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Design considerations for an harmonic radar to investigate the flight of insects at low altitude

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Abstract

Most of our current knowledge about the behaviour of insects flying at high altitude has been derived directly from observations made with conventional entomological radars. Until recently it was not possible to apply this very powerful technique to study the behaviour of insects flying close to the ground because the strong radar echoes, reflected from ground features and from vegetation ('clutter'), almost always mask the very weak signals returned from insects. This constraint has been overcome, at least for insects weighing more than ≈ 50 mg, by the development of an harmonic radar, and of transponder tags small enough to be carried by these insects without impeding their flight performance. Because the transponders have to be carried by insects in flight, extreme miniaturisation was obviously essential and it was achieved by using a passive, frequency-doubling technique, so that no on-board battery was needed. Transponders with all-up weights of between 1 and 12 mg were produced, the weights varying according to the degree of mechanical robustness required. The frequency-doubled signals from the transponder are selectively detected by the radar so that the tagged insects can be located even in the presence of very strong clutter. The system has three major advantages over conventional visual and video methods of observing low-flying insects. Firstly, and most importantly, its range of operation (up to 900 m) allows surveillance and flight tracking over hundreds of thousands of m^2, i.e. four orders of magnitude greater than is possible with conventional methods. Secondly, it provides dynamic and geometrically correct records of the insects' horizontal flight paths and thirdly, it works equally well by day and night. The technique has introduced a new era in the study of insect flight at low altitude. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Harmonic radar; Flight; Bees

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1. Introduction

Because flying insects tend to be small and fast moving, they are very difficult to follow by eye or with video equipment over ranges of more than a few metres (Riley, 1993; Reynolds and Riley, 2002). As a result, prior to the late 1960s, little was known about insect flight behaviour over medium and longer scales. The introduction of radar to entomology at that time (Schaefer, 1969, 1976, 1979; Riley, 1974, 1975, 1980) dramatically changed this situation, because it permitted direct observation of airborne insects at ranges of up to 2 km, at least for high-flying migrants. Over the past 30 years, the technique has led to a spectacular increase in our knowledge of insect flight behaviour, mainly as a result of intensive short term field studies (Drake and Farrow, 1988; Riley, 1989; Reynolds and Riley, 1997). More recently, entomological radars have been configured to allow inexpensive long-term monitoring of the abundance and synoptic movement of migrant insects (Smith et al., 1993, 2000; Chapman et al., 2002; Drake et al., 2002a,b). Although radar had proved to be a uniquely powerful tool for investigating migratory flight at altitude, its utility for observing low flying insects was extremely limited. This is because strong radar echoes reflected from ground features and from vegetation ('clutter') almost always mask the very weak signals returned from insects. Conventional radar observations of low flying insects are thus possible only over very flat and featureless terrain (Loper and Wolf, 1986).

A very common radar technique for overcoming the ground clutter problem is to fit the target of interest with a 'transponder'. When this device detects a radar transmission, it replies by immediately emitting a pulse on another frequency. The radar carries a narrow-band receiver selectively tuned to this shifted frequency and so detects the target while remaining insensitive to obscuring clutter reflections from ground features. The reply pulse can also carry a code identifying the target and even giving its altitude (Skolnik, 1990). Commercial radar transponders and even specially developed devices for wild-life tracking (e.g. French and Priede, 1992), are far too massive to be used on insects, so we considered the possibility of developing a passive, lightweight transponder of a type originally suggested by Vogler et al. (1967). This device, which was later investigated by Shefer et al. (1974), for automobile collision avoidance applications, channelled incoming radar signals to a diode which, because of its non-linear electrical conductivity, generated a current that contained harmonic frequencies of the original signal. These currents were then used to radiate signals at multiples of the original radar frequency, and tuning the radar receiver to a selected harmonic achieved clutter rejection in the same manner as with conventional transponders. The great advantage of the harmonic concept for insect tracking is that the power to operate the device comes from the radar transmissions. The transponder thus avoids the usual limiting requirement of an on-board battery and so extreme miniaturisation becomes feasible. An attempt was made at the University of North Dakota in the late 1970s to exploit this possibility by building a harmonic radar specifically to track the flies of the screw worm (*Cochliomyia hominivorax*), but the initiative unfortunately failed to produce a working system (Klempel, 1977; Shiao, 1978; Barbie, 1978; Boyd, 1979).

