THE FEASIBILITY OF USING VERTICAL-LOOKING RADAR TO MONITOR THE MIGRATION OF BROWN PLANTHOPPER AND OTHER INSECT PESTS OF RICE IN CHINA

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Abstract The recent development of automatically operating, inexpensive vertical-looking radar (VLR) for entomological purposes has made it practical to carry out routine, automated monitoring of insect aerial migration throughout the year. In this paper we investigate whether such radars might have a role in monitoring and forecasting schemes designed to improve the management of the Brown Planthopper (BPH), *Nilaparvata lugens*, and of associated rice pest species in China. A survey of the literature revealed that these insects typically migrate at altitudes between 300 to 2 000 m above ground level, but calculations based on BPH radar scattering cross-sections indicated that the maximum altitude at which they individually produce signals analysable by current VLRs is only ~ 240 m. We also show that coverage over most of the flight altitudes of BPH could be achieved by building a VLR using a wavelength of 8.8 mm instead of the 3.2 cm of existing VLR, but that such a radar would be expensive to build and to operate. We suggest that a more practical solution would be to use a 3.2 cm VLR as a monitor of the aerial movement of the larger species, from which the migration of rice pests in general might be inferred.

Key words Radar, migration, flight, brown planthopper, rice pests.

1 INTRODUCTION

Almost all of our current knowledge about insect flight behaviour at high altitude has been acquired since 1968 when radar was first introduced to entomological research. (Schaefer, 1969, 1976; Drake 1982, Reynolds 1988, Riley 1989, Reynolds and Riley 1997). More recently, the development of automatically operating, vertical-looking radar (VLR) specifically for entomological purposes (Drake, 1993, Riley *et al*. 1993, Smith *et al*. 1993) has made it practical to carry out routine, automatic monitoring of insect aerial migration throughout the year (Smith *et al*. 2000, Chapman *et al*. 2002 a and b Chapman *et al*. in press). This in turn has raised the possibility that such radars might have a valuable role in schemes designed to improve the management of migrant insect pests of agriculture (Drake *et al*. 2002 a and b). One such migratory pest of great economic importance in China and elsewhere, is the brown planthopper (BPH), *Nilaparvata lugens*, and in this paper we investigate the feasibility of using VLR to monitor migration by BPH and associated rice pest species. Factors of key importance in the investigation are the altitudes at which these small insects normally migrate, and the degree to which they reflect radar signals (their 'radar scattering cross-section') because this quantity determines the maximum altitude at which they can be detected.

2 MATERIALS AND METHODS

2.1 Principles of operation of VLR

The principle of operation of rotating polarisa-

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tion, nutating beam vertical-looking radar is discussed elsewhere (Riley *et al*. 1992). Our description here is consequently limited to an outline of the essentials.

The radar projects a narrow, vertically pointing and circular beam of linearly polarized radar pulses, whose plane of polarisation is rotated continuously. The beam also nutates (wobbles) about a vertical axis (Fig. 1), and the rotation and nutation together generate a low frequency amplitude modulation of the radar echoes returned from any target flying through the beam. This modulation (Fig. 2) contains information about the target's speed and direction of movement, its azimuthal orientation, and three parameters related to its mass and shape. Extraction of this information is achieved with a unique algorithm specially developed by for the purpose (Smith *et al*. 1993). Estimated mass can be a very important clue to target identity, and its availability from VLR data is one of the major advantages of the technique. Technical details of the radars we have been using for the last four years at Rothamsted and Malvern in the UK, are given in Appendix I. Each radar is controlled and monitored by a desk-top computer, which also analyses the signal modulation, and stores the parameters extracted from each target.

2.2 Signal capture and analysis

The information encoded in the signal modulation is extracted as follows. Any returned pulses (echoes) are amplified by the radar receiver, and some of these are then collected by a series of 15 peak sample-and-hold circuits. These circuits or *range gates* capture and retain the maximum amplitude of any pulses returned within pre-selected intervals after each radar transmission, *i.e.* echoes from targets within 15 pre-selected range intervals. The gates take a sample each time the radar transmits, and the output from each gate is low-pass filtered, before being re-sampled by an analogue-to-digital converter, and stored in the computer (Smith and Riley 1996). The low-pass filter cut-off (100 Hz) and re-sample (300 Hz) frequencies are chosen to capture the highest frequency likely to be

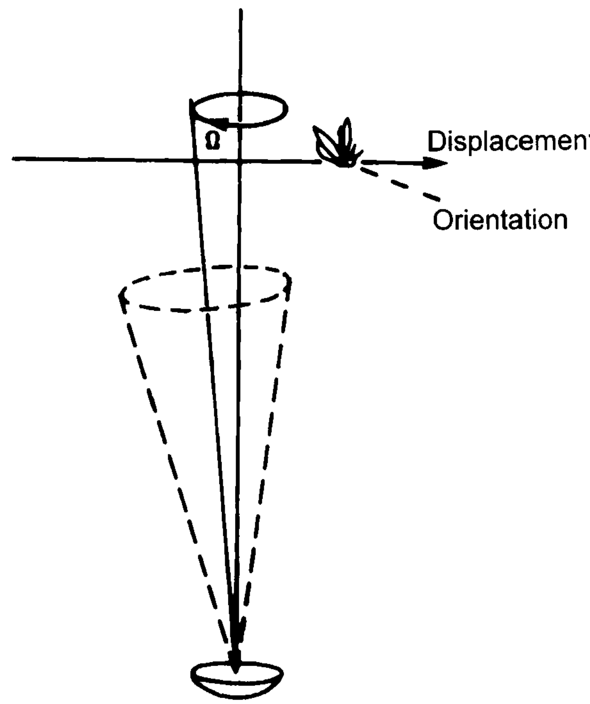

Fig. 1 Geometry of the VLR configuration. The beam (illustrated as the dotted cone) nutates around the vertical axis at Ω revolutions per second, the same frequency at which the polarisation rotates. The diagram illustrates the case of an insect flying in a crosswind, where its direction of *displacement* is not the same time as its heading or *orientation*.

of interest in the signal modulation (100 Hz), but at the same time to allow as much integration of signal power as is possible (Chapman *et al*. 2002a). With a transmitter pulse repetition frequency of 1.5 kHz the filter and re-sample regime achieves an integration of 5 pulses, giving an improvement in signal-to-noise of ~ 6dB (Skolnik 1970). A recent modification of the VLR observational procedure is to periodically stop beam rotation and nutation, and simply record the signals generated as insects fly through the stationary beam (Drake *et al*. 2002b). This procedure preserves any signal modulation produced by wing-beating action, and hence provides a

