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The potential of portable harmonic radar technology for the tracking of beneficial insects

(*Keywords:* marking, coccinellid, *Harmonia axyridis*, *Hippodamia convergens*)

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Abstract. Visual observation enables a good understanding of beneficial insect behaviour within a locality, but once the rapidly dispersing beneficial insects walk or fly, they are soon lost from view. The harmonic radar tracking system developed to follow Colorado potato beetles, *Leptinotarsa decemlineata* (Say) in flight is proposed as a useful technique to increase the study range of beneficial insects from that of the plant to that of the landscape. These insects belong to a wide array of orders and families and many are small in size. Nevertheless, we estimated that some 15% of beneficial insects are at least similar in length to the chrysomelid beetle for which the feasibility of using a portable harmonic radar has been successfully demonstrated. As for the Colorado beetle, the pulsed radar transmitter, the tag, the antenna gain and the receiver of the portable radar system must be carefully designed to provide both a sufficient tracking range and a sufficient beam width. The construction of the tag is strongly limited by the load-carrying ability of the beneficial insect to be tracked. For the tracking of normal insect dispersal tags must, by definition, be lighter than the maximum carrying ability for extra loads and within the wing loading range of each species. It has been shown that in herbivorous insects and mosquitoes the ability to fly may be traded against the opportunity to acquire a large meal. This trade-off, which limits the ability of the insects to carry extra loads, should be less likely to occur with beneficial species that have to remain highly mobile to locate and capture prey for example. This was supported by our findings for *Hippodamia convergens* and *Harmonia axyridis* (Coccinellidae), both of which retain their ability to fly over the full range of their wing loading values. Tests conducted in the laboratory showed that these two beneficial insects can display normal flight behaviour with tags representing a similar percentage of their body mass as those successfully developed for the Colorado beetle and only slightly higher than for the other ones reported in the literature. The application of the portable harmonic radar technology to the study of flight by beneficial insects is therefore feasible and worth developing further. The main challenge is in the development of electronic tags with a sufficiently small absolute mass. Many options available immediately and others with potential are discussed.

1. Introduction

Integrated insect pest management programmes have reached a stage of complexity that requires an understanding of beneficial insect ecology and insect interrelationships not only within a field or a forest but also across the landscape (Ekbom *et al.*, 2000). The spatial distribution of insect pests and beneficial insects within the habitat is becoming better known and it is now our understanding of the spatial distribution of insects across fields that is wanting. Understanding the spatial distribution of insects is an integral part of pest management (Weisz *et al.*, 1996). It is particularly applicable to biological control, whether one considers classical or inundative biological control (Ives and Settle, 1997; Hassell, 2000).

Biological control may be at a turning point as a pest management method. In Canada, for example, the number of candidate biological control agents for introduction is declining as research in molecular biology and genetic engineering is replacing research in organismal biology (Mason and Huber, 2002). In the mean time, known effective biological control agents are not reaching the marketplace due to insufficient funding for the development of industrial mass production methods and to an inadequate knowledge of their dispersal behaviour. As shown in this paper (and elsewhere in this special issue) recent developments in marking techniques can make it possible for researchers to determine the searching and dispersal rates necessary to establish reliable biocontrol release programmes. This is important not only for pest management but also for conservation and environmental studies.

The foraging behaviour of beneficial insects has received attention in the literature but the mid- to long- range dispersal behaviours of these insects has received remarkably little attention (Godfray, 1994). Much has been written on the flight dispersal of insect pests and the effectiveness of different control methods against alate stages of pests (e.g., Giles and Justum, 1989) but relatively little on the role of alate control agents in pest management (Pedgley, 1993; Ives and Settle, 1997). Even entomophagous insects that are active against the pests during their larval stages depend on the mobile stages of their life cycle for their expansion and sustained effect against the pests. The paucity of information results partially from the absence of suitable methodologies for tracking insects.

Novel marking methodologies have recently been developed but they have traditionally been for the study of insect pests (Osborne *et al.*, 2002). However, many may be applicable to beneficial insects (Riley and Smith, 2002). The stationary harmonic radar method for tracking insect pests and some beneficials such as bees, bumblebees and predatory ground beetles (Carabidae) is one example (Riley *et al.*, 1996; Osborne *et al.*, 1999). A prototype portable harmonic radar has been developed for the Colorado beetle (Colpitts *et al.*, 2000; Boiteau

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and Colpitts, 2001). The biological and engineering advantages and limitations of the latter for the tracking of beneficial insects are examined in this document.

2. Beneficial insects

The aerodynamics (Riley *et al.*, 1996) and the weight restrictions for insect flight are such that marking tags used in insect ecology research must be small in size and light in weight. Correspondingly, candidate beneficial insects for radar tagging must exceed a minimal mass and/or such a large wing area that they can lift additional loads. Unfortunately, mass and wing loading values are not readily available for most beneficial insects. However, body length is a good estimator of wing loading and was therefore used to estimate the proportion of beneficial insects that could be considered candidates for harmonic radar tracking. The list of insects used or considered as biological control agents over 20 years in Canada (Mason and Huber, 2002) was considered representative of the range of taxa available to insect pest managers. Approximate body lengths for 88 species from this list were obtained from the literature and entomology textbooks. Of the 88 species, 60%, 25%, and 15% were, respectively, less than 5 mm, less than 10 mm and 10 mm or more in body length. An electronic tag weighing 23 mg for a prototype portable harmonic radar has already been successfully mounted on an insect (Boiteau and Colpitts, 2001) measuring between 9.0 and 11.5 mm in length (Jacques, 1988). It is estimated that some 15% of beneficial insects that could be considered for biological control could be tracked using this technology and the same tag. The development of lighter tags would be required to use this technology over a wider range of beneficial insects. Listed potential biocontrol species with bodies 10 mm or more in length belonged to the Coleoptera (Cerambycidae, Curculionidae), Hemiptera (Pentatomidae), Lepidoptera (many families), Mantodea and Neuroptera (Chrysopidae) (figure 1). The suitability of each insect family or species within these orders for electronic tags varies considerably. For example, it may be easier to mount the tags on strongly sclerotized insects such as the Coleoptera than on soft-bodied insects such as the Neuroptera. Many of those factors are considered in the following sections, beginning with the tracking radar and the electronic tags themselves.

