2.566	0.186	49.42	0.186	49.42	-3.45	1.073	1.239	0.254
22	C	70	15	15	3	1.107	0.202	39.67	0.202	39.67	-1.13	0.475	0.531	0.101
23	C	75	14	16	4	2.353	0.206	63.20	0.206	63.20	6.85	0.974	1.127	0.252
24	C	79	15	15	4	2.259	0.194	38.75	0.194	38.75	-2.17	0.964	1.087	0.208
25	C	98	15	16	4	2.615	-0.272	107.19	0.272	72.82	18.32	1.106	1.211	0.299
26	C	140	16	18	5	1.91	0.241	72.88	0.241	72.88	-0.58	0.792	0.900	0.219
27	C	190	16	18	6	2.494	0.441	81.78	0.441	81.78	2.67	1.156	1.004	0.333
28	C	130	14	18	4	2.314	-0.188	116.57	0.188	63.43	-13.54	0.947	1.116	0.251
29	C	370	19	25	4	2.229	0.637	91.05	0.637	91.05	9.82	1.169	0.662	0.398
30	C	320	20	23	3	2.881	0.556	101.83	0.556	101.83	11.80	1.332	0.995	0.554
31	C	320	19	23	3	3.426	-0.421	75.08	0.421	104.92	3.10	1.420	1.409	0.597
32	C	300	17	23	3	2.019	0.511	96.35	0.511	96.35	3.38	0.926	0.746	0.347
33	C	520	21	25	4	2.33	0.8	94.13	0.800	94.13	2.21	1.399	0.419	0.511
34	C	380	20	27	4	1.661	0.823	81.94	0.823	81.94	12.58	1.093	0.268	0.300
35	C	310	19	25	3	2.575	0.569	106.95	0.569	106.95	-6.32	1.171	0.871	0.533
36	C	470	22	27	3	0.921	0.884	94.55	0.884	94.55	-6.55	0.599	0.101	0.221
37	C	1820	47	46	5	1.589	1.596	25.59	1.596	25.59	3.87	2.686	-1.229	0.133
38	C	3150	50	64	6	5.984	1.307	0.00	1.307	0.00	-14.31	8.033	-2.119	0.070
39	C	2590	47	49	7	2.124	1.921	49.12	1.921	49.12	-3.20	4.403	-2.857	0.578
40	C	2950 NA		52	6	3.05	1.452	27.59	1.452	27.59	3.40	4.536	-1.690	0.204
41	C	2700	53	48	6	4.599	1.295	43.25	1.295	43.25	-4.97	5.701	-1.557	0.454
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4	C	3070	51	54	6	4.114	1.953	33.92	1.953	33.92	12.51	9.094	-5.789	0.809
5	C	2770	62	53	6	5.438	-1.526	131.63	1.526	48.37	6.19	8.166	-3.613	0.884
6	C	2520	58	59	6	6.188	-1.593	156.90	1.593	23.10	-1.38	10.476	-4.757	0.470
7	C	2020 NA		49	5.9	1.729	1.904	55.82	1.904	55.82	1.45	3.461	-2.269	0.537
8	C	3080 NA		64	6.5	1.516	2.078	46.07	2.078	46.07	4.96	3.570	-2.515	0.461
9	C	3120 NA		56	6	3.309	1.599	28.11	1.599	28.11	-2.76	5.580	-2.576	0.304
10	C	3506	50	53	6	1.556	1.957	0.00	1.957	0.00	-9.00	3.579	-2.202	0.178
11	C	2650	53	53	5	7.209	1.237	49.87	1.237	49.87	-0.21	8.277	-1.911	0.843
12	C	4120	56	60	7	6.601	1.637	20.63	1.637	20.63	-1.24	11.637	-5.544	0.508
13	C	1450	45	43	5	2.6693	1.1837	16.30	1.184	16.30	-0.75	3.162	-0.535	0.043
14	C	1420	46	41	6	4.8729	0.8185	19.92	0.819	19.92	18.38	3.989	0.804	0.080
15	C	1300	42	39	6	3.306	1.16	38.72	1.160	38.72	-5.56	3.656	-0.571	0.221
16	C	1300	42	38	4	2.352	1.344	45.38	1.344	45.38	-1.15	3.030	-0.948	0.270
17	C	1600	42	41	4	2.481	1.354	26.28	1.354	26.28	-7.85	3.389	-1.034	0.126
18	C	1550	43	43 NA		1.69	1.5	0.00	1.500	0.00	15.41	2.693	-1.056	0.053
19	C	2000	55	59	4	2.658	1.74	63.43	1.740	63.43	-6.96	4.532	-2.695	0.821
20	C	1650	51	45	4	1.804	1.876	83.46	1.876	83.46	-4.79	3.154	-2.272	0.923
21	C	220	15	16	5	1.2211	0.3525	14.63	0.353	14.63	-9.43	0.619	0.535	0.067
22														
23	S			16	1	4.62216	-0.06159	22.46	0.062	157.54	-1.22	1.674	2.302	0.646
24	S			16	1	5.38	-0.07829	0.00	0.078	180.00	3.02	1.925	2.674	0.782
25	S			16	1	5.3861	-0.088	32.14	0.088	147.86	0.02	1.935	2.672	0.779
26	S			16	1	5.5189	-0.0451	0.00	0.045	180.00	0.13	2.012	2.754	0.753
27	S			30	0.5	3.41654	0.04458	93.94	0.045	93.94	-3.59	1.281	1.705	0.431
28	S			16	1	5.50297	-0.07237	7.81	0.072	172.19	-3.49	1.976	2.737	0.790
29	S			16	1	5.44251	-0.06216	14.25	0.062	165.75	-2.78	1.967	2.711	0.765
30	S			16	1	4.0825	-0.02637	180.00	0.026	0.00	-4.10	1.559	2.040	0.484
31														
32						0.537	0.264	0.0	0.264	0.00	-21.9	0.251	0.250	0.036
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ar polarization in laboratory rigs and with