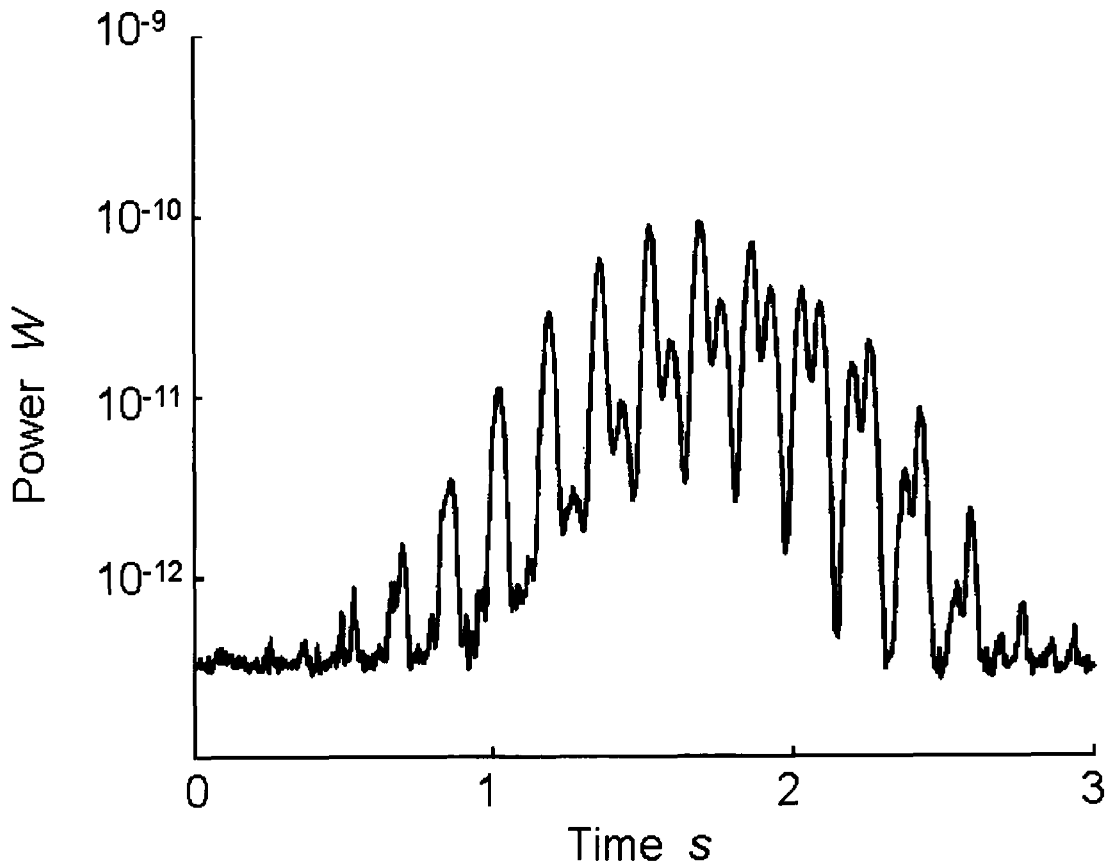

Fig.2 A typical VLR signal returned by an insect flying through a range gate. The overall envelope approximately 2.5 seconds wide is produced by the insect's transect through the Gaussian radar beam, and the regular modulation results from beam nutation combined with the interaction of polarisation rotation with the insect scattering cross-section terms.

measure of wing-beat frequency which can be a clue to target identity (Riley 1974, Schaefer 1976).

The computer is usually set to turn the radar on for five minutes once every 15 minutes, *i.e.* four times an hour. During the 'on' period the outputs from the range gates are digitized and stored, and then in the remaining 10 minutes of the cycle, they are analysed, the extracted target parameters are logged, and the original signals deleted.

2.3 The operational altitude range

The *minimum* altitude at which measurements can be made is determined primarily by the time taken for the radar magnetron, duplexer and receiver to reach a quiescent state after each 25 kW outgoing pulse from the transmitter. In the case of our VLR, this 'recovery' time is ~ 1 μs which corresponds to a minimum altitude of 150 m. The *maximum* altitude for measurements depends on how strongly the insect of interest reflects radar signals; larger insects generally have larger *radar backscattering cross-sections* (Skolnik 1970) and so can be detected up to higher altitudes. VLR has been primarily used to monitor species with masses above a few tens of mg, and for these insects the maximum extends beyond 1 km (Chapman *et al.* 2002a). Unfortunately, for smaller insects, radar cross-section decreases very rapidly with mass (Riley 1985), and the principal objective of this study is to investigate whether this effect allows the use of conventional VLR as a means of monitoring the migration of insects as small as BPH.

3 RESULTS

3.1 The altitudinal distribution of airborne rice pests and other insects in China

If VLR is to be used to monitor the movement of insect pests of rice, it should be able to detect them up to at least the altitudes at which they normally migrate. This section describes the results of our investigation into what is known about the altitudinal distribution of migratory BPH and other pest species in China.

3.1.1 ***Nilaparvata lugens* and *Sogatella furcifera*** There have never been any long-term measurements of the high altitude flight of rice pests in China or elsewhere, so it is impossible to give a comprehensive description of their altitudinal distribution during migration. However, some useful information on the flight height of *N. lugens* and the white back planthopper, *Sogatella furcifera*, has been obtained by trapping insects in nets attached to aircraft (Dung 1981, Zhu *et al*. 1982). Planthoppers were caught at altitudes as high as 2500 m above ground in east central China in summer (July), although only at a low average density (0.25 per 10^4 m^3 for *N. lugens* and 5.5 per 10^4 m^3 for *S. furcifera*). Lower down, these species were much more numerous, most being caught between 1500 and 2000 m in July, but between 500 and 1000 m in autumn (September-October). Zhu *et al*. (1982), sampling in Guangdong Province in southern China, caught *N. lugens* and *S. furcifera* up to a height of 2000 m early in the year (April-May), so it is clear that there is seasonal variation in the species' altitudinal distribution (see aerial densities in Table 1). Dung also found that *S. furcifera* tended to be more common than *N. lugens* in the summer catches, but in the autumn catches this tendency was reversed. Together, the two species formed a substantial percentage (20%—80%) of the total catch of insects.

Our only detailed knowledge of the vertical distribution of the autumn migrations of *N. lugens*, and of its diurnal variation with time and temperature, has been derived from studies using azimuthally-scanning entomological radars (with wavelengths of 8.8 mm and 3.2 cm), supplemented by kytoon-borne aerial nets. These studies were carried out at Jiangpu, southern Jiangsu Province, in 1988 (Riley *et al*. 1990, 1991) and 1990 (Riley et al. 1994; Cheng *et al*. 1994), and at Dongxiang, northern Jiangxi Province, in 1991 (Riley *et al*. 1995). The observations lasted only a few weeks and were undertaken in only two locations, but although the information is certainly not comprehensive, it does at least provide a good description of height /density profiles which *can* occur in the autumn. We found that after mass take-off in the late afternoon or dusk, *N. lugens* climbed at an average rate of ~ 0.2 m/s for between 30 and 60 minutes, and then embarked on level flight, often forming dense layers between about 400—1000 m above ground level. These layers frequently persisted for several hours, with aerial densities tending to increase up to a sharply-defined ceiling where the air temperature had fallen to about 16℃. If surface temperatures were high enough, there was a second period of mass emigration at dawn which sometimes also produced layers, but these were generally less intense and less persistent than those following the late afternoon /dusk emigration.

During the intense nocturnal migrations resulting from serious *N. lugens* outbreaks in Jiangsu Province in September 1988, the average density derived from kytoon netting was 28 *N. lugens* per 10^4 m^3 and the maximum 274 per 10^4 m^3. Radar estimates of aerial density in the overflying layers above the altitude accessible to our kytoon-supported net were as high as 500 per 10^4 m^3 (Riley *et al*. 1991). In the perhaps more typical autumns of 1990 and 1991, when the radar was not overflown by *N. lugens* from outbreaks, average densities measured by aerial netting were ~ 2 per 10^4 m^3, which are not dissimilar to the averages of 4 – 5 per 10^4 m^3 found by Dung (Table 1). Mean aerial densities for *S. furcifera* in autumn, from both Dung's (1981) and our results, were in the range 0.4—1.6 per 10^4 m^3. Not surprisingly, his July values were much higher (8.7 per 10^4 m^3).

Table 1 Comparison of aerial density (numbers per 10^4 m^3) and flux values* (numbers per m^2 per hour) for *Nilaparvata lugens*, *Sogatella furcifera*, *Recilia dorsalis* and *Cyrtorhinus lividipennis* derived from aerial samples taken at sites in China.