When our work on this topic began in 1992, the harmonic transponder technique was already well established as a means of locating skiers buried under snow. In this application, the principle advantage of battery-free operation was not that the devices could be made very small (they were not) but because, needing no battery, they remained functional for the lifetime of the ski garments into which they were sewn. The associated locating 'radars' operated in the 30 cm band, and strictly speaking, were not radars at all (they did not measure target range), but were hand-held direction finders which allowed location of transponders from ranges of a few tens of metres. Equipment of this type first found application in entomology when Mascanzoni and Wallin (1986) ingeniously used it to trace the movement of burrowing carabid beetles that had been 'tagged' with diodes fitted with trailing thin wire antennas. This method worked very well for locating stationary or slow moving pedestrian targets from close range (Wallin and Ekbom, 1988; Hockmann et al., 1989; Wallin, 1991; Kennedy, 1994) and for identifying settled butterflies (Roland et al., 1996), but it was of very limited use for tracking flying insects. Our approach was therefore to attempt to build a true harmonic radar, able to record the flight trajectories of low-flying insects over ranges of hundreds of metres. This paper describes the results.

2. Factors influencing the system design

2.1. Choice of wavelength

Two conflicting factors influence the selection of wavelength. A short wavelength is desirable because it means that a narrower radar beam—and therefore more precise target location—can be achieved for a given size of transmitting antenna. Importantly, a short wavelength also reduces the length of the antenna required on the transponder. On the other hand, longer wavelengths give improved penetration of vegetation (Skolnik, 1990), which could be very important in some applications. In the event, our selection was guided primarily by the practical consideration that our existing entomological radars used rugged, inexpensive 3.2 cm marine transmitters that were eminently suitable for field use. With a 1.52 m diameter transmitting antenna also from our existing radar, this wavelength produced a circular beam with half-power width of only 1.4° and a highly efficient half-wave dipole antenna on a transponder would be only 16 mm long. This beam-width and antenna size were considered to be satisfactory and although the rather high degree of absorption at this wavelength by vegetation would preclude use of the radar in wooded areas, over clear terrain it could be expected to yield many exciting and novel results.

2.2. Choice of radar configuration

We decided that the task of recording flight trajectories of low flying insects in the field could best be achieved by building an azimuthally scanning (rather than point-and-track) harmonic radar. This was because such a scanning system automatically registers on its display any targets fitted with transponders that appear within range and within line of sight of the radar, and it does not need to be 'locked on' to selected targets that have been pre-located by some other means. Tagged insects in flight are thus automatically picked up and if they pass temporarily behind vegetation or ground features, only those segments of their flight paths that lie behind these obstructions are lost. Fortunately, a scanning system was also the best choice from a practical point of view because it could be based on the mechanical components used in the scanning antenna of our conventional entomological radars. By contrast, building a tracking system from scratch would have been extremely expensive.

2.3. Choice of radar transmission type

Conventional radars of potential interest to entomologists occur in two main types that are classified by the temporal characteristics of their transmissions. As the name suggests, frequency modulated continuous wave (FMCW) radars emit a steady stream of electromagnetic radiation. They achieve measurement of target range by modulating the transmission frequency and comparing the frequency of outgoing and returning signals (Skolnik, 1990). This process avoids the need for high peak transmitted power, allows the detection of very small targets and also offers high precision in the measurement of range, but these radars are built for specialist applications only and consequently, are costly. By contrast, pulse radars, which emit short, discrete bursts of high power radiation and estimate target range from the time elapsing between transmission and reception of a returned signal, have found wide application in the marine market. They are consequently mass produced, rugged and inexpensive and as a result conventional radar entomology equipment has been based almost exclusively on marine radar transceivers. A marine pulse transmitter was therefore the obvious practical choice for our planned harmonic radar, but happily once again the practical choice was also the best theoretical option. This is because the efficiency of harmonic conversion in a transponder normally increases with increasing incident power (Shefer et al., 1974), so pulse transmissions with high peak power are intrinsically better for a harmonic radar, than FMCW techniques.