3. Suitability of harmonic radar technology for beneficial insects

3.1. The portable harmonic radar system

The portable harmonic tracking system (figure 2) was developed around a pulsed magnetron source that provides the high power microwave electromagnetic pulses that illuminate the

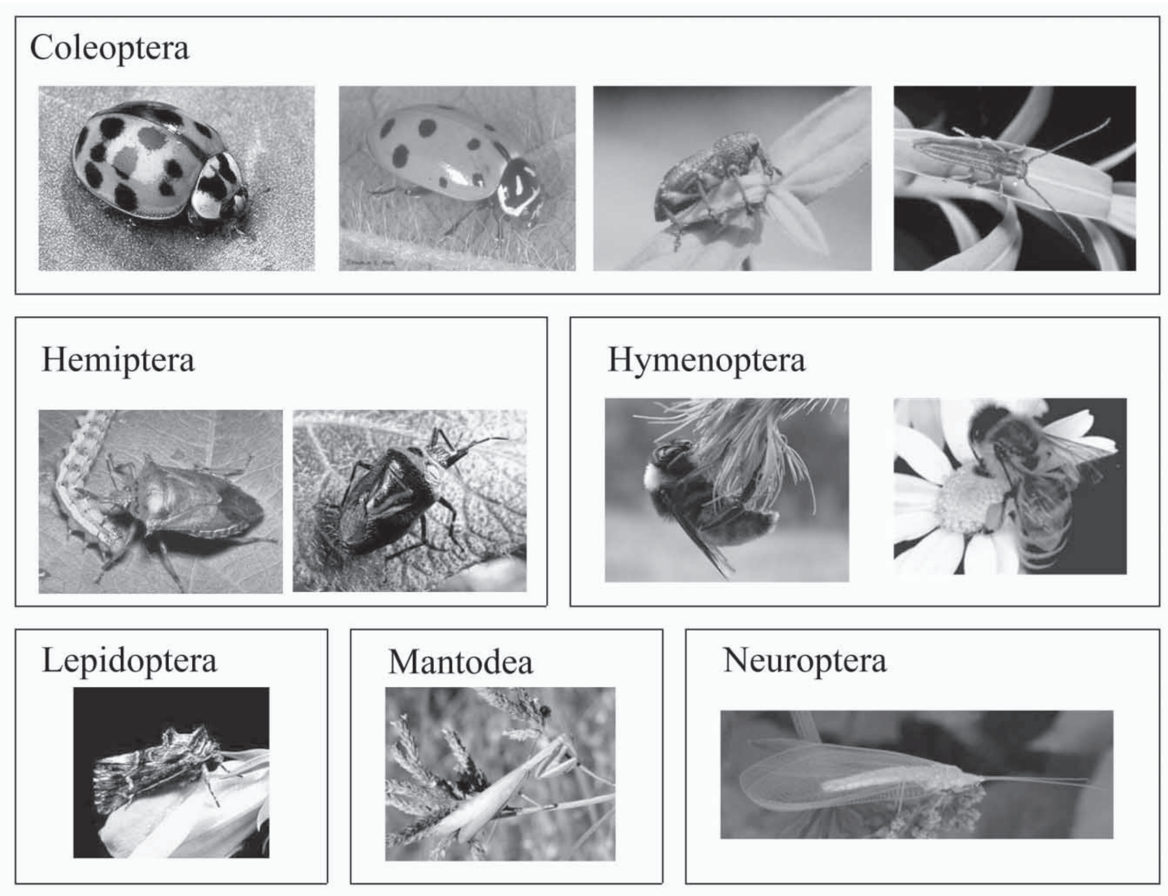

Figure 1. Examples of beneficial insects belonging to different orders with good potential for the use of harmonic radar tracking in research: Coleoptera: Harmonia axyridis *(Pallas) (general predator),* Hippodamia convergens *G.-M. (general predator),* Hylobius transversovittatus *(purple loosestrife control agent),* Oberea erythrocephala *(Schrank)) (leafy spurge control agent); Hemiptera:* Podisus maculiventris *(Say) (general predator),* Perillus bioculatus *(Fabricius) (Colorado beetle control agent); Hymenoptera:* Megabombus spp *(pollinator),* Apis mellifera L. *(pollinator); Lepidoptera:* Calophasia lunula *(Hufnagel) (weed control agent); Mantodea:* Mantis religiosa religiosa L. *(general predator) and Neuroptera:* Chrysoperla carnea *Say (general predator).*

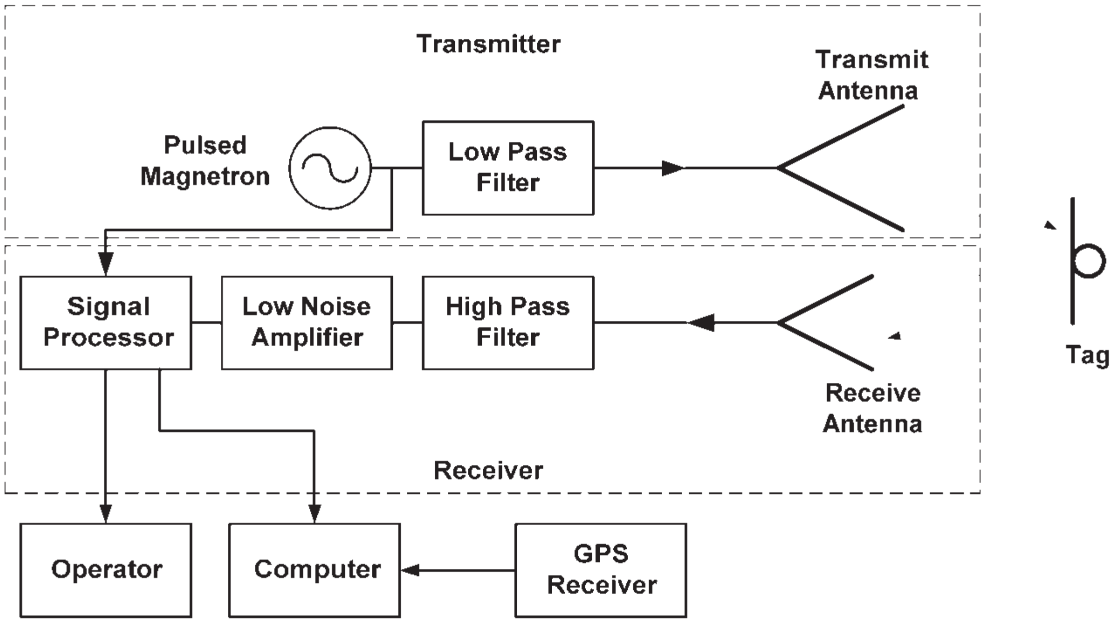

Figure 2. Block diagram of the portable harmonic radar tracking system showing the transmitter and receiver sections along with the GPS receiver and computer for recording position information.

target. This source operating at a frequency in the marine radar band near 9.4 GHz (fundamental) is directed through an antenna, which is used to radiate the fundamental frequency pulse in a specific direction. The electromagnetic pulse travels to the tagged insect where a portion of the signal energy is captured by the tag, is then converted to the second harmonic of the incident signal, and then reradiated away from the tag. A portion of this harmonic signal reaches the location of the radar where a second antenna captures it and directs it to the receiver for detection. This system is fundamentally governed by the harmonic radar equation (Colpitts and Boiteau, 2004), inspection of which will allow one to understand the fundamental principles and performance trade-offs that were encountered in developing the system. The same constraints would apply to the customization of this Colorado potato beetle, *Leptinotarsa decemlineata* (Say), tracking radar for beneficial insect species. The equation is as follows:

$$r_{max} = \sqrt{\frac{\lambda h}{4\pi}\sqrt{\frac{P_{stf\sigma h} G_{sf} G_{sh}}{P_{srh} 4\pi}}} \quad \text{(Harmonic Radar Range Equation)} \tag{1}$$

where: r_{max} is the maximum range of the radar system; P_{stf} is the pulse power delivered to the antenna from the magnetron at the fundamental frequency; σ_h is the harmonic-cross-section of the target, which consists of the insect and the attached radar tag; G_{sf} is the gain, or the ability to concentrate the radiated energy in a given direction, of the transmitting antenna at the fundamental frequency; G_{sh} is the gain of the receiving antenna at the harmonic frequency; P_{srh} is the minimum power detectable by the receiver; λ_h is the free space wavelength of the harmonic frequency and is fixed with the choice of operating frequency. The system designer has control over the parameters P_{stf}, σ_h, G_{sf}, G_{sh} and P_{srh}. From the equation one can see that an increase in any of the first four parameters will result in the radar having an increased maximum range while a decrease in the fifth term will be needed to increase range.