Location	Month	Year	Height above Surface (m)	*Nilaparvata lugens*			*Sogatella furcifera*			*Recilia dorsalis*			*Cyrtorhimus lividipennis*		
				Mean Density	Max. Density	Mean Flux	Mean Density	Max. Density	Mean Flux	Mean Density	Max. Density	Mean Flux	Mean Density	Max. Density	Mean Flux
Jiangpu, near Nanjing, Jiangsu Province	Sept.	1988	140 – 450	28.0	274.0 500.0 §	72.0	0.56	3.9	1.4	0.30	3.3	0.71	0.41	3.1	1.00
Jiangpu, near Nanjing, Jiangsu Province	Aug.-Sept.	1990	140 – 250	2.1	13.0	4.6	0.43	2.6	0.96	0.54	12.0	1.30	0.25	1.5	0.56
Dongxian, Jiangxi Province	Sept.-Oct.	1991	80 – 380	1.9	7.6	2.9	1.60	6.7	3.00	0	0	0	4.60	17.0	11.00
Hubei, Hunan, Jiangxi &Anhui Provinces†	July	1977 – 79	1500 – 2000	4.8	48.0		8.70	42.7							
Hubei, Hunan, Jiangxi &Anhui Provinces†	Sept.-Oct.	1978 – 79	500 – 1000	4.6	39.0		1.00	14.0							
Hubei, Hunan, Jiangxi &Anhui Provinces†	Sept.-Oct.	1978 – 79	100	4.4			1.20								
East China Sea *ca*. 126°E, 31°N‡		1977 – 80	18		29.4			42.2							

* The migration *flux* is the rate at which insects pass through a hypothetical 'window' of 1 m^2 orientated at right angles to the general direction of movement, and was calculated by multiplying the number of insects per m^3 by the wind speed in m/s,

§ Density calculated from radar data.

† Data from Dung, 1981.

‡ Data from Kisimoto, 1991.

Table 2 Comparison of aerial density (numbers per 10^4 m^3) for aphids, minute insects, *Cnaphalocrocis medinalis* and Noctuid moths derived from aerial netting samples taken at sites in China.

Location	Month	Year	Height above Surface (m)	Aphids			Minute Insects			*Cnaphalocrocis medinalis*			Noctuid moths		
				Mean Density	Max. Density	Mean Flux	Mean Density	Max. Density	Mean Flux	Mean Density	Max. Density	Mean Flux	Mean Density	Max. Density	Mean Flux
Jiangpu, near Nanjing, Jiangsu Province	Sept.	1988	140 – 450	0.78	5.4	2.0	13	68	29	0.07	0.52	0.13	0.02	0.35	0.04
Jiangpu, near Nanjing, Jiangsu Province	Aug.-Sept.	1990	140 – 250	2.40	11.0	4.6	24	80	51	0.09	1.50	0.27	0.04	0.34	0.10
Dongxiang, Jiangxi Province	Sept.-Oct.	1991	80 – 380	6.80	34.0	11.0	15	43	32	0.26	2.70 7.0 §	0.73	0.05	0.35	0.14

Generally, all sample periods were taken into account when calculating these densities, irrespective of whether the species concerned was caught in a particular sample. *C. medinalis* and the Noctuid moths were not caught at altitude during the day, so the aerial densities of these taxa were calculated from the dusk ot dawn samples only.

§ Density calculated from radar data

3.1.2 Other small insects Some of the species commonly caught in our netting samples (namely, the leafhopper *Recilia dorsalis*, the Heteropteran bug *Cyrtorhinus lividipennis*, and aphids) are given in Tables 1 & 2. Their aerial densities were occasionally high (*e.g.* a maximum of 34 per 10^4 m^3 for aphids and 17 per 10^4 m^3 for *C. lividipennis*, both at Dongxiang), but they did not approach those found during the intense overflights of *N. lugens* observed in September 1988. Very minute insects (~ 0.05 mg), such Cecidomyid Diptera, were often present at even higher densities (Table 2).

3.1.3 Larger insects: *Cnaphalocrocis medinalis* and other moths Very few insects with a body-size larger than *N. lugens*, were caught in our netting studies at Jiangpu and Dongxiang, but amongst them was the rice leaf roller moth, *Cnaphalocrocis medinalis*, (8—9 mg) which is an important pest species. Almost all current knowledge on the altitudinal distribution of migrating *C. medinalis* in China comes from these studies, and from observations made by an 8-mm wavelength radar in 1991 at Dongxiang (Riley *et al*. 1995). The data were acquired in the autumn, during north-to-south migrations; altitudinal distributions may well be different during the spring and summer movements.

Cnaphalocrocis medinalis moths were caught in the aerial net only during the period from dusk up until midnight. This agreed well with the radar observation that targets in the 8 – 9mg size range were most numerous at about 18.30—19.00 hours. Maximum density typically occurred between 250 and 550 m above ground, and a well-defined layer containing many *C. medinalis* formed on some nights, particularly on those with strong northerly or northeasterly winds at flight altitude. Besides this dense layer, weaker and less well-defined layers were sometimes detected up to ca. 800 m or more, but these appeared to be composed mainly of larger moths and tended to decline through the evening. The radar showed that aerial densities were usually low after midnight and mainly comprised of larger insects at densities too low to be detected by our aerial netting regime, but it is quite likely that some *C. medinalis* were amongst them. In contrast to our findings for *N. lugens*, there was no evidence that the upper boundary of the *C. medinalis* layers corresponded to the species' low temperature threshold for sustained flight. The majority of migrants flew at an altitude where the wind speed was highest, and this sometimes corresponded to the height of a pronounced low-level wind jet. The cues used by the migrants to select and to maintain at their flight altitudes are not known.

The mean densities of *C. medinalis* estimated from aerial netting data at Jiangpu (Table 2) were rather low (< 0.1 per 10^4 m^3). At Dongxiang they were higher (0.3 per 10^4 m^3); the highest value (2.7 per 10^4 m^3) occurred during an overflight of 17 October when *C. medinalis* accounted for 23 of the 26 moths caught. On the same occasion, radar observations at higher altitude indicated that *C. medinalis*-like targets were present at densities of ~ 7 per 10^4 m^3 (Riley *et al*. 1995).

Other smallish moths were occasionally common at altitude, for example, the radar recorded very high densities of emigrating *Omiodes indicata* at Jiangpu in 1990 (Riley et al. 1995, Reynolds and Riley 1997). These density values were admittedly near to infested soya bean fields which were the main source of the moths, but aerial sampling later in the night still produced a maximum density of 0.8 per $10^4 m^3$ for this species.

Larger Lepidoptera were, not surprisingly, much less common, and only occasional specimens were taken in aerial nets (Riley *et al*. 1995). It is nevertheless relevant to note that on occasions when the aerial densities of small insects are high enough to produce continuous radar echo and their densities are assessed by volume reflectivity methods (Drake 1981), the presence of even small numbers of Noctuids such as *Mythimna separata* and *Agrotis ipsilon* may introduce significant errors. This is because their relatively large size (~ 80 – 100 mg) means that their radar cross-sections are ~ 10^3 times greater than those of planthoppers, (see below) so a single noctuid would contribute as much radar reflectivity as a thousand planthoppers. The mean density of Noctuid moths estimated from our netting samples was 0.02 – 0.05 per 10^4 m^3, with maximum densities of about 0.3 per 10^4 m^3 (Table 2). Similarly, Drake and Farrow (1985) in inland Australia, found aerial densities of large moths to be typically in the range 0.01 – 0.1 per 10^4 m^3.