Orth - Orthoptera; Cal - calibration target.

uid), Mo - Moth (other), O - other; Di - Dipole.

. Smith and D.R. Reynolds, unpublished; W - Wolf

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om Hobbs and Aldhous (2006); for C and S by  
ie table are derived from these.  
produce equivalent values with  $\varepsilon < 0$ .)  
both +ve.  
system to  $(\alpha_2, \alpha_4)$ ; see Drake et al. (submitted).  
in line 10.

it legs were down have been omitted from this dataset.  
a near-natural position.  
and legs-down measurement?

ilable, and 1 for which  $q$  is not available).

adar cross sections and polarization patterns of insects at X band and their relation to size and form." *International Journal of Remote Sensing*. doi:10.1080/0143  
its for Radar Entomology." *IEE Proceedings – Radar, Sonar and Navigation* 153: 502-508. doi:10.1049/ip-rsn:20060019  
5.13135  
urements and Target Classification." *Transactions of the American Society of Agricultural Engineers* 36: 949-954. doi:10.13031/2013.28420

$\alpha_2$	$\alpha_4$	$\sigma_{xx}/\sigma_{yy}$	$a_0$	$p$	$q$	Notes
Note 8				Note 9	Note 9	
0.996	0.145	14.35	-6.01	1.00	1.13	
1.271	0.281	260.15	-7.44	1.00	1.54	
0.858	0.128	7.34	-5.53	0.96	0.97	
0.970	0.136	12.66	-10.38	1.00	1.10	
0.892	0.199	6.82	-2.02	0.87	1.04	
1.131	0.249	20.11	-4.10	0.94	1.34	
1.305	0.360	48.23	3.73	0.96	1.67	
1.307	0.428	22.68	2.38	0.94	1.81	
1.270	0.406	19.75	3.16	0.92	1.71	
1.283	0.557	10.34	1.95	0.91	NA	No $q$ as $\alpha_4 > 0.5$ .
1.267	0.474	13.22	1.88	0.90	2.00	
0.809	0.102	6.51	-1.37	0.98	0.91	
0.606	0.161	3.19	-4.82	0.80	0.69	
0.929	0.203	7.76	-8.53	0.88	1.08	
0.892	0.192	6.96	-5.53	0.88	1.03	
0.944	0.200	8.35	-1.55	0.90	1.10	
0.989	0.179	11.41	-0.81	0.95	1.14	
1.127	0.281	15.62	0.13	0.91	1.36	
1.062	0.265	11.41	-3.10	0.89	1.27	
0.933	0.204	7.89	-0.56	0.89	1.09	
1.054	0.206	14.79	1.76	0.95	1.23	
0.991	0.204	10.27	-0.09	0.92	1.15	
1.133	0.283	16.13	0.79	0.91	1.37	
1.040	0.246	11.11	1.00	0.89	1.23	