Note also that, of the five terms, four are associated with the portable radar system, with only σ_h being related to the insect and tag. The double square root indicates a fourth order relationship between the design parameters and the maximum range of the system. Thus, in order to double the system range would require a 16 fold increase in the transmit power, harmonic cross section, or antenna gain. Each one of the design parameters has a particular relation to the behaviour of the portable harmonic radar, as can be seen in the following examination.

3.1.1. Pulsed radar source (P_{stf}). The source power is limited by available magnetrons, which are readily available at low cost in the 2 kW–12 kW range. There are marine radar units available with 50 kW output power. However, from the standpoint of mobility we must be concerned with the weight of the transmitter tube as well as its power consumption. Also the fourth power relationship means that a doubling of transmission power will only yield a 19% increase in maximum range. Conversely, if transmitting only one-half power resulted in significant weight savings and longer battery life or fewer batteries, then the performance reduction in terms of range would be 16%.

The width of the transmitted pulse is typically variable from 0.1 μS to 1.0 μS, which has several implications for the performance of the system. Shorter pulses yield improved range resolution but at the price of reduced maximum range, since there is less energy in a single pulse and more bandwidth is required. The effect of increased bandwidth will be discussed in the received power section. Longer pulses deliver greater range but may cause significant interference with the receiver when used at close range. Consider that a 1.0 μS pulse in free space is 300 m in length. Thus, the leading edge of the scattered pulse from a target at a range of 150 m or less will reach the receiver before the trailing edge of the pulse leaves the transmitter. A 0.1 μS pulse reduces this range to 15 m.

3.1.2. Harmonic radar tag (σ_h). The harmonic-cross-section, σ_h of the tagged insect is the key to tracking while at the same time it involves attachment, mobility and loading issues for the insect. From an entomological perspective this is the dominant issue. Our currently employed tags were developed for Colorado beetles, which have a typical mass of 110 mg and are very active, regularly climbing each other's tags. This rough behaviour resulted in tags formed from American Wire Gage (AWG) #36 copper wire being severely deformed; therefore AWG #34 copper-cladded steel wire is now used. The tags are formed from a single length of wire, which is wrapped around a mandrel to form a 1mm loop at the centre. This 1 mm loop provides physical support for the dipole and provides the tuning inductance and direct current path for the diode (figure 3). Harmonic-cross-sections in the range of 10 mm^2 to 40 mm^2 can be expected. For a tag in isolation it was found that a dipole length of 12 mm yielded the largest harmonic radar cross section (Colpitts and Boiteau, 2004) while for the case of the antenna attached to a Colorado beetle the optimum length lowered to 8 mm. In this instance the insect formed a portion of the antenna. The harmonic-cross-section of the tag is governed by a complex relationship of impedance matching and drive level. The matching between the dipole antenna, inductive loop combination and the diode at the fundamental frequency will heavily influence the power delivered to the diode. This matching is dependent upon the signal intensity so it is necessary to optimize the design for a given drive level. The tags designed for this project were optimized for a drive level corresponding to the maximum range of 200 m where the best tag performance would be required. At closer ranges than the optimum the drive signal is larger resulting in an increased impedance mismatch between the antenna and the diode. The overall effect of ranges closer than the optimum is to reduce the harmonic-cross-section of the tag. For example at 200 m range our tag has a harmonic-cross-section of 40 mm^2 which reduces to 25 mm^2 at 100 m and 14 mm^2 at 50 m. The improved performance of the diode in producing second harmonic signal at higher drive levels is more than offset by the reduction in impedance match when we move away from the optimum conditions. However, with the optimum design being at the maximum range point any point closer will require less performance from the tag and be easily overcome by the fourth power range dependence of the radar system.

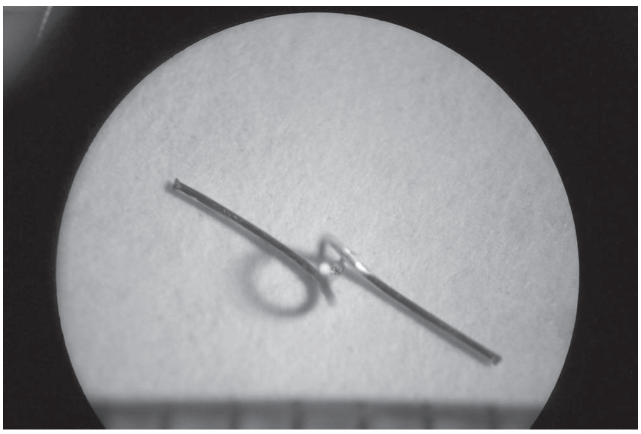

Figure 3. Image of a tag with the beam lead diode attached across a 1 mm diameter loop using conductive epoxy. The wire is American Wire Gage (AWG) #34 copper coated steel.

Table 1 shows important properties of the materials for use in tag fabrication. The material conductivity is used to determine the skin depth (Pozar) of the material, which determines the thickness of coatings required when plating a non-conductor. For example, a conductive coating of only two to three skin depths in thickness is required for a glass fibre to act as a conducting dipole antenna. Thus, a 2 μm coating of gold would be sufficient. The density of the material is used to determine the tag mass, while Young's Modulus reflects the elasticity of the material, its stiffness, or resistance to bending. Thus, the choice of copper-coated steel wire utilizes the stiffness of steel with the conductivity of copper.

Fabrication of a 12 mm dipole and 1 mm loop requires 15.1 mm of wire along with the beam lead diode and conductive epoxy. The mass of the diode can be estimated from its constituent materials; gold, glass and silicon; and their dimensions to be 23 μg. Compared to the mass of the wire this value is insignificant in all cases except the 25 μm diameter bond wire as shown in table 2.

3.1.3. Antenna gain (G_{sf}, G_{sh}). The antennas used with the harmonic radar system have a very significant influence on its operation. The use of high gain antennas will result in an increased range for the radar system but the penalty will be physically larger antennas along with reduced antenna beam-widths. From a portability point of view the high gain antennas become more difficult to manoeuvre because of their size, and the pointing accuracy required as a result of the narrow beam width makes operation challenging. An analogy here would be to consider illuminating a moving target with a floodlight compared to a flashlight compared to a laser pointer. In this analogy, each step represents an increase in the gain of the optical antenna. Table 3 shows the relationship between gain and beam-width for a range of antenna gains that could be used in a radar system based upon the work of Balanis (1982).