3.1.4 The range of detection required The most important fact to emerge from the above survey of altitudinal distributions is that long distance BPH migration occurs predominantly in the altitude range from 300 to 2000 m above ground level. Thus if VLR is to be used as a migration monitor in the 'single target mode' (where quantitative data on insect mass and shape is available as an aid to identification), the radar must be able to make measurements on individual targets of mass equal to and larger than BPH over this altitude range. To calculate the maximum altitude at which current VLR could detect individual BPH and similar sized rice pests, we first need to know (or be able to estimate) their scattering cross-sections. In the following section we have therefore compiled all the information available on the radar cross-sections of BPH, and of other migratory pests of rice.

3.2 Radar cross-sections of BPH, and of other insects associated with rice

3.2.1 BPH The only published data on BPH radar cross-sections are those of Riley (1985), which were obtained from live BPH, in a parallel-plate transmission line. The measurement wavelength was 3.2 cm (a frequency of 9.4 GHz), the same as that used in current VLR, and both the E-vector and insect principal body axis were horizontal. Cross-sections were obtained for broadside (σ_s) and end-on aspects (σ_e), and this data was later combined with data on other larger and smaller insects, to produce an empirical expression relating cross-section to mass (Riley 1992):

$$\sigma_s \approx m^2 \times 6.4 \times 10^{-5}\ \text{cm}^2,$$
$$\sigma_e \approx m^2 \times 5.0 \times 10^{-6}\ \text{cm}^2,$$

where m is the body mass in milligrams. It was found from BPH collected in the field that their mass distribution was approximately normal, with $m = 2.24 \pm 0.24$ mg for females, and $m = 1.46 \pm 0.25$ mg for males. Thus typically for females: $\sigma_s \approx 3.2 \times 10^{-4}$ cm^2 and $\sigma_e \approx 2.5 \times 10^{-5}$ cm^2; and for males: $\sigma_s \approx 1.4 \times 10^{-4}$ cm^2 and $\sigma_e \approx 1.1 \times 10^{-5}$ cm^2.

However, because a VLR views overflying targets from directly underneath, the radar cross sections needed here are those which correspond to *underside aspect*, with the E-vector parallel to, and perpendicular to, the insect's principle body axis (Smith *et al*. 1993). BPH bodies are approximately cylindrically symmetric, so provided that the insects fly with their principle body axis near to the horizontal, we can reasonably assume that the required 'parallel' cross section σ_{xx}, will be equal to the broadside cross section, σ_s described above. There remains the problem of estimating a value for σ_{yy}, the cross section for underside aspect, but with the E-vector *perpendicular* to the body axis. We note from Fig. 2 of Riley (1985), that for *Spodoptera littoralis* with a body mass of 95 mg, the ratio of σ_{xx}/σ_{yy} is 5, and from Fig. 4 of (Riley, 1985), that for aphids of mass ~ 0.4 mg, this ratio is between 5 and 7. The mass of BPH lies between these two, so it seems safe to conclude that similar ratios will hold for this species, and therefor that σ_{xx} will be greater than σ_{yy}. Thus σ_{xx} is the cross-section term that will determine the maximum altitude for detection for BPH.

More generally, when the E-vector is at some intermediate angle (ϕ) to the body axis at which σ is a maximum (for small insects this axis is the longitudinal body axis (Riley 1985)), the radar cross section may be described by the expression (Aldous 1989, Smith *et al*. 1993):

$$\sigma(\phi) = a_0 + a_2 \cos 2\phi + a_4 \cos 4\phi \quad (1)$$

where:

$$a_0 = 3/8(\sigma_{xx} + \sigma_{yy}) + 1/4\ (\sigma_{xx}\sigma_{yy})^{1/2} \cos \mu, \quad (2)$$
$$a_2 = 1/2(\sigma_{xx} - \sigma_{yy})$$
$$a_4 = 1/8(\sigma_{xx} - \sigma_{yy}) - 1/4(\sigma_{xx}\sigma_{yy})^{1/2} \cos \mu.$$

The terms a_0, a_2 and a_4 are those delivered by our VLR analysis procedure (Smith *et al*. 1993) and μ is a phase angle, which→0 for small targets which lie in the Rayleigh scattering region.

It can be seen that $\sigma(\phi)$ averaged over the range $\phi = 0$ to 180° is equal to a_0.

Conversely:

$$\sigma_{xx} = a_0 + a_2 + a_4$$

$$\sigma_{yy} = a_0 - a_2 + a_4$$

$$\cos\mu = (a_0 - 3a_4)/(a_0^2 - a_2^2 + a_4^2 + 2a_0a_4)^{1/2}.$$

3.2.2 Estimation of radar cross-sections of other insects associated with rice We have selected for examination those insect pests of rice believed to be high altitude migrants, and which we have encountered in our radar studies of planthopper and leafhopper migration in China (Riley *et al*. 1990, 1991, 1994, 1995). The cross-section data in Table 3 were estimated using the procedure described above, with σ_{xx} derived from insect mass using empirical formulae derived from laboratory measurements (Aldous 1989, Chapman *et al*. 2002a). Thus:

For

$$\sigma_{xx} \leqslant 0.0032\ cm^2,$$

$$m = (\sigma_{xx} \times 10^5/6.4)^{0.5}\ \text{mg}.$$

For

$$\sigma_{xx} > 0.0032\ \text{cm}^2 \text{ and } a_0 < 0.25\ \text{cm}^2,$$

$$m = (a_0 \times 10^5/6.4)^{0.5}\ \text{mg}.$$

And for

$$a_0 \geqslant 0.25\ \text{cm}^2,$$

$$\log_{10}(m) = 2.205 + 0.8729 \times \log_{10}(a_0) + 0.3323 \times \{\log_{10}(a_0)\}^2 (\text{m in mg}).$$

The table does not include all economically important migrants, but approximate estimates of cross-section data for other insect species of interest can be readily derived using this procedure, if the insects' masses are known.

Table 3 Cross-section data estimated from mass, for a wavelength of 3.2 cm, for some insects associated with rice, and other migrants known to fly over east-central China.

Scientific name	Common name	Sex	Mass mg	σ_{xx} cm^2
Toya propingua	planthopper	M	0.45	1.30×10^{-5}
Toya propingua	planthopper	F	0.87	4.84×10^{-5}
Sogatella furcifera	White Back Planthopper	M	0.68	2.96×10^{-5}
Sogatella furcifera	White Back Planthopper	F	1.19	9.06×10^{-5}
Cyrtorhinus lividipennis	mirid bug	F	0.87	4.84×10^{-5}
Recilia dorsalis	Zig-Zag Leafhopper	M	0.88	4.96×10^{-5}
Recilia dorsalis	Zig-Zag Leafhopper	F	1.39	1.24×10^{-4}
Nilaparvata lugens	Brown Planthopper	M	1.46	1.36×10^{-4}
Nilaparvata lugens	Brown Planthopper	F	2.24	3.21×10^{-4}
Nysius ericae	lygaeid bug	F	2.50	4.00×10^{-4}
Nephotettix cinciticeps	green leafhopper	F	3.30	6.97×10^{-3}
Cnaphalocrocis medinalis	Rice Leaf Roller Moth	M	8.43	8.09×10^{-3}
Cnaphalocrocis medinalis	Rice Leaf Roller Moth	F	8.95	9.12×10^{-3}
Hymenia perspectalis	pyralid moth	F	14.10	2.26×10^{-2}
Omiodes indicata	pyralid moth	M	12.20	1.69×10^{-2}
Omiodes indicata	pyralid moth	F	15.90	2.88×10^{-2}
Spodoptera litura	noctuid moth	M	86.00	5.00×10^{-1}
Agrotis ipsilon	noctuid moth	F	100.00	6.00×10^{-1}

3.3 The maximum working altitude of current vertical looking radars

Current VLRs, designed for general entomological use, are able to monitor medium-sized to large insects at altitudes of up to two kilometers (Smith *et al*. 2000). Their maximum working altitude for smaller insects like BPH will be much less than this, and in this section we use the information on their radar cross-sections, compiled above, to calculate what this maximum altitude will be.