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4	0.914	0.156	8.55	0.85	0.94	1.04
5	1.113	0.245	17.80	1.82	0.94	1.32
6	1.080	0.234	15.02	2.10	0.93	1.28
7	0.736	0.134	4.71	2.67	0.90	0.83
8	0.836	0.168	6.04	2.65	0.89	0.96
9	0.813	0.247	4.75	2.20	0.77	0.97
10	0.898	0.319	5.26	-0.13	0.73	1.11
11	0.762	0.079	5.81	4.35	1.00	0.85
12	0.536	0.238	2.53	2.01	0.65	0.63
13	0.926	0.147	9.35	2.74	0.96	1.05
14	0.380	0.233	1.89	2.65	0.60	0.45
15	0.331	0.215	1.75	3.67	0.62	0.39
16	0.128	0.228	1.23	3.58	0.55	0.15
17	0.127	0.231	1.23	4.32	0.55	0.15
18	0.556	0.351	2.40	2.47	0.49	0.70
19	0.278	0.215	1.59	4.07	0.60	0.33
20	0.077	0.221	1.13	3.96	0.56	0.09
21	0.887	0.167	7.34	3.44	0.91	1.02
22	-0.102	0.167	1.19	3.34	0.67	-0.12
23	-0.541	0.285	2.46	6.14	0.58	-0.66
24	-0.352	0.180	1.85	6.60	0.69	-0.41
25	-0.367	0.259	1.82	6.65	0.55	-0.44
26	-0.494	0.228	2.35	7.21	0.65	-0.58
27	-0.175	0.116	1.37	6.84	0.78	-0.20
28	-0.223	0.026	1.55	9.65	0.96	-0.24
29	-0.767	0.241	4.23	7.35	0.75	-0.91
30	-0.479	0.100	2.54	9.84	0.87	-0.54
31	-0.460	0.111	2.41	10.36	0.84	-0.52
32	-0.899	0.243	6.22	8.55	0.82	-1.06
33	-0.745	0.189	4.36	12.25	0.81	-0.86
34	0.904	0.160	8.07	2.53	0.93	1.04
35	0.951	0.172	9.59	-3.87	0.94	1.09
36	0.692	0.311	3.23	-1.08	0.62	0.85
37	0.616	0.274	2.87	0.17	0.63	0.74
38	1.029	0.480	5.56	0.13	0.73	1.68
39	1.074	0.400	7.59	-0.86	0.79	1.43
40	0.932	0.152	9.47	-8.24	0.96	1.06
41	0.925	0.122	10.41	-3.87	1.00	1.04
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4	0.662	0.117	3.91	1.70	0.90	0.75
5	1.132	0.277	16.66	-2.76	0.92	1.37
6	1.074	0.185	20.29	-10.91	0.99	1.24
7	0.985	0.265	8.03	-18.90	0.84	1.18
8	0.901	0.116	9.41	-23.05	1.00	1.02
9	0.794	0.086	6.44	-18.94	1.00	0.89
10	0.792	0.310	4.06	1.57	0.68	0.98
11	0.663	0.248	3.26	1.07	0.69	0.79
12	0.547	0.364	2.34	-3.59	0.47	0.70
13	1.205	0.284	31.39	-8.31	0.96	1.46
14	1.010	0.150	15.39	-3.27	1.00	1.15
15	1.205	0.325	21.10	-13.45	0.92	1.50
16	1.093	0.183	25.38	-6.13	1.00	1.26
17	1.219	0.420	13.08	-1.26	0.88	1.67
18	0.750	0.341	3.53	-0.85	0.62	0.94
19	0.841	0.249	5.12	1.91	0.78	1.00
20	1.150	0.227	31.18	-4.73	0.98	1.35
21	1.111	0.240	18.17	-3.02	0.94	1.31
22	1.154	0.266	21.53	-3.02	0.94	1.38
23	1.001	0.147	14.72	-5.55	1.00	1.14
24	1.056	0.171	19.36	-5.99	1.00	1.21
25	0.983	0.247	8.44	-1.86	0.86	1.17
26	0.692	0.104	4.35	-12.53	0.93	0.78
27	1.070	0.264	11.98	-2.75	0.89	1.28
28	0.920	0.179	8.09	-13.85	0.91	1.06
29	1.163	0.433	9.60	-0.48	0.83	1.63
30	0.971	0.237	8.28	-1.76	0.86	1.15
31	0.798	0.087	6.52	-6.86	1.00	0.89
32	0.954	0.131	11.78	-4.69	1.00	1.08
33	1.113	0.314	12.06	-2.30	0.87	1.37 Possibly somewhat dehydrated
34	1.014	0.335	7.32	-0.24	0.79	1.27 Possibly somewhat dehydrated
35	1.097	0.255	14.90	-1.56	0.92	1.31