3. Theoretical estimation of maximum detection range

Given that the choice of radar type and wavelength would be decided by the considerations described above, an early step in the development program was to make a theoretical assessment of the maximum range of detection that we could expect to achieve. To do this, we note that the power, P_a, available for collection by a transponder positioned on the axis of the radar beam is found by multiplying A_{df}, the effective aperture presented by the half-wave dipole, by the power density of the radar transmitted signal, P_d at the transponder position. Thus, as:

$$P_d = P_t \times G_f/(4\pi \times R^2 \times L_{gf})\ \mathrm{Wm}^{-2}$$

where G_f is the gain of the radar transmitting antenna, L_{gf} is the transmission loss in the waveguide from this antenna to the transmitter, P_t is the transmitter output power (W) and R is the distance from the radar to the transponder (m),

$$P_a = A_{df} \times P_t \times G_f/(4\pi \times R^2 \times L_{gf})\ \mathrm{W} \tag{1}$$

We define the overall efficiency of power conversion by the transponder to the second harmonic to be E_{dh}, such that the total harmonic power radiated by the antenna will be $E_{dh} \times P_a$. Because the antenna is a vertical, full-wave dipole with broadside-on gain G_{dh}, at the harmonic frequency, the power density, P_{2d}, of the radiated harmonic signal received back at the radar will be:

$$P_{2d} = E_{dh} \times P_a \times G_{dh}/(4\pi \times R^2)\ \mathrm{Wm}^{-2}$$

Thus, the second harmonic power, P_c, captured by the radar's receiving antenna is:

$$P_c = P_{2d} \times A_2 \times E_{a2}\ \mathrm{W} \tag{2}$$

where A_2 is the aperture of the harmonic receiving antenna and E_{a2} is its efficiency.

If the attenuation in the waveguide run between the receiving antenna and receiver is L_{gh}, the harmonic power P_r delivered to the receiver input is:

$$P_r = P_{2d} \times A_2 \times E_{a2}/L_{gh}\ \mathrm{W} \tag{3}$$

Combining Eqs. (1)–(3) gives:

$$P_r = E_{dh} \times A_2 \times E_{a2} \times G_f \times P_t \times G_{dh} \times A_{df}/\{(4\pi R^2)^2 \times L_{gh} \times L_{gf}\}\ \mathrm{W} \tag{4}$$

If the transponder is to be detected, P_r must exceed the noise power at the receiver by a 'visibility factor', V_f, chosen to produce an acceptable false alarm probability (Skolnik, 1990).

Now the noise power at the receiver input is N_p, where:

$$N_p = k \times T \times B \times 10^6 \times N_f\ \mathrm{W}$$

where k is Boltzmann's constant, T the absolute temperature, B the receiver bandwidth in MHz and N_f the noise figure of the receiver amplifier.

So the minimum received power required for detection, P_m, is:

$$P_m = k \times T \times B \times 10^6 \times N_f \times V_f\ \mathrm{W} \tag{5}$$

Combining Eq. (4) and Eq. (5), with $P_r = P_m$, gives the required expression for maximum range, R_m.

$$R_m = \{(E_{dh} \times A_2 \times E_{a2} \times G_f \times P_t \times G_{dh} \times A_{df})/(L_{gh} \times L_{gf} \times (4\pi)^2 \times P_m)\}^{0.25}\ \mathrm{m}$$

Using the values shown in Table 1, this reduces to:

$$R_m = \{E_{dh}\}^{0.25} \times 3001\ \mathrm{m} \tag{6}$$

We did not know at the outset what value to attribute to E_{dh}, but made the assumption that an overall conversion efficiency of between 0.1 and 1% should be achievable and putting these values into Eq. (6), predicted a maximum detection range of between 534 and 949 m. Although this is very small by normal radar standards, it very much greater than the ranges at which insects can be followed by eye and this encouraged us to proceed with the radar development. Field experiments later showed that R_m was actually ≈ 900 m, suggesting that our transponders had an E_{dh} of $\approx 0.8\%$, at least at the fundamental frequency power density prevailing at this range (30 Wm^{-2}). This figure for E_{dh} was subsequently confirmed by laboratory experiments (Section 5.5).