The signal power S received by a radar from a target on the beam axis, at range r is

$$S = \frac{P_t \lambda^2 G_0^2 \sigma}{4^3 \pi^3 r^4 \times 2G_L} \text{ W (Skolnik, 1970)},$$

but

$$G_0^2 = \frac{\pi^4 D^4 \rho^2}{\lambda^4},$$

so

$$S = \frac{P_t \pi D^4 \rho^2 \sigma}{4^3 r^4 \times 2G_L \lambda^2} \text{ W}, \quad (3)$$

where P_t = transmitter power (W),

λ = radar wavelength (m),

D = antenna diameter (m),

ρ = antenna efficiency,

G_L = waveguide, duplexer, rotation joint, and radome one-way losses,

σ = target radar cross-section (m^2).

Rearranging equation (3) and putting $S = S_{min}$, gives the maximum range at which the target can be detected, r_0.

$$r_0 = \left(\frac{P_t \pi D^4 \rho^2 \sigma}{4^3 \times 2G_L \lambda^2 S_{min}} \right)^{0.25} \text{ m}, \quad (4)$$

where S_{min} is the minimum signal power required by the radar receiver in order to register a target.

Now

$$S_{min} = kT \frac{B}{0.76} \times 10^{\frac{(N_f + V_f - I_n)}{10}} \text{ W}, \quad (5)$$

where $k = 1.38 \times 10^{-23}$ $WHz^{-1}K^{-1}$ (Boltzmann's constant),

T = 273 K,

B = receiver bandwidth, Hz,

N_f = receiver noise figure, dB,

I_n = integration improvement factor, dB,

V_f = visibility factor, dB.

The terms P_t λ, D, ρ, G_L, B, N_f, and I_n are known from the radar specification, but to complete the calculation for r_0, we need to assign a value to V_f, the factor that specifies the signal-to-noise ratio required for a given probability of target detection. It depends on the target fluctuation characteristics, and how long the signal is available, but in the case of the VLR *detection* threshold we arbitrarily specify a 90% detection probability and 10^{-3} false alarm rate, and this requires a signal-to-noise ratio of approximately 11dB (Fig. 2.7, Skolnik 1970).

For VLR signal analysis, however, we require more than just target detection: the returned signal must remain above the detection threshold throughout a beam nutation cycle if our analysis algorithm is to work satisfactorily. A rough estimate of this value can be obtained by noting that the minimum signal in a polarisation cycle is determined by σ_{yy}. For a typical insect target, σ_{yy} is ≈ 6 times (7.8 dB) smaller than σ_{xx}, so the pre-integration visibility factor required for signal analysis capability would be 11 + 7.8 ~ 19 dB. Taking into account the integration improvement of 6 dB achieved by our sampling routine, this indicates that the post-integration signal-to-noise ratio required when an insect target is presenting its maximum cross-section (σ_{xx}) is (19 − 6) = 12 dB. An alternative empirical estimate, derived from analyses of simulated signals to which different levels of artificial noise had been added, indicated that a slightly lower post-integration signal-to-noise (~10 dB) was needed for satisfactory extraction of target parameters (Smith *et al*. 1993), perhaps because cycle-length integration procedures in the analysis itself achieved a further degree of noise suppression. We have therefor used 17dB for V_f and 6dB for I_n in our estimates of maximum range for analysis.

Substituting V_f, I_n and the radar parameters listed Appendix I into equations (4), and (5) gives the expression for maximum range for analysis:

$$R_0 = 2226 \times (\sigma_{xx})^{0.25} \text{ m}, \quad (6)$$

where here σ_x is expressed in cm^2.

To find the maximum altitude at which observations of BPH migration could be made by a 3.2 cm wavelength VLR of the specification above, we substitute the average value of σ_{xx} for males (the smaller of the two sexes) in equation (iv). This value (1.4×10^{-4} cm^2) predicts that satisfactory measurements can be expected up to an altitude of only 242 m.

3.3.1 Calculation of the volume sensed in each

range gate interval The effectiveness of VLR as a migration monitor depends on the volume of air that the radar samples, and in this section we describe a method of calculating the volume sampled within in a selected range interval. The calculation takes into account the fact that radar signals become weaker for targets that are further away from the radar beam axis, and further away in range. For a radar with a circular beam, this effect is described by the equation:

$$S = S_0\left(\frac{r_0}{r}\right)^4 \exp\left[-8\ln2\left(\frac{\theta}{\theta_{3dB}}\right)^2\right] \text{ W},$$

where S is the signal received from a target of known cross-section at range r and at angle θ from the beam axis. S_0 is the signal strength that would be returned by the target when on axis at some specified range r_0, and θ_{3dB} is the angle between the half-power points in the radar beam (Skolnik 1970).

We can define an iso-echoic contour, $r = f(\theta)$, from which this target will return signals of strength S_0, by putting $S = S_0$ in this equation, and re-arranging it to give:

$$r = r_0\exp\left[-2\ln2\left(\frac{\theta}{\theta_{3dB}}\right)^2\right] \text{ m}.$$

Such a contour is plotted in Fig. 3 which illustrates how the volume of revolution of the contour defines the volume within which the selected target will produce signals $> S_0$. If r_0 is the maximum range at which the target can be detected, then the volume sensed by the radar for targets of this size, lying between ranges r_2 and r_1, is that bounded by the contour and by the sections of the spherical surfaces of radii r_2 and r_1. We have shown elsewhere (Chapman *et al*. 2002a) that if $r_0 > r_2$, this volume, V_s is:

$$V_s = \frac{\pi\theta_{3dB}^2}{18\ln2}\left\{r_0^3\left[\exp\left(-3\ln\frac{r_0}{r_2}\right) - \exp\left(-3\ln\frac{r_0}{r_1}\right)\right] + 3\left[r_2^3\ln\frac{r_0}{r_2} - r_1^3\ln\frac{r_0}{r_1}\right]\right\}\text{m}^3. \quad (7)$$

If $r_2 \geqslant r_0$:

$$V_s = \frac{\pi\theta_{3dB}^2}{18\ln2}\left\{r_0^3\left[1 - \exp\left(-3\ln\frac{r_0}{r_1}\right)\right] - 3r_1^3\ln\frac{r_0}{r_1}\right\}\text{ m}^3.$$

Of course, if $r_1 \geqslant r_0$, $V_s = 0$.

For example, to calculate the volume sensed for BPH within a range gate of our VLR radar, we note that for this species $r_0 = 242$ m for analysable signals. We then select a gate position within this range, say, 190—235 m, and substitute these values for r_1, r_2 and r_0 in equation (7), together with the θ_{3dB} for our radar (2.53×10^{-2} radians (1.45°)), to obtain a sensed volume of 368 m^3.

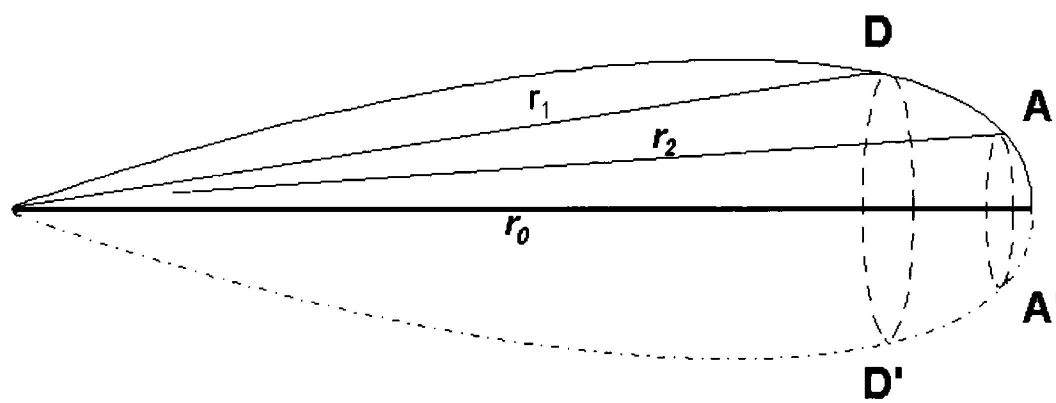

Fig.3 An illustration of the volume enclosed by an iso-echoic contour of a circular, Gaussian beam. The figure also shows the volume, **D A A' D**, which would be sensed by a range gate opening at r_1 and closing at r_2. The beam width has been exaggerated by a factor of 10 to make the geometry clear.