36	0.673	0.380	2.90	1.89	0.53	0.88
37	0.672	0.260	3.28	2.38	0.67	0.80
38	1.116	0.306	12.74	-1.98	0.88	1.37
39	1.016	0.178	13.49	-3.21	0.96	1.17
40	1.071	0.173	21.86	-6.08	1.00	1.23
41	1.047	0.213	13.66	-2.25	0.94	1.22
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4	1.148	0.296	16.54	-1.58	0.91	1.40
5	1.056	0.334	8.62	0.32	0.82	1.32
6	1.021	0.154	16.38	-3.14	1.00	1.17
7	1.160	0.248	27.38	-0.65	0.96	1.38
8	0.961	0.321	6.34	0.04	0.77	1.19
9	0.737	0.291	3.66	2.54	0.67	0.90
10	0.949	0.209	8.29	-2.16	0.89	1.11
11	0.929	0.262	6.58	0.02	0.81	1.11
12	0.947	0.317	6.13	0.75	0.76	1.17
13	1.168	0.234	36.51	-8.85	0.98	1.38
14	1.205	0.238	73.05	-6.16	1.00	1.42
15	0.767	0.136	5.16	-11.77	0.91	0.87
16	1.074	0.330	9.41	0.96	0.83	1.34
17	1.133	0.252	19.93	1.51	0.94	1.35
18	1.075	0.253	13.13	1.07	0.91	1.28
19	1.115	0.194	29.22	-0.81	1.00	1.29
20	1.136	0.202	35.43	-1.46	1.00	1.32
21	1.154	0.237	28.91	0.31	0.97	1.36
22	1.117	0.213	24.51	-3.23	0.98	1.31
23	1.156	0.259	23.56	-0.11	0.95	1.38
24	1.127	0.215	26.57	-0.16	0.98	1.32
25	1.095	0.270	13.52	0.44	0.90	1.32
26	1.136	0.276	17.22	-1.01	0.92	1.37
27	0.869	0.288	5.14	0.63	0.75	1.05
28	1.178	0.265	28.29	-0.24	0.96	1.41
29	0.567	0.341	2.46	0.68	0.51	0.71
30	0.747	0.415	3.23	1.25	0.55	1.02
31	0.993	0.421	5.64	1.52	0.72	1.36 LTU
32	0.805	0.374	3.83	-0.33	0.62	1.04
33	0.300	0.365	1.56	1.46	0.34	0.39
34	0.245	0.275	1.48	0.39	0.48	0.30
35	0.743	0.455	3.09	0.69	0.53	1.09
36	0.168	0.369	1.28	-2.22	0.29	0.22
37	-0.458	0.049	2.55	4.29	0.96	-0.51
38	-0.264	0.009	1.71	9.05	1.00	-0.29
39	-0.649	0.131	3.69	6.44	0.87	-0.73 LTU
40	-0.373	0.045	2.11	6.57	0.95	-0.41
41	-0.273	0.080	1.68	7.56	0.86	-0.30 LTU
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-0.637	0.089	3.81	9.59	0.94	-0.71	LTU
-0.442	0.108	2.33	9.12	0.84	-0.50	LTU
-0.454	0.045	2.54	10.20	0.97	-0.50	LTU
-0.656	0.155	3.63	5.39	0.83	-0.75	
-0.705	0.129	4.32	5.53	0.89	-0.80	
-0.462	0.055	2.56	7.47	0.95	-0.51	
-0.615	0.050	3.83	5.54	1.00	-0.68	
-0.231	0.102	1.53	9.18	0.81	-0.26	LTU
-0.476	0.044	2.68	10.66	0.97	-0.53	LTU
-0.169	0.014	1.40	5.00	0.98	-0.19	
0.202	0.020	1.49	6.01	0.97	0.22	OUT
-0.156	0.061	1.35	5.63	0.89	-0.17	
-0.313	0.089	1.81		0.85	-0.35	LTU
-0.305	0.037	1.83	5.30	0.95	-0.34	LTU
-0.392	0.020	2.25		1.00	-0.43	LTU, no w.
-0.595	0.181	3.03	6.56	0.76	-0.69	LTU
-0.721	0.293	3.52	4.99	0.66	-0.88	LTU
0.864	0.109	8.05	-2.08	0.99	0.97	
1.375	0.386	263.62	2.24	1.00	1.80	
1.389	0.406	163.15	2.84	1.00	1.87	
1.381	0.402	129.13	2.87	1.00	1.85	
1.369	0.375	491.64	3.04	1.00	1.77	
1.331	0.336	503.18	1.08	1.00	1.67	Length uncertain; either 30 or 34 mm.
1.385	0.400	190.93	2.96	1.00	1.85	
1.378	0.389	258.81	2.94	1.00	1.81	
1.308	0.310	1438.07	1.93	1.00	1.61	
0.996	0.145	14.35	-6.01	1.00	1.13	