Table 1. Fundamental material properties of potential tag materials

	Skin depth (nm) @ 9.41 GHz	Conductivity (S/m)	Young's Modulus (Gpa)	Density (g/cm^3)
Copper	681	5.8×10^7	117	8.89
Aluminium	842	3.8×10^7	73	2.7
Gold	810	4.1×10^7	75	19.3
Silver	660	6.2×10^7	72	10.5
Steel	3669	2×10^6	200	7.8
Glass	n/a	Non-conducting	72	2.4–2.8

Table 2. Tag mass in milligrams for a range of wire diameters and materials for the case of a 12 mm dipole with 1 mm loop including the 23 μg beam lead diode

Wire Diameter (AWG)	25.4 μm	101 μm (38)	127 μm (36)	160 μm (34)	202 μm (32)
Copper	0.068	1.076	1.700	2.700	4.302
Aluminium	0.021	0.327	0.516	0.820	1.307
Gold	0.148	2.335	3.692	5.860	9.340
Silver	0.080	1.270	2.008	3.188	5.081
Steel	0.060	0.944	1.492	2.368	3.775
Glass	0.020	0.315	0.497	0.789	1.258

Table 3. Antenna beam-width as a function of gain

Gain (dB)	Gain (ratio)	Half-Power Beam-width of Antenna (degrees)
15	31.6	34
20	100	19
25	316	11
30	1000	6.0
35	3160	3.4

The harmonic antenna requires only one-quarter the aperture area of the fundamental antenna in order to have the same gain. Current systems utilize antennas of equal gain and thus equal beam-width at both the fundamental and harmonic frequencies. However, an increase in either antenna's gain will increase the system range at the price of a narrower beam-width. Due to the reduced wavelength at the harmonic frequency an antenna with gain equal to that at the fundamental frequency is only one-half the linear dimensions, or in the case of an aperture, one-quarter the area. Thus, it could be advantageous to use antennas of equal physical size in the portable system.

3.1.4. Received power (P_{srh}). The final parameter to be considered is the received power of the second harmonic signal at the radar. This received power must be well above the noise floor of the receiver for rapid detection. Thus it is important to use a low noise amplifier (LNA) and have very little signal loss between the receive antenna and the amplifier. Currently available narrow band amplifiers have noise figures of less than 2 dB at 18.82 GHz. The amount of noise entering the receiver is in part dictated by the bandwidth of the signal. Short pulses require more bandwidth than do longer pulses thus to receive short pulses more noise is received and the signal-to-noise ratio is reduced. Not only do short pulses have less energy than long pulses, and therefore less signal, they are received with more noise which further reduces signal-to-noise performance. Therefore, there is a trade-off between system range and resolution with long pulses delivering superior range with corresponding loss in resolution.

3.1.5. Electromagnetic interference (EMI). Self-interference is a potential problem in these systems particularly when used at short range. In this case there is not enough of a time delay between the transmission of the radar pulse and the reception of the scattered pulse to distinguish them in time. Care must be taken to filter the second harmonic from the transmitted signal (magnetrons produce some energy at the second harmonic). Also, the direct coupling of the very powerful fundamental frequency pulse into the receiver LNA will cause the generation of second harmonics. Employing a low-pass filter before the LNA is essential to block the fundamental frequency pulse from the LNA while allowing the second harmonic to pass with minimal attenuation. In addition, there is a strong requirement for general electromagnetic interference (EMI) control between the transmitter and receiver. This was achieved using separate solid aluminum enclosures and exercising great care when routing and attaching power and communications lines.

3.2. Load-carrying ability of beneficial insects

The use of pole-like tags glued on the pronotum of insects introduces new variables that can affect flight, such as aerodynamic drag (Riley *et al*., 1996), entanglement (Roland *et al*., 1996) and overloading (Boiteau and Colpitts, 2001). The potential for overloading is discussed here. The ability of an insect to carry extra loads at flight takeoff and during flight is less limited in some species than in others. It is probably less limited if as in the case of bees, the carrying of extra loads (pollen) is an integral part of the life system. In nature, loads may consist of prey, mates, or pollen and nectar. According to Dudley (2000), some insects produce forces substantially in excess of body mass. For example, wasps foraging for animal prey or nectar may return with loads 20 to 70% of body mass, nectar loading in bumblebees can double body mass and tsetse-flies can fly with large blood loads. Overall, available studies show that insects can lift weights representing 0.5 to three times their body mass.

However, the ability of many insects to carry heavy loads in flight must be distinguished from the ability of these insects to carry extra loads without negatively affecting flight performance. It is likely that maximum loads for flight all affect some aspects of flight performance. There are many factors determining insect flight performance including the ratio of thoracic muscle mass to body mass, wing loading and energy. Maximum load lifting is better related to the ratio of thoracic muscle mass to body mass than to wing loading according to Dudley (2000). Based on that ratio, the orders Diptera, Lepidoptera, and Odonata possess the greatest ability to lift loads while, the Mantodea, Hemiptera, and Coleoptera have the lowest ability (Dudley, 2000). These measurements can help determine the upper limit of weights for electronic tags. These tags would allow takeoff and even flight but they would not reflect normal insect flight behaviour.

Wing loading measures the ability of an insect to carry its own weight in flight. It is the ratio of body weight, expressed in Newtons (N), over wing area and is proportional to body length (Price, 1997). Wing loading generally increases with weight. It can be high and similar to that of swifts and swallows at 12–40 N/m^2 for some large Coleoptera but can also be as low as a fraction of one N/m^2 for some small butterflies (Price, 1997). Many of the wing loading values available have been measured for a sample of individuals from a population and represent an average value for the species. There are indications that the value of the wing loading can vary significantly less between individuals of a same species than it does throughout the day or from day to day as the weight of the species is modified by feeding, drinking, ovipositing, etc. (Boiteau and Colpitts, 2001). In the same manner that large insects must generate more muscle power to fly than small insects, both large and small insects must generate more or less relative muscle power to fly as they eat, drink and oviposit. In some species, the wing area and therefore wing loading differs according to seasonal and latitudinal air temperature changes (Dudley, 2000). Wing loading provides a closer assessment of the minimum values for electronic tags although it does not by itself provide a measure of the ability of the species for extra loads without flight performance reduction. Insects of same mass can show very different wing loadings. For example, Dudley (2000) reports that bumblebee workers have a wing loading of 15 N/m^2 but that some Lepidoptera with a similar mass but twice the wing area have a wing loading of 1.5 N/m^2.

The determination of muscle ratios and wing loadings are important indicators of insect flight abilities but it is essential to assess the flight performance itself for each species of tagged insects to ensure that the results of the tracking are as close as possible to the natural, unencumbered flight behaviour of each beneficial insect. It is unlikely that tags with no performance restrictions can be produced for most insect species. Knowledge of restrictions on flight performance will however, at the very least, assist in interpreting the limits of the data obtained. This will be discussed further later on as we present our observations on two species of Coccinellidae.