3.4 Calculation of aerial density

A quantity of primary biological interest is the aerial density of an airborne population. In this section we describe how estimates of this quantity may be made from VLR data. Thus, once a target has been detected in a particular gate, the volume sensed V_s, by the gate for that target can be calculated by substituting the target's σ_{xx} in equation (6) to obtain a value for r_0, and then using equation (7) to find V_s. The aerial density of the target is then estimated by working out the proportion of the observational period that the target actually occupied V_s. For example, if V_s were occupied all of the time, the aerial density for this target would be $\geqslant 1/(1 \times V_s)$ m^{-3}. 1/10th occupancy would indicate a density of $1/(10 \times V_s)$, 1/40th would indicate $1/(40 \times V_s)$, and so on.

One convenient way to find the proportion of time that V_s is occupied, is to first convert the target's distance of closest approach from half-power beamwidths (P), to metres (P_m) at the height of the centre of the gate. Thus:

$$P_m = \{(r_1 + r_2)/2\} \times \sin(\theta_{3dB} \times P) \text{ m},$$

P_m is then used to estimate the horizontal length (l) of the target flight path within the sensed volume:

$$l = 2 \times (a_m^2 - P_m^2)_{0.5} \quad \text{m},$$

where a_m is the mean radius of the sensed volume. For $r_0 > r_2$

$$a_m = \{V_s/(r_2 - r_1)\pi\}^{0.5},$$

but if $r_1 < r_0 < r_2$

$$a_m \approx (r_1 \times \sin\theta)/2,$$

where $\theta = \theta_{3dB} \times [\{\log_e(r_0/r_2)\}/(2 \times \log_e 2)]^{0.5}$.

Then the time, t, that the target takes to travel this distance is:

$$t = l/v \quad \text{s},$$

where v is the displacement speed of the target (ms^{-1}), as determined by the analysis procedure. Finally, the aerial density of the target, D, is given by:

$$D = (1/V_s) \times t/T \times 10^7 \text{ insects per } 10^7 \text{ m}^3,$$

where T is the duration of the sample period (usually 300 s). The mean aerial density of targets within a selected size range is simply the sum of the individual aerial densities of all the targets within this range. If data from several sample periods are combined, the mean density is given by dividing the overall sum of all the individual densities, by the number of periods.

The ability to calculate aerial densities, rather than simply considering uncorrected counts of overflying insects, greatly increases the potential of the VLR as a tool for monitoring insect migration because it makes possible objective comparisons of the abundance of insects of different size classes, at different sampling altitudes. However, the minimum target size that can be detected throughout the 15 range gates of our VLR is 15 mg, with insects smaller than this only detectable in the lower gates. Thus, comparisons of aerial density across the full sampling range may be carried out only for targets of 15 mg or more; comparisons of smaller insects must be restricted to the lower range gates (Chapman *et al*. 2002a).

3.5 Complications caused by the presence of other insects

In most circumstances, BPH and other rice pests will not be the only insects in the air, so the feasibility of using VLR to monitor pest migration depends on how well the radar can discriminate between the pest species and other airborne insects.

3.5.1 Very minute species Very minute insects (~ 0.05 mg) will have radar cross-sections about 900 times smaller than BPH (average mass ~ 1.5 mg), and so even if individually detected at close range by the radar, they would certainly not be confused with BPH. They would also contribute comparatively little to estimates of BPH density made from volume reflectivity measurements, unless 1000 times more numerous than BPH.

3.5.2 Insects of mass comparable to BPH The VLR technique is relatively new, and there have not yet been any thorough field evaluations (using aerial netting) of its accuracy in estimating the mass of individual overflying insects. Laboratory measurements on BPH suggest that mass estimates based on the σ_{xx} component of radar cross section have a 90% probability of lying within ±40% of the true value (Riley, unpublished data). Field measurements will inevitably widen the range of uncertainty, so it would probably be unsafe to assume at this stage that the masses of individual small insects like BPH can be estimated to better than a factor of two. It is clear from this that when several species of similar mass are aloft at the same time, VLR will be unable to separately identify them on the basis of mass alone. On the other hand, if it is known from other evidence that one species largely dominates the aerial population, the accuracy of estimates of the *average* mass will be very much higher, and could provide a necessary, though not sufficient, criterion of identification.

Laboratory measurements (Aldous 1989) of the radar cross-section terms of medium-sized to very large insects revealed no reliable indicator of length/width ratios. However, recent results (Chapman *et al*. 2002b) obtained from the diamond backed moth, *Plutella xylostella*, indicate that for this species (which has mass in the range ~ 2 to 6 mg), a high length-to-width ratio (~4:1) corresponds to a high ratio of σ_{xx}/σ_{yy} (~10:1). It thus seems reasonable to conclude that for the smaller species, like BPH, this ratio will provide at least a crude indication of body shape, and therefore could in principle be used to discriminate between insects of similar mass but of substantially different morphology. Nevertheless, until this has been demonstrated, it seems prudent to assume that it may not be possible to identify BPH from radar returns alone when other insects of similar mass are airborne at the same time. On the basis of this conservative assumption, BPH could probably not be distinguished amongst an airborne population containing *Recilia dorsalis*, *Cyrtorhinus lividipennis*, *Sogatella furcifera*, *Nephotettix cincticeps*, etc.

3.5.3 *Cnaphalocrocis medinalis* and other moths Insects weighing more than 6 mg should be readily distinguishable from BPH, so *C. medinalis* at 8—9 mg would be easily separated. In addition, this species and most other moths have air speeds significantly greater than the 1—2 ms^{-1} to be expected for insects the size of BPH (see p.167 of Lewis and Taylor 1967) and so would also be distinguishable on this basis.

4 DISCUSSION

4.1 Implications for the use of VRL as a monitor of BPH migration

Our compilation of information on altitudinal distributions of BPH migration shows that it occurs predominantly in the altitude range from 300 to 2000 m above ground level. This is well above the 242 m maximum altitude at which the current generation of VLR can be expected to produce quantitative data on the size, shape and displacement of individual BPH. It is thus clear these radars cannot be used in their normal mode as migration monitors for this species. This does not necessarily mean that they would not yield *any* relevant information, because if BPH densities become so high that very many individuals occupy the radar beam, their collective radar returns (their volume reflectivity) may be detectable at greater altitudes, and provide at least an indication of mass migrations. It is therefor instructive to calculate the maximum altitude to which concentrations of BPH could be detected.

4.2 Calculation of returned signal power in terms of volume reflectivity

The gain G_θ of a Gaussian beam at an angle θ to the beam axis is:

$$G_\theta = G_0 \exp\left[-4\ln 2\left(\frac{\theta}{\theta_{3dB}}\right)^2\right] \text{ (Skolnik 1970)}, \quad (8)$$

where θ_{3dB} = angular distance between the half-power points.