4. Details of system design and construction

4.1. The radar

A Racal-Decca 90 series marine radar transceiver was mounted directly behind a 1.52 m diameter parabolic reflector and both were supported on a platform that rotated in azimuth at 20 rpm. The platform could be tilted while revolving so that the transmitted beam could be elevated within the range $-1°$ to $+3°$ relative to the horizontal and the whole assembly was supported on a stout 0.6 m high steel tripod. The transceiver communicated with the reflector via waveguide 16 and a high-power, low-pass filter (Filtronics Components Ltd., Type WL019-F2). Without this essential component, harmonics generated in the transmitting magnetron would have contaminated the outgoing signal and their reflections would have generated unacceptable ground clutter. The reflector was fed by a matched rectangular horn, and produced an approximately circular beam of 1.4° half-power width, with vertical linear polarisation. Although the system normally received second

Table 1

P_t	25 kW
G_f	14,454 (41.6 dB)
L_f	1.17 (0.7 dB)
A_{df}	1.33×10^{-4} m^2*
G_{dh}	2.31 (3.64 dB)**
A_2	0.46 m^2
E_{a2}	0.65
L_{gh}	1.58 (2 dB)
V_f	10 (10 dB)
N_f	2.4 (3.8 dB)
B	20 MHz
T	290 K
k	1.38×10^{-23} WHz^{-1} K^{-1}

* The broadside-on gain, G_{df} of a half-wave dipole is 2.14 dB (Hall, 1991), and for any antenna, the gain, G, is: $G = A_e \times 4p/\lambda^2$, where A_e is the effective aperture presented by the antenna and λ is the wavelength. Thus: $A_{df} = (0.032^2 \times 10^{0.214})/4p = 1.33 \times 10^{-4}$ m^2.

** The broadside-on gain of a full-wave dipole, (G_{dh}) is 3.64 dB (Tai, 1952).

harmonic signals via a separate antenna, we retained the 3.2 cm wavelength marine duplexer and receiver, so that conventional, single-frequency radar operation via the transmitting antenna remained available.

Second harmonic signals returned by the transponders were captured with a 0.76 m diameter parabolic reflector and matched rectangular horn, mounted immediately above the transmitting antenna (Fig. 1). To ensure optimal utilisation of the transmitted energy, the transmitted and received beams should have the same widths and this was achieved by the 2:1 ratio in the diameters of the two reflectors. Both antennas were carefully aligned on test signal sources at a distance of ≈ 600 m, so that the transmission and reception beams would be closely collinear over most of the planned working range (100–900 m). The captured harmonic signals were transferred via a short section of waveguide 19 to a low-noise 18 GHz amplifier (Microwave International Ltd., Quinstar QLN-19102720-XX) which was mounted just behind the bottom edge of the reflector. The amplifier output was connected via semi-rigid co-axial cable to an image rejection mixer, fitted in front of the transmitter. This combination yielded an overall signal-to-noise ratio of 3.8 dB at 18.8 GHz. The signal and power supply lines from the rotating platform were passed via slip rings to the radar control and data capture system, which was housed in an adjacent, extended-roof Landrover.

4.2. Signal capture

Our initial system measurements were carried out using a conventional radar plan position indicator (PPI) display, which showed targets as bright spots at the appropriate range and azimuth round the radar, once every 20 s. A permanent record was obtained by filming the display with a 16 mm, time lapse ciné camera, taking one frame per revolution of the antenna (Riley et al., 1996). This method of operation allowed us to establish the capabilities of our system, but it had three serious operational limitations.

- Frame by frame extraction of target co-ordinates from the radar film required a special projector and was very tedious and time consuming.
- Both the PPI display and the camera were obsolete and becoming unreliable.
- Filming the PPI display meant that the radar cabin had to be kept dark (door closed) and this in turn resulted in the need for air-conditioning.