3.3. *Flight behaviour of beneficial insects*

It can be presumed that insects have evolved a ratio of thoracic muscle mass to body mass and a wing loading that are optimal for their life system. The flight related behaviours of beneficial insects will be influenced by the changes in their body mass, whether they are natural or artificial such as with the addition of radar tags. Most of the literature available on flight performance relates to the behaviour of prey and their ability to escape from aerial and terrestrial predators. For example, Dudley (2000) refers to the significantly higher relative muscle mass in palatable compared with unpalatable butterfly species, consistent with the reduced flight speeds and lower evasive capacities characteristic of the latter group. Increases in effective body mass reduce takeoff performance and the ability to escape from predators. Dudley (2000) provides the example of foraging insect taxa that carry substantial food volumes and insect migrants that must fly with heavy lipid loads. The ability to carry loads already influences the selection and aerial transport of prey by some of the beneficial insects (Dudley, 2000). The behavioural strategies of mate acquisition will also be influenced by body mass.

The addition of a marking tag becomes another factor determining the flight performance of each species. The role of this factor must be minimized to ensure that ecologically sound dispersal is tracked. Tags tested to date with stationary and portable harmonic radars on Lepidoptera (Roland *et al*., 1996), Hymenoptera (Riley *et al*., 1996) and Coleoptera (Boiteau and Colpitts, 2001) represented weights as low as 0.1 – 0.9%, 1.5% and 2.4% of the body mass, respectively. Unfortunately the carrying ability of insects is known only for a few species. Boiteau and Colpitts (2001) and MacQuarrie (2002) showed that the carrying ability of the Colorado beetle is so limited that the insect is grounded after a large meal. There are indications that the flight takeoff of mosquitoes is limited in a similar manner following a blood meal (Roitberg *et al*., 2003). Trading flight for feeding, due to excessive wing loading, may subject an insect to an increased risk of predation, as recently reported for mosquitoes (Roitberg *et al*., 2003). However, insects such as the Colorado beetle may use alternate escape strategies to deal with predator harassment, such as feigning death (thanatosis) (MacQuarrie, 2002). Through thanatosis, these beetles can consume large amounts of foliage that functionally inhibit flight yet still retain the ability to escape rapidly from the plant. It is possible that the phenomenon described for the Colorado beetle may exist in other insect species, especially herbivorous insects that routinely consume large meals when feeding on suitable hosts. It is less likely for predatory species that depend on their mobility to find and secure prey. The carrying ability of some insect species such as honeybees is less limited although load weight can still affect behaviour (e.g., Schmid-Hempel, 1986). These issues were considered in studying the suitability of two species of beneficial Coccinellidae for harmonic radar tracking. The study is presented below.

4. Case study – Coccinellidae

4.1. *Harmonia axyridis and Hippodamia convergens*

Two common species of predatory Coccinellidae were chosen for the study (Coderre *et al*., 1995; Hodek and Honek, 1996). *Harmonia axyridis*, (figure 1) also known as the multicoloured Asian ladybird beetle, varies in colour from pale yellow-orange to bright red-orange, with or without black spots on the wing covers. The adults are strongly oval and convex, about 6 mm long and 5 mm wide. Both the larvae and the adults of *H. axyridis* are voracious predators of arthropods. They have been introduced from Asia to control many species of injurious soft-bodied insects such as aphids, scales, and psyllids. Their numbers have become so high in some areas of North America that they have actually become a nuisance insect and a secondary pest of orchards. *Hippodamia convergens,* also known as the convergent ladybird beetle, is one of the best-known and most common ladybird beetles and is found from southern Canada to South America. Convergent ladybird beetle adults are slightly elongated in shape and can range from 4 – 7 mm in length. They have a prominent black and white pattern behind the head, and black spots on red forewings. The adults and larvae prey mainly on aphids although if aphids are scarce, they may feed on small insect larvae, insect eggs, mites, and, occasionally, nectar, and honeydew secreted by aphids and other sucking insects. It is one of the most widely used beneficial insect control agents.

4.2. *Experimental setup*

Adult Coccinellidae were obtained from Natural Insect Control, Ontario. Beetles used in a test on any given day were of the same age class. Although some of the same beetles were reused within a test, different groups of beetles were used for each test.

4.2.1. Load carrying ability test. The two species of Coccinellidae were kept individually in Petri dishes provided with a potato leaflet inserted in a waterpik and a number of *Macrosiphum euphorbiae* aphids for food. Beetles were kept at 25°C and light : dark regime of 17.5 h L : 6.5 h D. Beetles dying during the test were replaced by new ones maintained under the same conditions. Beetles were weighed individually prior to each flight test. Weights simulating radar tags of three different weights were glued on the pronotum of approximately half of the beetles (Instant Krazy® Glue; Elmer's and Toagosei Co. Ltd., US) of each species.

Three tests were carried out with each species to compare the flight propensity of a group of beetles carrying extra weight with a group without extra weight. The extra weight or tag consisted of wire sections glued to the pronotum of the beetles. To reduce the cost of the study, diodes were not included in the design of the tags. The beetles were flown individually in a screened arena (49 cm wide × 75 cm high × 48 cm deep). Each beetle was placed at the apex of a 4 cm square pointed wooden stake using a paintbrush, and was then given five consecutive periods of 1 min maximum to takeoff by flight. Every flight was recorded for a maximum of five flights per beetle. Beetles were disturbed with the paintbrush after each minute of no flight to encourage flight. Short flights at a negative angle from the top of the stake were called downward flights. Flights initiated at a positive angle from the top of the stake were called upward flights. The upward flights correspond to the dispersal flights outdoors and the downward flights correspond to the local, plant to plant, flights. The arena was placed on the floor of a room with 14 fluorescent lights (two 2.4 m HO tubes per light) at ceiling level. All walls were white and the floor was grey. The setup encouraged the beetles to fly off the release stake.

4.2.2. Wing loading test. Three different groups of each beetle species were used consecutively to measure the wing loadings. Beetles were kept individually and tested daily over a period of ten days in the flight chamber described above. Each beetle weight was measured before each session in the flight chamber using an analytical balance. The number of upward flights was recorded for each beetle that flew each day. At the end of the experiment, one hind wing of each beetle was detached from the body, at the attachment point, and then laid flat between two plastic sheets under a weight to dry overnight. The wing was then coloured with red permanent ink and scanned (WinFolia, version 4.2a by Instruments Regents Inc., Quebec) to measure its surface area. The number obtained was multiplied by two to obtain the total wing area necessary to calculate wing loading.

4.3. Statistical analysis

A χ^2 analysis (Microsoft Corporation, 1997) (Microsoft Excel 97) was used to determine if the presence of extra weight on the pronotum of beetles affected the ratio of upward and downward flights. The expected ratio was obtained from the group of beetles without extra weight. The total number of downward and upward flights for each of the nine flight sessions for each test were cumulated to form the observed (tagged) and the expected (non-tagged) ratios.