Referring to Fig. 4, and using equations (3) and (8), it can be seen that the signal power (δS) returned to the radar at **O** from the elemental annular volume δV defined by δr and $\delta\theta$ is

$$\delta S = \frac{P_t \pi D^4 \rho^2}{4^3 \times 2 G_L \lambda^2} \delta V B \exp\left[-8\ln 2\left(\frac{\theta}{\theta_{3dB}}\right)^2\right],$$

where δr is the radar pulse length in m, and B is the collective cross-section or *volume reflectivity* of insects in the altitude region occupied by δV.

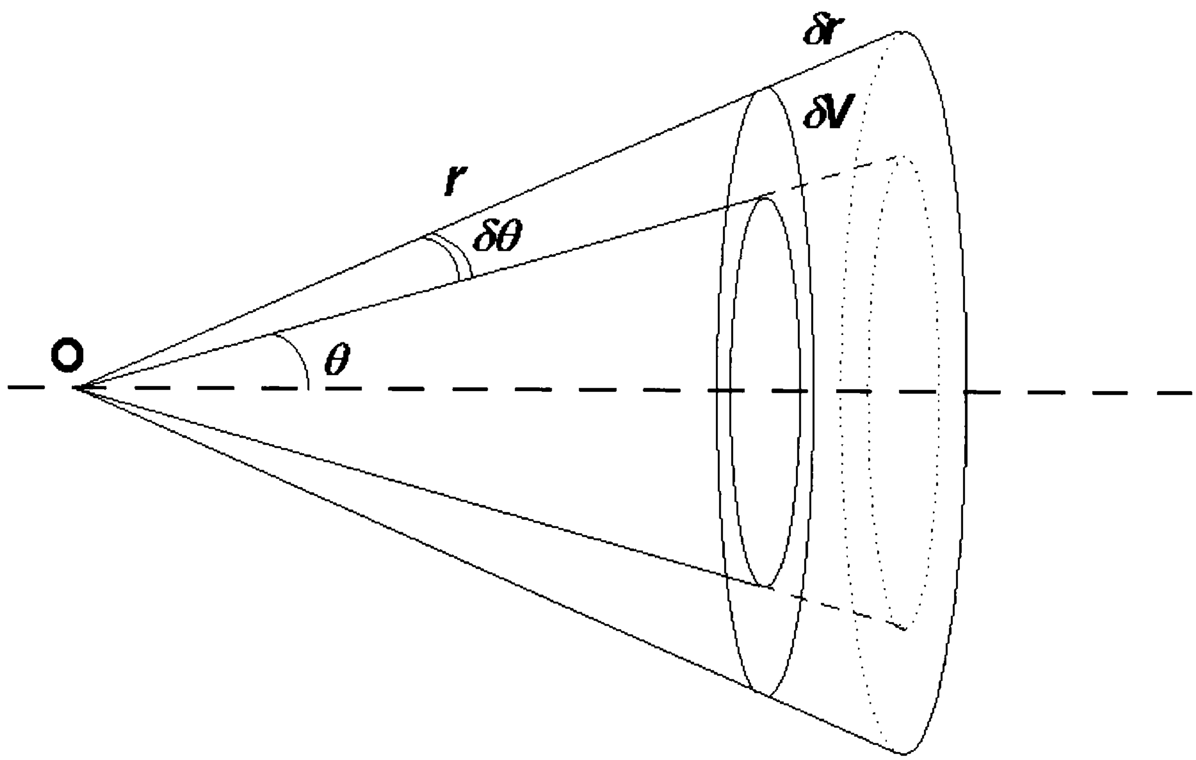

Fig. 4 The diagram shows the annular elemental volume δV, at range r which subtends an angle θ to the radar beam axis. The strength of the radar signals illuminating δV, and of the reflected signals captured from it, are determined by the gain of the antenna in this direction, G_θ.

Now

$$\delta V = 2\pi r \sin\theta r \delta\theta \delta r = 2\pi r^2 \theta \delta\theta \delta r,$$

for small θ.

So

$$S = \left[\frac{P_t \pi D^4 \rho^3 B \times 2\pi r^2 \delta r}{4^3 \times 2 G_L \lambda^2 r^4}\right] \int_0^\theta \exp\left[-8\ln 2\left(\frac{\theta}{\theta_{3dB}}\right)^2 \theta\delta\theta\right].$$

The integral I on the right hand side may be solved by the substitutions

$$c^2 = \frac{8\ln 2}{\theta_{3dB}^2} \text{ and } c^2\theta^2 = x,$$

so

$$\theta\delta\theta = \frac{\partial x}{2c^2},$$

thus

$$I = \frac{1}{2c^2}\int_0^{x_m} \exp(-x) = -\frac{1}{2c^2}[\exp(-x)]_0^{x_m}.$$

We extend the integral out to $\theta = 10 \times \theta_{3dB}$,

$$x_m = c^2 \times 100\theta_{3dB}^2 = 8\ln 2 \times 100,$$

then

$$I = \frac{\theta_{3dB}^2}{16\ln 2}[1 - \exp(-8\ln 2 \times 100)] = \frac{\theta_{3dB}^2}{16\ln 2}.$$

Thus

$$S = \frac{P_t \pi^2 D^4 \rho^2 \delta r}{4^3 G_L \lambda^2 r^2} \times \frac{\theta_{3dB}^2 B}{16\ln 2},$$

where S is the total power returned to the radar from the range interval δr. An equivalent expression has been derived by Probert-Jones (1962) for the case of rainfall measurement by meteorological radars. Re-arranging this equation gives B

$$B = \frac{16\ln 2 S 4^3 G_L \lambda^2 r^2}{P_t \pi^2 D^4 \rho^2 \delta r \theta_{3dB}^2}. \qquad (9)$$

Hence, provided that the radar parameters are known, B can be found by measuring the power, S, returned from the range interval δr, and using equation (9). If an average value for the cross-sections (σ) of the insects occupying this range interval is also known, the aerial density D_e, is simply:

$$D_e = B/\sigma,$$

provided that the aerial density of the insects is high enough to ensure that many insects (> 10) occupy the radar pulse volume. Otherwise, time above-threshold methods must be used to estimate D_e (Drake 1981).

The maximum range R_{max}, at which the VLR could detect the presence of insects of volume reflectivity B, is found by re-arranging equation (9), and replacing S with the minimum signal power which the radar can detect, S_{min}.

Hence:

$$R_{max} = \left[\frac{BP_t \pi^2 D^4 \rho^2 \delta r \theta_{3dB}^2}{16\ln 2 G_L \lambda^2 4^3 S_{min}}\right]^{0.5}. \qquad (10)$$

We use equation (5) to determine S_{min}, but as we are dealing with extended regions of volume reflectivity, rather than with a single target, a V_f of ~ 3 dB is probably adequate to allow detection. Putting this value in equation (5), and substituting in equation (10) gives a rough estimate of the maximum range at which concentrations of BPH could just be detected by a VLR. For example, an aerial population of male and female BPH, of average cross-section of 1.1×10^{-4} cm^2 and a density of 50 per 10^4 m^3, would be detectable up to an altitude of ~ 680 m by one of our 3.2 cm standard VLRs. Aerial densities of migrating BPH as high as 500 per 10^4 m^3 have been recorded during outbreaks (Riley *et al*. 1991), and these would be detectable up to more than 2000 m, *i.e*. over almost of the whole altitude range likely to be occupied by BPH. However, as shown in the preceding section on the aerial distribution of BPH, during more normal years their migration density appears to be typically 2 – 5 per 10^4 m^3, which is far too low to be detectable as collective echo. Thus existing 3.2 cm wavelength VLR would be capable of detecting only the highest concentrations of BPH typical of outbreak years; other movements, especially those occurring above a few hundred meters, would be probably be missed. The inescapable conclusion is that these radars could not function as effective monitors of BPH migration.