To overcome these problems, we designed and built an interface to connect the radar receiver's rectified i.f. output (the radar 'video' signal) to a standard desktop PC. The interface allows the computer hard disc to record a pre-processed version of the radar video data and the computer monitor to function as a PPI display. Since the harmonic radar signals are essentially clutter-free, most of the display is 'white space' and the recording requirement is limited to acquisition of the time, range and azimuth (t, R, θ) of the very limited number radar returns exceeding a pre-set amplitude threshold.

An advantage of using the computer monitor as the radar screen is that it constitutes a highly flexible, programmable background on which to display insect flight trajectories in real time. For example, it can be used to mark the positions of

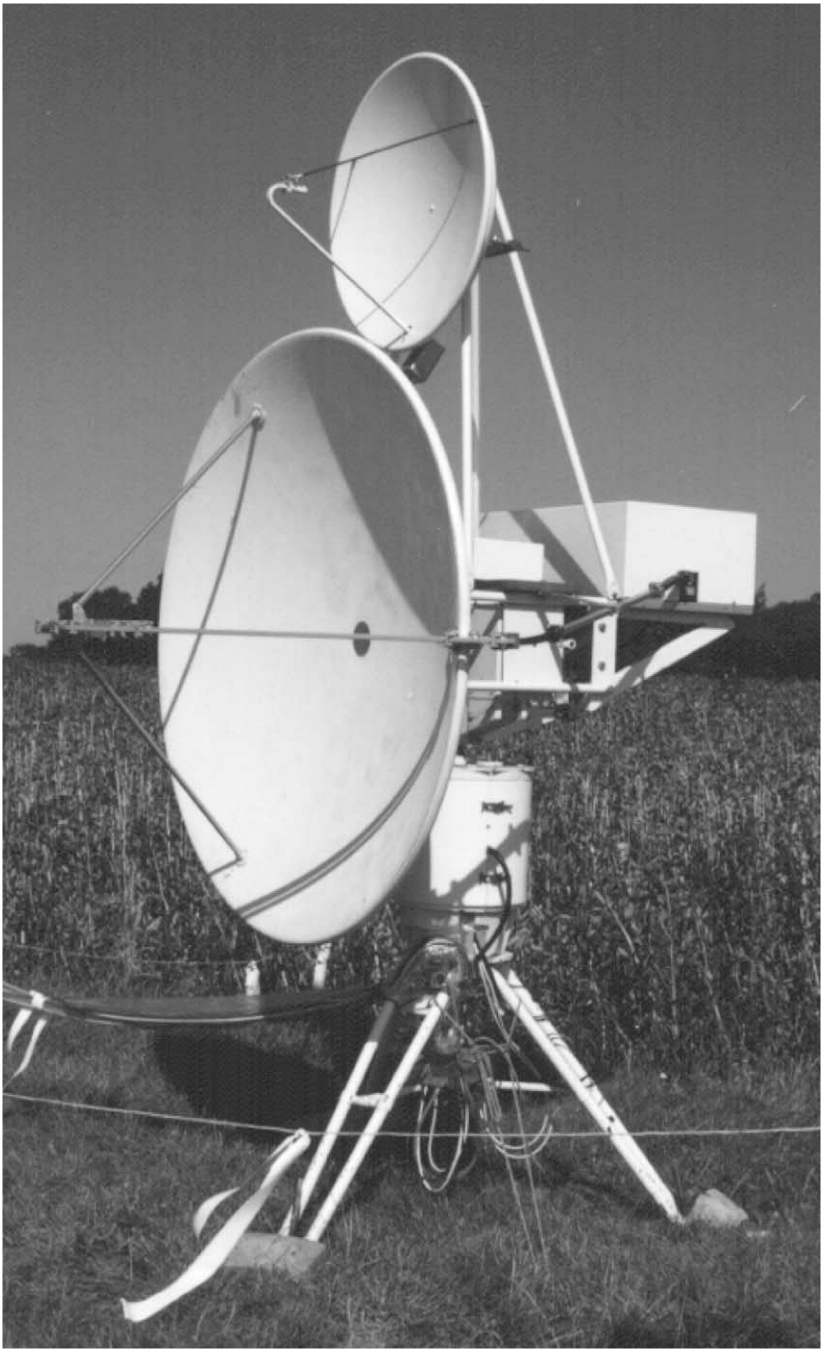

Fig. 1. The harmonic radar. The top edge of the upper (harmonic) dish is ≈ 2.5 m above ground level.

individual fixed objects of interest, such as nests, forage sources and crop boundaries. Features can be shown in different colours to aid clarity and the display can be restricted to a selected area and 'zoomed' to expand features of particular interest. The radar co-ordinates of any target can be conveniently acquired and displayed by using the computer mouse to place a cursor over the target.