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**Supplementary file 2 of 2 for:-**

"Ventral-aspect radar cross sections and polarization patterns of insects at X band and their relation  
Dataset compiler/contact: V. A. Drake (ORCID 0000-0001-9031-7906, a.drake@adfa.edu.au). Data  
This Excel workbook contains a single sheet that is 'protected' (locked) to safeguard data integrity. L

**Radar Cross Sections of Insects (X band)****Sheet 2:  $\sigma_{xx}$  and  $\sigma_{yy}$ .**

Note 1

Species (Scientific name) (Also sex if available)	Species (Common name)	Order - group within order
	Note 2	Note 3
<i>Nilaparvata lugens</i> M	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> M	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> M	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> M	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> M	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> M	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> F	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> F	Brown planthopper	Hem - delphacid planthopper
<i>Nilaparvata lugens</i> F	Brown planthopper	Hem - delphacid planthopper
(Unidentified aphid)	Aphid	Hem - aphid
(Unidentified aphid)	Aphid	Hem - aphid
(Unidentified aphid)	Aphid	Hem - aphid
(Unidentified aphid)	Aphid	Hem - aphid
(Unidentified aphid)	Aphid	Hem - aphid
(Unidentified aphid)	Aphid	Hem - aphid
(Unidentified aphid)	Aphid	Hem - aphid
<i>Colystigia pectinataria</i> M	Green carpet moth	Lep - geometrid moth
<i>Colystigia pectinataria</i> M	Green carpet moth	Lep - geometrid moth
<i>Colystigia pectinataria</i> F	Green carpet moth	Lep - geometrid moth
<i>Cabera pusaria</i> M	Common white wave moth	Lep - geometrid moth
<i>Cabera pusaria</i> M	Common white wave moth	Lep - geometrid moth
<i>Agonum dorsale</i>	Carabid sp. 1	Col - carabid beetle
<i>Pterostichus cupreus</i>	Carabid sp. 2	Col - carabid beetle
<i>Nebria brevicollis</i>	Carabid sp. 3	Col - carabid beetle
<i>Pterostichus cupreus</i>	Carabid sp. 2	Col - carabid beetle
<i>Chrysoperla carnea</i> s.l.	Green lacewing	Neu - lacewing
<i>Chrysoperla carnea</i> s.l.	Green lacewing	Neu - lacewing
<i>Chrysoperla carnea</i> s.l.	Green lacewing	Neu - lacewing
<i>Chrysoperla carnea</i> s.l.	Green lacewing	Neu - lacewing
<i>Chrysoperla carnea</i> s.l.	Green lacewing	Neu - lacewing
<i>Chrysoperla carnea</i> s.l.	Green lacewing	Neu - lacewing
<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird

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2	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
3	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
4	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
5	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
6	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
7	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
8	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
9	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
10	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
11	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
12	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
13	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
14	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
15	<i>Harmonia axyridis</i>	Harlequin ladybird	Col - ladybird
16	<i>Episyrphus balteatus</i>	Hoverfly sp. 1	Dip - hoverfly
17	<i>Episyrphus balteatus</i>	Hoverfly sp. 1	Dip - hoverfly
18	<i>Episyrphus balteatus</i>	Hoverfly sp. 1	Dip - hoverfly
19	<i>Episyrphus balteatus</i>	Hoverfly sp. 1	Dip - hoverfly
20	<i>Episyrphus balteatus</i>	Hoverfly sp. 1	Dip - hoverfly
21	<i>Episyrphus balteatus</i>	Hoverfly sp. 1	Dip - hoverfly
22	<i>Episyrphus balteatus</i>	Hoverfly sp. 1	Dip - hoverfly
23	<i>Eupeodes luniger</i>	Hoverfly sp. 2	Dip - hoverfly
24	<i>Eupeodes luniger</i>	Hoverfly sp. 2	Dip - hoverfly
25	<i>Dasysyrphus albostrigatus</i>	Hoverfly sp. 3	Dip - hoverfly
26	<i>Coccinella septempunctata</i>	Ladybird - 7-spot	Col - ladybird
27	<i>Coccinella septempunctata</i>	Ladybird - 7-spot	Col - ladybird
28	<i>Coccinella septempunctata</i>	Ladybird - 7-spot	Col - ladybird
29	<i>Coccinella septempunctata</i>	Ladybird - 7-spot	Col - ladybird
30	<i>Coccinella septempunctata</i>	Ladybird - 7-spot	Col - ladybird
31	<i>Adalia bipunctata</i>	Ladybird - 2-spot	Col - ladybird
32	<i>Adalia bipunctata</i>	Ladybird - 2-spot	Col - ladybird
33	<i>Adalia bipunctata</i>	Ladybird - 2-spot	Col - ladybird
34	<i>Adalia bipunctata</i>	Ladybird - 2-spot	Col - ladybird
35	<i>Adalia bipunctata</i>	Ladybird - 2-spot	Col - ladybird
36	<i>Adalia bipunctata</i>	Ladybird - 2-spot	Col - ladybird
37	<i>Notiophilus biguttatus</i>	Carabid sp. 4	Col - carabid beetle
38	<i>Notiophilus biguttatus</i>	Carabid sp. 4	Col - carabid beetle
39	<i>Notiophilus biguttatus</i>	Carabid sp. 4	Col - carabid beetle
40	<i>Notiophilus biguttatus</i>	Carabid sp. 4	Col - carabid beetle
41	<i>Plutella xylostella</i> F	Moth - diamondback moth	Lep - plutellid
42	<i>Plutella xylostella</i> F	Moth - diamondback moth	Lep - plutellid
43	<i>Plutella xylostella</i> F	Moth - diamondback moth	Lep - plutellid
44	<i>Plutella xylostella</i> M	Moth - diamondback moth	Lep - plutellid