4.3 A millimetric wavelength version of VLR

Reducing radar wavelength has the effect of dramatically increasing the radar cross-section, and hence the maximum range of detectability of small insects. For example, because BPH sized targets are in the Rayleigh scattering region at centimetric wavelengths (Riley, 1985), their radar cross-sections scale as the inverse fourth power of wavelength, so a typical maximum cross-section for BPH males at a wavelength of 0.88 cm ($\sigma_{0.88}$) is related to their equivalent cross section at 3.2 cm wavelength ($\sigma_{3.2}$) by:

$$\sigma_{0.88} \approx \sigma_{3.2} \times \left(\frac{3.2}{0.88}\right)^4$$

$$= 1.4 \times 10^{-4} \times \left(\frac{3.2}{0.88}\right)^4 \text{ cm}^2$$

$$= 2.5 \times 10^{-2} \text{ cm}^2.$$

We have exploited this effect by designing and building a scanning 8.8 mm wavelength radar specifically for flight studies of BPH (Riley 1992), and this radar proved to be extremely effective in BPH migration research (Cheng *et al*. 1994, Riley *et al*. 1987, 1990, 1991, 1994, 1995). In principle, millimetric wavelengths could also be used in a vertical-looking radar, and a reasonable specification might be:

P_t = 25 kW,
λ = 0.88 cm,
D = 1.52 m,
θ_{3dB} = 0.4° = 7×10^{-3} radians,
ρ = 0.6,
G_L = 3.16 (= 5 dB) ,
B = 20 MHz,
N_f = 4.5 dB,
I_n = 6 dB,
Range gate width = 0.3 μs ($\equiv$ 45m),
Radar pulse length = 0.1 Ms ($\equiv$ 15m)

As with the 3.2 cm systems, for detection only, $V_f = 9$ dB, for signal analysis, $V_f = 17$ dB.

Substituting these values into equations (4) and (5) shows a greatly increased maximum range for analysis for BPH males of ~ 1260 m. However, because its beam is narrow, this radar would have a smaller sensed volume than conventional VLR working with medium to large sized insects, and so would be less sensitive than these radars to low density migrations. For example, substituting 7×10^{-3} radians for θ_{3dB}, and 1 260 m for r_0 in equation (7), shows that the sensed volume at an altitude of 800 - 845 m would be ~ 1263 m^3. Thus with a migration density of, say, 0.1 BPH per 10^4 m^3, the radar would be detecting signals in each range gate for only 1.2% of the time. Nevertheless, because the data collection is automatic, this low % would not necessarily be a problem, and with normal migration densities, a much higher occupancy would be common. A more serious constraint arises from the fact that the use of a shorter wavelength increases the 'far field distance' ($= 2D^2/\lambda$) of the antenna from ~ 140 m (in the case of 3.2 cm wavelength), to ~ 580 m for a wavelength of 8.8 mm. As targets get closer than this distance, the simple Gaussian expression for antenna gain that is assumed in our analysis procedure becomes progressively less accurate (Skolnik 1970), and the analysis results are therefore less reliable. This means that for BPH, the effective operational altitude for an 8.8 mm radar of the type described above would be limited to the interval from 580 to 1260 m. Coverage below 580 m could be achieved if the radar were equipped with a secondary, smaller antenna, and the transmissions switched between the two.

4.4 Practical considerations

The calculations presented in the previous section show that it is possible in principle to build a vertical-looking radar able detect BPH migration. Unfortunately, there are several practical reasons why such a radar is unlikely to be a cost-effective proposition for routine monitoring. The most important is that the marine transceivers on which existing 3.2 cm VLRs are based, have been intensively developed over many generations to be extremely reliable. This level of reliability, which is essential for long term monitoring, would not even be approached with a one-off millimetric design, so a substantial level of on-going technical support would be needed throughout its operational lifetime. Marine radars are mass produced and therefor inexpensive, but the cost of components for a millimetric radar are much higher, typically ten times higher, and spares may not be readily available. Significant complications and extra costs would also be introduced by the need for at least two antenna systems of high mechanical precision, and by the need to use gas compressed above atmospheric pressure inside the waveguide components to prevent arcing (Riley 1992).

One way forward would be to use a standard 3.2 cm VLR to establish the practical value of monitoring the high altitude migration of medium to large-sized insect pests in China-accepting that the system would be of very limited use against BPH. The practical advantage of this approach is that the radar would be based on an established design, and could be built with confidence to a well-determined and modest budget. If monitoring with this radar proved successful, it could be supplemented at a later date with a simple, non-nutating millimetric vertical looking radar able to provide at least qualitative indication of any small insects flying above the 3.2 cm radar's detection range.

5 CONCLUSIONS

There is no doubt that vertical-looking radars, based on 3.2 cm wavelength marine radar transmitters, provide a highly effective and inexpensive means of routinely monitoring the migration of medium to large sized insects. This study has demonstrated however, that because BPH migrate at high altitudes and have such small scattering cross-sections, these 3.2 cm VLRs could not by themselves provide adequate coverage of migration by this species. The study has also shown that while the adoption of a shorter VLR wavelength (8.8 mm), and multiple antenna sizes would make quantitative monitoring of BPH a possibility, such a radar would be much more costly to produce and to maintain than existing VLR. A more practicable proposition would be to use a standard 3.2 cm VLR to assess the value of monitoring the high altitude migration of medium to large-sized insect pests in China. If the migration data was found to improve the management of these pests, consideration could be given to adding a relatively simple vertical looking radar, working at millimetric wavelengths, able to provide a qualitative measure of the migration of insects the size of BPH.

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在中国应用垂直波束雷达监测褐飞虱和其他水稻害虫迁飞的可行性

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近年来,可用于昆虫迁飞研究且可自动运行的垂直波束雷达(vertical-looking radar, VLR)的发展使得对迁飞性害虫的周年长期自动监测成为可能。本文提供了我们对能否将这种雷达应用于中国的褐飞虱和其他水稻害虫的监测与预测体系以改善其综合治理的可行性研究结果。以往的研究已经表明,这些害虫一般在 300 ~ 2000 m 高度迁飞;而我们根据褐飞虱的雷达和射有效截面的计算结果表明,目前使用的 3.2 cm 波长的 VLR 对褐飞虱个体目标的最大可检测高度仅约 240 m;虽然建造一部 8.8 mm 波长的 VLR 即可覆盖褐飞虱迁飞高度的绝大部分,但其造价和维护费用均过于昂贵。为此,一个更可行的解决方案是,以 3.2 cm 波长的 VLR 作为包括大多数水稻害虫在内的个体较大的迁飞性害虫的监测工具。

关键词 雷达 迁飞 飞行 褐飞虱 水稻害虫

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APPENDIX I

Details of the vertical-looking radars operating at Rothamsted and Malvern

Antenna configuration: vertically pointing paraboloid, equipped with cylindrical microwave absorbing shroud and sloping membrane radome.

Radar details:

wavelength, λ	= 3.2 cm
nominal peak power, P_t	= 25 kW
pulse length	= 0.1 μs = 15 m
pulse repetition frequency	= 1.5kHz
diameter of parabolic antenna, D	= 1.52 m
feed type	double dipole
f/D ratio	= 0.3
half-power beamwidth, θ_{3dB}	= 1.45°
antenna efficiency, ρ	= 0.6
one way loss, duplexer, waveguide, and radome, G_l	= 1.58 (2 dB)
beam nutation offset	= 0.15°
nutation frequency	= 5.9 Hz
receiver bandwidth,	= 20 MHz
receiver noise figure, N_f	= 3.5 dB
pulse integration inprovement, I_n	= 6 dB
range gate width	= 0.3 μs = 45 m
dynamic range	= 80 dB