The flight data for each beetle in the wing loading test were ranked according to tag weight to determine the minimum and the maximum body weights as well as the weight beyond which no flight was recorded. Regressions between the surface area of the hind wings and the maximum weight, the minimum weight, and the weight beyond which flight did not occur were carried out using Microsoft Excel 97 and the significance level of a regression was determined using GLM (SAS, 1990). Differences between slopes and elevations of regression lines were determined using Student's *t*-tests (two-tailed) or ANOVAs for regressions (Zar, 1974). The wing loading is expressed in Newtons (*N*) per square meter of sustaining wing area as in Weis-Fogh (1973).

5. Results

5.1. Tags and flight parameters

Flights were recorded in all tests from beetles with and without additional weights (table 4 and 5). There was an obvious relation between the size of the extra weight and the total number of flights recorded. Except for the lighter extra weights, there was a tendency for a smaller total number of flights. The behaviour of ladybird beetles is to readily disperse by upward flights. It was therefore expected that in an arena, a majority of beetles released would readily fly upward. The addition of tags of increasing weight did reduce the proportion of the flights directed upwards. The ratio of upward to downward flights for *H. axyridis* carrying extra weights of 33 pN differed significantly from the expected ratio for beetles without extra weights (table 4). The ratio of upward to downward flights for *H. convergens* carrying extra weights of 17 and 33 pN differed significantly from the expected ratio for beetles without extra weights (table 5). The change in the proportion of the total flights that were upwards and therefore suitable for moderate or large scale dispersal was inversely proportional to the change in the weight of the tags. Extra weights of 17 and 5 pN did not change the ratio significantly from that for beetles without tags for *H. axyridis* and *H. convergens* respectively.

5.2. Wing loading

H. axyridis is a heavier beetle than *H. convergens* averaging 32.2 mg (N = 22) compared to 18.8 mg (N = 28), respectively. In

Table 4. Effect of extra weight on the ratio of upward to downward flights of Harmonia axyridis

Test	Extra weight (μN)	Statistic	Ratio of flights: # upward flights		Ratio of flights: # downward flights	Total # flights
1	33	Observed	0		26	26
		Expected	19		7	61
		χ^2		70.5714		
		P		$<< 0.0001$		
2	17	Observed	30		10	40
		Expected	30		10	59
		χ^2		0		
		P		1		
3	9	Observed	59		18	77
		Expected	47		30	64
		χ^2		7.8638		
		P		0.0050		

Table 5. Effect of extra weight on the ratio of upward to downward flights of Hippodamia convergens

Test	Extra weight (μN)	Statistic	Ratio of flights: # upward flights		Ratio of flights: # downward flights	Total # flights
1	33	Observed	3		59	62
		Expected	38		24	72
		χ^2		83.2785		
		P		$<< 0.0001$		
2	17	Observed	13		28	41
		Expected	29		12	73
		χ^2		30.1609		
		P		$<< 0.0001$		
3	9	Observed	41		42	83
		Expected	47		36	89
		χ^2		1.7660		
		P		0.1839		

our tests, they had respective average wing loadings of 5.18 and 4.76 N/m^2.

The minimum and maximum weights of individual Asian ladybird beetles were not correlated to changes in the surface area of the wing ($y = 0.4075 - 2.0666x$; $r^2 = 0.0675$; slope not significantly different from 0 ($F = 0.65$; $df = 1, 9$; $P > 0.05$)); $y = 0.5236 - 2.5275x$; $r^2 = 0.0514$; slope not significantly different from 0 ($F = 0.49$; $df = 1, 9$; $P > 0.05$)), respectively (figure 4). The weights beyond which flights did not occur were similar to the maximum weights reached by Asian ladybird beetles and were not correlated to changes in the surface area of the wings either. The relationship was represented by $y = 0.5555 - 3.3161x$; $r^2 = 0.0844$, (slope not significantly different from 0 ($F = 0.83$; $df = 1, 9$; $P > 0.05$)). Essentially, the wing area of the Asian ladybird beetle seems to remain constant regardless of its body size. The larger beetles have therefore a larger wing loading than the smaller beetles.

The minimum and maximum weights of individual adult convergent ladybird beetles were correlated to the surface area of the hind wings ($y = 0.0657 + 3.4123x$; $r^2 = 0.6057$; slope significantly different from 0 ($F = 18.43$; $df = 1, 12$; $P < 0.0025$)); $y = 0.0808 + 3.8269x$; $r^2 = 0.4179$; slope significantly different from 0 ($F = 8.62$; $df = 1, 12$; $P < 0.025$)), respectively (figure 5).

Flights did not occur beyond a weight between the minimum and maximum body weight of each individual and represented by $y = 0.0686 + 4.0648x$; $r^2 = 0.4183$; slope significantly different from 0 ($F = 8.63$; $df = 1, 12$; $P < 0.025$). The slopes of these three regressions line were not significantly different ($F = 0.08$; $df = 2, 36$; $P > 0.05$) but their elevation was different ($F = 7.86$; $df = 2, 36$; $P < 0.0025$). The regression lines maximum weight and heaviest weight for flight had the same elevation (Newman-Keuls multiple range test, in Zar, 1974) with this beetle, larger and heavier beetles are also characterized by a larger wing area ensuring that the wing loading remained relatively constant regardless of beetle size (figure 5).

For both species, on the average, the heaviest weight reached by any given beetle corresponded to the heaviest weight with upward flight. This suggests fewer weight limitations within these two species contrary to what has been reported for the Colorado beetle.

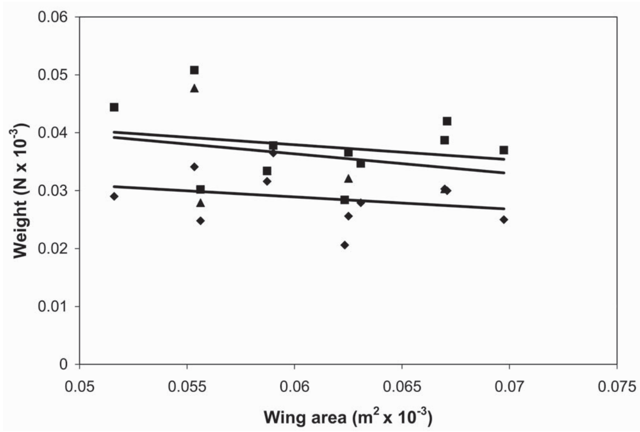

Figure 4. Relationship between the minimum weight of individuals (◆), maximum weight of individuals (■), heaviest weight that resulted in flights (▲), and total wing area for x H. axyridis *beetles.*