Water-filled glass capillary

Cal - W

Formula (Note 8)

#### Notes

- 1 Measured at 9.4 GHz; all with linear | freeze-killed and thawed specimens.
- 2 Not all these species have recognise
- 3 Col - Coleoptera, Dip - Diptera, Hem
- 4 Simple code for use if required in an
- 5 Bc - Beetle (carabid), BI - Beetle (lad
- Ms - Moth (small), Ta - Tiny (aphid),
- 6 R85 - Riley (1985); C&S - J.W. Chap

See Drake et al. (submitted) for further  
7 Weight and dimensions are for water  
8 Formula used to calculate the derivative  
Not available

NA

Count (insects)

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*References*

Drake, V. A., J. W. Chapman, K. S. Lim, D. R. Reynolds, J. R. Riley  
Riley, J. R. 1985. "Radar Cross Section of Insects." *Proceedings of*

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to size and form" (V. A. Drake, J. W. Chapman, K. S Lim, D. R. Reynolds, J. R. Riley, and A. D. Smith.) *Internation*  
 iset released (date, TBA).

Users needing to make modifications can copy the data to another workbook.

Species code	Species index	Group code	Source	Mass (mg)	Wing length (mm)	Body length (mm)	Body width (mm)	$\sigma_{xx}$ (cm <sup>2</sup> )	$\sigma_{yy}$ (cm <sup>2</sup> )	
Note 4		Note 5	Note 6							
BPHm	41	Tp	R85	1.42	NA	NA	NA	9.79E-05	NA	
BPHm	41	Tp	R85	1.16	NA	NA	NA	1.03E-04	NA	
BPHm	41	Tp	R85	1.11	NA	NA	NA	8.03E-05	NA	
BPHm	41	Tp	R85	1.15	NA	NA	NA	6.00E-05	NA	
BPHm	41	Tp	R85	0.95	NA	NA	NA	6.21E-05	NA	
BPHm	41	Tp	R85	0.98	NA	NA	NA	5.39E-05	NA	
BPHf	41	Tp	R85	4.12	NA	NA	NA	1.12E-03	NA	
BPHf	41	Tp	R85	3.84	NA	NA	NA	6.69E-04	NA	
BPHf	41	Tp	R85	2.17	NA	NA	NA	2.77E-04	NA	
Aph	42	Ta	R85	2.18	NA	NA	NA	4.45E-04	NA	
Aph	42	Ta	R85	1.81	NA	NA	NA	2.92E-04	NA	
Aph	42	Ta	R85	1.23	NA	NA	NA	1.61E-04	NA	
Aph	42	Ta	R85	0.47	NA	NA	NA	2.37E-05	NA	
Aph	42	Ta	R85	0.44	NA	NA	NA	2.63E-05	NA	
Aph	42	Ta	R85	0.37	NA	NA	NA	1.79E-05	NA	
Aph	42	Ta	R85	0.18	NA	NA	NA	4.68E-06	NA	
MgGC	43	Mg	C&S	14.3	14.1	10.4	2.5	8.50E-03	2.30E-03	
MgGC	43	Mg	C&S	11.5	12.8	9.8	2.2	2.40E-02	1.90E-03	
MgGC	43	Mg	C&S	22.9	12.9	11.0	2.4	7.80E-02	4.80E-03	
MgCWW	44	Mg	C&S	18.2	16.4	11.7	3.0	2.80E-02	3.60E-03	
MgCWW	44	Mg	C&S	21.4	16.6	NA	2.8	5.20E-02	3.50E-03	
CcAd	46	Bc	C&S	12.4	NA		7	2.5	3.30E-03	2.50E-04
CcPc	47	Bc	C&S	65.3	NA	NA	NA	4.60E-02	9.00E-03	
CcNb	48	Bc	C&S	80.1	NA		12.2	4.7	9.00E-01	1.50E-01
CcPc	47	Bc	C&S	75.4	NA		11.6	4.8	3.70E-01	5.40E-02
NcGL	45	Lc	C&S	12.4	NA		10.5	1.5	2.40E-02	1.10E-03
NcGL	45	Lc	C&S	12.5	NA		10.1	1.4	2.40E-02	1.10E-03
NcGL	45	Lc	C&S	8.5	NA		8.2	1.5	4.20E-03	2.30E-04
NcGL	45	Lc	C&S	13.3	NA		10.1	1.6	2.40E-02	1.50E-03
NcGL	45	Lc	C&S	10.2	NA		10	1.4	1.80E-02	9.50E-04
NcGL	45	Lc	C&S	9	NA		9.1	1.3	1.60E-02	8.00E-04
CoHL	49	Bl	C&S	39	NA	NA	NA	8.50E-02	1.40E-02	
CoHL	49	Bl	C&S	35	NA	NA	NA	8.50E-02	2.50E-02	
CoHL	49	Bl	C&S	32	NA	NA	NA	6.00E-02	2.10E-02	
CoHL	49	Bl	C&S	47	NA	NA	NA	1.70E-01	3.10E-02	
CoHL	49	Bl	C&S	41	NA	NA	NA	1.20E-01	3.80E-02	
CoHL	49	Bl	C&S	44	NA	NA	NA	1.50E-01	4.40E-02	
CoHL	49	Bl	C&S	38	NA	NA	NA	8.50E-02	2.50E-02	