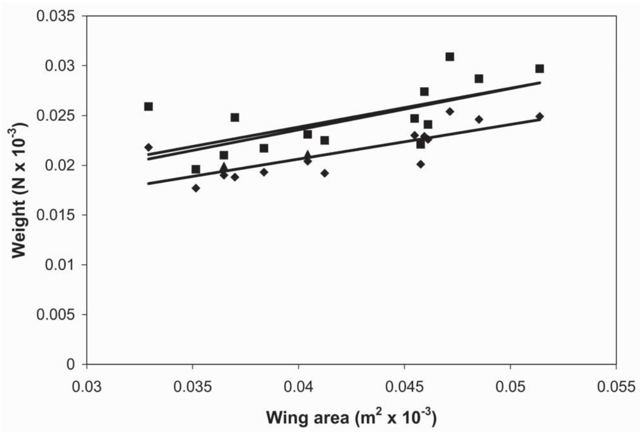

Figure 5. Relationship between the minimum weight of individuals (◆), maximum weight of individuals (■), heaviest weight that resulted in flights (▲), and total wing area for x H. convergens *beetles.*

6. Potential for tags of reduced mass

Obviously, designing a tag with its mass below the threshold at which insect movement is measurably impaired is especially critical and challenging in the case of beneficial ones. Thus, it is not only a detailed knowledge of the payload ability of the insect that is essential but also details of the tag electromagnetic interaction with the insect. Considering the above, we present the following methods to further reduce tag mass in order that a wider range of beneficial insects be tracked with portable harmonic radar:

(1) Use the insect as part of the antenna where dimensions are appropriate. The optimum antenna length without the insect was found to be mm (Colpitts and Boiteau, 2004). Using the insect for half of the antenna would reduce this length to mm.
(2) The fundamental length of the antenna is fixed by the radar operating frequency which in this case is 9.GHz. Smaller antennas could be used at even higher frequencies but the availability of equipment to generate high power pulses of electromagnetic energy is reduced along with the ability of the waves to penetrate objects such as leaves, branches or grass. Doubling the radar frequency would cut the dipole length in half but would also decrease the range of the radar system. Since the radio spectrum is highly regulated one cannot arbitrarily select an operating frequency but must use a frequency band assigned for particular applications. Another radiolocation band exists from 33.GHz to 34.GHz (Canadian Table of Frequency Allocations, 2000).
(3) Use small diameter wire that will provide sufficient stiffness or use a rigid, lightweight material that can have vacuum deposited conductor plating (Riley and Smith, 2002). One could use a glass fibre as the dipole and mounting structure with gold bonding wire of 25 μm diameter to form the inductive loop all gold plated to yield a structure of 125 μm diameter. The total mass of this unit would be only 0.5 mg.
(4) Use the same frequency but decrease the tag length and thus the harmonic-cross-section of the tag. As the tag length decreases the gain of the dipole antenna decreases at both the fundamental and at the harmonic frequency. Additionally the radiation resistance diminishes resulting in a more challenging impedance matching situation. Assuming the same conversion efficiency can be maintained with the shorter dipole then the reduction in harmonic-cross-section resulting from using only one half of the original tag length is as follows. The original design has a one wavelength dipole at the harmonic frequency with gain equal to 2.41 while the same dipole has a gain of 1.64 at the fundamental frequency. Cutting this dipole in half will result in the harmonic gain becoming 1.64 and the fundamental gain now only slightly above unity. Since the harmonic-cross-section is related to the product of these gains it is reduced by over 50% not accounting for any reduction in conversion due to reduced radiation resistance. The net effect on range can be seen from the harmonic radar range equation which indicates a 16% reduction.
(5) A trailing tag no longer requires the stiffness to maintain an upright position but can simply trail along behind the insect. In this case the polarization of the system will need to be horizontal instead of vertical in the previously discussed cases. In situations where the insect is traveling away or towards the radar the tag will become invisible since the view will be of the end of the tag only, not the broadside where performance in maximized. Without the requirement for maintenance of a vertical stance this tag can be formed from 25 μm gold bond wire resulting in 12 mm tag masses of 171 μg, or by using aluminum this can be reduced to under 50 μg.

7. Conclusion

Insect flight performance is affected by many factors related as much to their morphology and their physiology as to their environment. Tags will always have an effect on flight performance. The challenge is to minimize the importance of this factor on the overall flight performance of beneficial insects.

Our investigation of the two beneficial coccinellids, *H. convergens* and *H. axyridis* revealed that these predators can undertake normal flights with extra weights representing 2.65% and 5.28% of their body mass respectively. In the case of *H. convergens* this represents the same proportion of the body mass than the Colorado potato beetle could carry (2.4%) without loss of flight performance but twice that proportion in the case of *H. axyridis*. In contrast to the Colorado potato beetle, these two species of Coccinellidae retain their ability to fly over the whole range of their body weight fluctuations (figures 4, 5). As a result, these Coccinellidae are actually better candidates than the potato beetle for electronic tagging. Tags are less likely to affect their flight performance than they are for the Colorado potato beetle where flight performance is affected by daily weight variations alone. However, in absolute terms, the challenge remains to develop tags weighing less than the ones of 28 uN used for the Colorado potato beetle. Many avenues for research have been suggested in this paper. A tag formed on a strand of glass fibre can have a mass of 0.5 mg, suitable for *H. convergens*. Trailing tags of aluminum at 50 μg mass have weight of under 0.5 μN, this will be suitable for numerous beneficials. The results of our exploratory study with these two predators clearly demonstrate the feasibility of applying the technology developed for the Colorado potato beetle to beneficial insects but at the same time makes us fully aware of its physical limitations.

The portable harmonic radar tracking system is composed of many parts, which at this stage of development, leads to a highly complex system. Associated with the system is a high cost of the system components, its design and maintenance. In the long term, when standards are adopted and more units are in use, both the purchase price, operating and maintenance costs will decline. Disadvantages of the portable system include the requirement of a skilled operator who can follow the insect by interpreting an audio signal from the radar and manually point the antennas at the moving target. The battery powered unit will operate for only 2 h on a charge resulting in a shut down for battery changes which can result in the loss of a target. The complete unit weighs some 20 kg, which soon becomes uncomfortable for the operator, physical training is important. The tags require careful design, which includes how they are mounted on the insect. The finite size and mass of the tag will limit the tagging candidates to those capable of carrying the load. The tags are currently fabricated by the researchers, which require time and skill. The cost is mainly associated with the beam lead diodes which currently are available for $5.00 and $10.00 US each in quantities of 100 or more.

The use of the harmonic technique, whether it is as a direction-finder (e.g., Mascanzoni and Wallin, 1986) or as direction and range finders (e.g., Riley *et al*., 1996), provides access to some of the types of flight that are part of the life-histories of beneficial insects. The portable harmonic radar is ideally designed to study mid-range flights that bring insects to other fields or to overwintering sites within a farm. It provides information on travel time, number of interrupted flights, height of flight near the ground, and the general effect of landscape on flight behaviour (Osborne *et al*., 1999; Capaldi *et al*., 2000; Boiteau and Colpitts, 2001).

The advantages of portable harmonic radar include the ability to follow the insect over a range beyond the maximum range of the radar system by moving the radar as the insect travels. In this case the problem of the insect disappearing is minimized since the radar can be easily relocated to acquire the signal when the target has passed behind an obstacle or climbed above the beam of a fixed position radar. It is not, however, suitable to gather precise information as flight gains significant height; vertical-looking radars are required for that purpose (e.g., Chapman *et al*., 2003). Since the portable radar is small enough to be carried, it is also easily transported in a van, and is self-contained which facilitates rapid startup. To overcome the issue of the radar base motion a GPS receiver with differential correction is employed along with an electronic compass to yield the antenna pointing angle. This, combined with the range information to the target, allows the mapping of the insect movement over a long period of time and long distance. The system can operate both day and night; and can be utilized to generate a continuous tracking of an insect that is rapidly moving or to search for and periodically locate a more slowly moving target. Since the tags are passive components they will last for several years, depending upon their durability relative to the insect activity and their resistance to corrosion.

References

BALANIS, C. A., 1982. *Antenna Theory Analysis and Design* (New York, USA: Harper & Row Publishers).

BOITEAU, G. and COLPITTS, B., 2001. Electronic tags for the tracking of insects in flight: Effect of weight on flight performance of adult Colorado potato beetles. *Entomologia Experimentalis et Applicata*, **100,** 187 – 193.

CANADIAN TABLE OF FREQUENCY ALLOCATIONS, 2000. Spectrum Management and Telecommunications Policy, Industry Canada: Ottawa.

CAPALDI, E. A., SMITH, A. D., OSBORNE, J. L., FAHRBACH, S. E., FARRIS, S. M., REYNOLDS, D. R., EDWARDS, A. S., MARTIN, A., ROBINSON, G. E., POPPY, G. M. and RILEY, J. R., 2000. Ontogeny of orientation flight in the honeybee revealed by harmonic radar. *Nature*, **403,** 537 – 540.

CHAPMAN, J. W., REYNOLDS, D. R. and SMITH, A. D., 2003. Vertical-looking radar: A new tool for monitoring high-altitude insect migration. *BioScience*, **53,** 503 – 511.

CODERRE, D., LUCAS, É. and GAGNÉ, I., 1995. The occurrence of *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae) in Canada. *The Canadian Entomologist*, **127,** 609 – 611.

COLPITTS, B. and BOITEAU, G., 2004. Harmonic radar transceiver design: miniature tags for insect tracking, IEEE Transactions on Antennas and Propagation, in press.

COLPITTS, B., LUKE, D. and BOITEAU, G., 2000. Harmonic radar for insect flight pattern tracking. Proceedings of the 2000 Institute of Electrical and Electronic Engineers, Canadian Conference on Electrical and Computer Engineering, pp. 302 – 306.

DUDLEY, R., 2000. *The Biomechanics of Insect Flight* (New York, USA: Princeton University Press).

EKBOM, B., IRWIN, M. E. and ROBERT, Y., 2000. *Interchanges of Insects between Agricultural and Surrounding Landscapes* (Boston, MA: Kluwer Academic Publishers).

GILES, D. P. and JUTSUM, A. R., 1989. Problems in the control of flying insect pests. In G. J. Goldsworthy and C. H. Wheeler (eds) *Insect Flight* (Florida: CRC Press), pp. 321 – 336.

GODFRAY, H. C. J., 1994. *Parasitoids: Behavioral and Evolutionary Ecology*. (New Jersey, USA: Princeton University Press).

HASSELL, M. P., 2000. Host-parasitoid population dynamics. *Journal of Animal Ecology*, **69,** 543 – 566.

HODEK, I. and HONEK, A., 1996. *Ecology of Coccinellidae.* (Boston, MA: Kluwer Academic Publishers).

IVES, A. R. and SETTLE, W. H., 1997. Metapopulation dynamics and pest control in agricultural systems. *American Naturalist*, **149,** 220 – 246.

JACQUES, R. L., Jr., 1988. *The Potato Beetles, Flora and Fauna Handbook No. 3* (New York, USA: E. J. Brill).

MACQUARRIE, C. J. K., 2002. Effect of food quality on Colorado potato beetle (*Leptinotarsa decemlineata* Say) flight. MSc thesis (New Brunswick, Canada: The University of New Brunswick).

MASCANZONI, D. and WALLIN, H., 1986. The harmonic radar: A new method of tracing insects in the field. *Ecological Entomology*, **11,** 387 – 390.

MASON, P. G. and HUBER, J. T., 2002. *Biological Control Programmes in Canada, 1981 – 2000* (New York, USA: CABI Publishing).

MICROSOFT CORPORATION,1997. Microsoft Excel 97. Microsoft Corporation, Redmond, Washington.

OSBORNE, J. L., LOXDALE, H. D. and WOIWOD, I. P., 2002. Monitoring insect dispersal: methods and approaches. In J. M. Bullock, R. E. Kenward and R. S. Hails (eds) *Dispersal Ecology* (Oxford, UK: Blackwell Publishing), pp. 24 – 49.

OSBORNE, J. L., CLARK, S. J., MORRIS, R. J., WILLIAMS, I. H., RILEY, J. R., SMITH, A. D., REYNOLDS, D. R. and EDWARDS, A. S., 1999. A landscape-scale study of bumblebee foraging range and constancy using harmonic radar. *Journal of Applied Ecology*, **36,** 519 – 533.

PEDGLEY, D. E., 1993. Managing migratory insect pests – a review. *International Journal of Pest Management*, **39,** 3 – 12.

PRICE, P. W., 1997. *Insect Ecology* (New York: John Wiley & Sons).

RILEY, J. R. and SMITH, A. D., 2002. Design considerations for a harmonic radar to investigate the flight of insects at low altitude. *Computers and Electronics in Agriculture*, **35,** 151 – 169.

RILEY, J. R., SMITH, A. D., REYNOLDS, D. R., EDWARDS, A. S., OSBORNE, J. L., WILLIAMS, I. H., CARRECK, N. L. and POPPY, G. M., 1996. Tracking bees with harmonic radar. *Nature*, **379,** 29 – 30.

ROITBERG, B. D., MONDOR, E. B. and TYERMAN, J. G. A., 2003. Pouncing spider, flying mosquito: Blood acquisition increases predation risk in mosquitos. *Behavioral Ecology*, **14,** 142 – 146.

ROLAND, J. G., MCKINNON, G., BACKHOUSE, C. and TAYLOR, P. D., 1996. Even smaller radar tags on insects. *Nature*, **381,** 120.

SAS INSTITUTE INC,1990. SAS/Stat User's Guide, Version 6. 4th ed. SAS Institute Inc., Cary, NC.

SCHMID-HEEMPEL, P., 1986. Do honeybees get tired? The effect of load weight on patch departure. *Animal Behavior*, **34,** 1243 – 1250.

WEIS-FOGH, T., 1973. Quick estimates of flight fitness in hovering animals including novel mechanisms for lift production. *Journal of Experimental Biology*, **59,** 169 – 230.

WEISZ, R., FLEISCHER, S. and SMILOWITZ, Z., 1996. Site-specific integrated pest management for high-value crops: Impact on potato pest management. *Journal Economic Entomology*, **89,** 501 – 509.

ZAR, J. H., 1974. *Biostatistical Analysis* (New Jersey, USA: Prentice-Hall, Inc.).