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2	CoHL	49 BI	C&S	40 NA	NA	NA	7.00E-02	1.90E-02	
3	CoHL	49 BI	C&S	42 NA	NA	NA	1.20E-01	3.40E-02	
4	CoHL	49 BI	C&S	37 NA	NA	NA	8.50E-02	2.10E-02	
5	CoHL	49 BI	C&S	28 NA	NA	NA	3.00E-02	1.05E-02	
6	CoHL	49 BI	C&S	36 NA	NA	NA	6.00E-02	2.00E-02	
7	CoHL	49 BI	C&S	35 NA	NA	NA	6.00E-02	2.20E-02	
8	CoHL	49 BI	C&S	38 NA	NA	NA	1.00E-01	3.20E-02	
9	CoHL	49 BI	C&S	35 NA	NA	NA	6.50E-02	2.20E-02	
10	CoHL	49 BI	C&S	40 NA	NA	NA	1.20E-01	4.40E-02	
11	CoHL	49 BI	C&S	30 NA	NA	NA	5.40E-02	1.50E-02	
12	CoHL	49 BI	C&S	37 NA	NA	NA	7.60E-02	1.70E-02	
13	CoHL	49 BI	C&S	31 NA	NA	NA	4.60E-02	1.80E-02	
14	CoHL	49 BI	C&S	40 NA	NA	NA	1.10E-01	3.60E-02	
15	DiHEb	50 Dh	C&S	21.5 NA		10.7	3.6	6.40E-02	6.80E-03
16	DiHEb	50 Dh	C&S	26.1 NA		11.4	3.3	1.10E-01	6.80E-03
17	DiHEb	50 Dh	C&S	18 NA		11.7	3.4	1.20E-01	1.80E-02
18	DiHEb	50 Dh	C&S	24.9 NA		10.7	3.7	6.00E-02	1.20E-02
19	DiHEb	50 Dh	C&S	26.7 NA		12.4	3.8	7.00E-02	1.20E-02
20	DiHEb	50 Dh	C&S	22.5 NA		11.7	3.1	6.00E-02	9.00E-03
21	DiHEb	50 Dh	C&S	14.6 NA		10.8	2.1	3.00E-02	2.50E-03
22	DiHEb	50 Dh	C&S	27.1 NA		11.1	3.1	1.20E-01	1.20E-02
23	DiHEI	51 Dh	C&S	30.5 NA		10.9	3.8	9.50E-02	1.00E-02
24	DiHEI	51 Dh	C&S	28.5 NA		9.7	3.5	8.50E-02	8.00E-03
25	CoL7	53 BI	C&S	29.4 NA		6.4	5	3.40E-02	2.30E-02
26	CoL7	53 BI	C&S	26.6 NA		6.5	5	3.40E-02	1.50E-02
27	CoL7	53 BI	C&S	24 NA		6.1	4.8	4.60E-02	1.80E-02
28	CoL7	53 BI	C&S	26.7 NA		6.7	4.9	4.60E-02	2.50E-02
29	CoL7	53 BI	C&S	32.2 NA		6.8	5	3.40E-02	2.50E-02
30	CoL2	54 BI	C&S	13.8 NA		5.4	4	1.00E-02	6.80E-03
31	CoL2	54 BI	C&S	16.6 NA	NA	NA		1.70E-02	4.00E-03
32	CoL2	54 BI	C&S	11.5 NA	NA	NA		8.50E-03	3.00E-03
33	CoL2	54 BI	C&S	11.5 NA		5	3.5	6.80E-03	2.60E-03
34	CoL2	54 BI	C&S	14.5 NA		5.3	4	1.20E-02	3.50E-03
35	CcNb	55 Bc	C&S	5.1 NA		5.5	2.1	2.00E-03	1.80E-04
36	CcNb	55 Bc	C&S	4.7 NA		4.9	1.8	3.00E-03	1.50E-04
37	CcNb	55 Bc	C&S	4.5 NA		4.9	1.9	2.40E-03	2.60E-04
38	CcNb	55 Bc	C&S	4.7 NA		4.9	1.9	1.90E-03	1.80E-04
39	MoDBM	56 Ms	C&S	5.77 NA		5.9	1.5	4.60E-03	3.40E-04
40	MoDBM	56 Ms	C&S	6.26 NA		6.5	1.5	2.40E-03	1.80E-04
41	MoDBM	56 Ms	C&S	2.29 NA		6	1	5.80E-04	6.00E-05
42	MoDBM	56 Ms	C&S	1.83 NA		5.3	1.1	5.80E-04	2.70E-04
43									
44	Cap	Ca	C&S	3.8		11.5	0.652	1.20E-02	1.80E-04
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polarization in a laboratory rig and with anaesthetized, freshly dead, or

d common names. Names with the form "sp. 1" are local to this dataset.

- Hemiptera, Lep - Lepidoptera, Neu - Neuroptera; Cal - calibration target.

alysis software. Local to this dataset.

ybird), Dh - Dipteran (hoverfly), Lc - Lacewing (Chrysoperla), Mg - Moth (geometrid)

Tp - Tiny (planthopper); Ca - Capillary.

man and A.D. Smith at Rothamsted Research, 2000-2009, mostly unpublished.

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2 er information.

3 only; also 6.87 mg of glass with outside diameter 0.78 mm.

4 d values. Data values are copied from line 26.

5  
6  
7 (including 40 for which dimensions are not available, and for 16 of these  $\sigma_{yy}$  is also not available).

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9  
10  
11 , and A. D. Smith. Submitted. "Ventral-aspect radar cross sections and polarization patterns of insects at X band an  
12 the *IEEE* 73: 228-232. doi:10.1109/PROC.1985.13135  
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4 *International Journal of Remote Sensing* (submitted 30 March 2017).  
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11  $\sigma_{xx}/\sigma_{yy}$  Notes  
12  
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14  
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16

17 NA

18 NA

19 NA

20 NA

21 NA

22 NA

23 NA

24 NA

25 NA

26 NA

27 NA

28 NA

29 NA

30 NA

31 NA

32 NA

33 NA

34 NA

35 NA

36 NA

37 3.70

38 12.63

39 16.25

40 7.78

41 14.86

42 13.20

43 5.11

44 6.00

45 6.85

46 21.82

47 21.82

48 18.26

49 16.00

50 18.95

51 20.00

52 6.07

53 3.40

54 2.86

55 5.48

56 3.16

57 3.41

58 3.40

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2	3.68
3	3.53
4	4.05
5	2.86
6	3.00
7	2.73
8	3.13
9	2.95
10	2.73
11	3.60
12	4.47
13	2.56
14	3.06
15	9.41
16	16.18
17	6.67
18	5.00
19	5.83
20	6.67
21	12.00
22	10.00
23	9.50
24	10.63
25	1.48
26	2.27
27	2.56
28	1.84
29	1.36
30	1.47
31	4.25
32	2.83
33	2.62
34	3.43
35	11.11
36	20.00
37	9.23
38	10.56
39	13.53 Gravid
40	13.33 Gravid
41	9.67
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For Peer Review Only

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id their relation to size and form." *International Journal of Remote Sensing*. doi:10.1080/01431161.201x.xx

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