The selection of different display options does not affect the recorded data, which is streamed to disc, unmodified. This recorded data can be subsequently re-displayed and each radar 'frame' examined in detail, allowing the creation of comma separated variable (CSV) files containing the (t, R, θ) co-ordinates of the position fixes forming each selected insect track (Section 4.3.3 below).

4.2.1. Hardware description

An-off-the-shelf, parallel, digital input/output board was used to connect the PC to the radar interface hardware. A number of very similar products are available, many based on CMOS versions of the Intel 8255 8 bit parallel peripheral interface and we opted for PC-DIO48 from Brain Boxes containing two CMOS 8255 chips. This board provides six 8-bit ports that are software programmable for either input or output and we configured five as inputs and one as an output. Four of the inputs are used for reading data, one for reading control signals (interface handshaking) and the output sends control signals (interface handshaking, clock select and multiplexing).

The radar interface was built in a separate box and has three primary functions. Firstly, it triggers the radar transmitter; secondly, it samples the radar video signal during a short period (< 9 μS) after each radar transmission; and thirdly, it measures the azimuth of the rotating antenna.

4.2.2. Triggering

A high frequency master oscillator (40 MHz clock) times all the functions within the radar interface and the radar trigger signal of $\approx$ 1.5 kHz is derived from this by a combination of binary counters and logic gates. The signal is passed to the transmitter via an open-collector buffer and a 50^{Ω} coaxial cable. The transmitter modulator control circuitry required some small modifications to allow operation under external trigger control.

4.2.3. Signal sampling

Since we are interested in the temporal position of peaks in the incoming video signal and not in their amplitude, the radar video is first passed through a (manually adjustable) threshold detector to convert any significant peaks into standard, 5 V logic levels. Following a pre-set time delay (typically 0.5 μs) after each outgoing trigger pulse, the resulting serial logic signal is clocked (sampled) at high speed (up to 40 MHz depending on the range resolution required) into a 112 bit, serial in, parallel out, shift register. Each 112 bit (14 byte) data set thus contains a record of any targets detected after the pre-set time delay that lie within the interval set by the product of clock period and register length. Target ranges are therefore encoded by their positions in the register and because a time delay of 0.1 μs corresponds to a target range of 15 m, sampling at the maximum rate of 40 MHz produces range measurement increments of 3.75 m over a span of $112 \times 3.75 = 420$ m. Optional lower sampling rates yield larger range spans, but with correspondingly larger increments. Target azimuth is indicated by a 2 byte number derived from an output from the antenna (see Section 4.2.4) and the total of 16 bytes constitute a standard data segment for computer processing and recording. As only four input ports are available to read the data, the segment is read four bytes at a time (bank switched or time division multiplexed).

To start sampling, the computer initialises the interface by pulsing the data-read handshake line high, arming the hardware to collect a sample after the next transmitter trigger. After each radar transmission, a data segment is collected by the interface, which then sets the data-ready handshake line high. The PC is polling this handshake line and when it detects high, it reads the data and then pulses the data-read handshake line high again. In this manner, the radar data is collected and continuously transferred to the PC.

4.2.4. Azimuth capture

The antenna motor is fitted with an optical switch which produces 2400 pulses per revolution of the radar antenna, each pulse corresponding to a rotational increment of 0.15°. Because the radar half-power beam-width is 1.4°, 600 increments of 0.6° provide adequate angular resolution, so the antenna angle synchronisation signal is divided by four before being transferred to the computer. To create the azimuth signal, the pulses are fed into two 8 bit binary counters which are reset to zero once per rotation at some pre-selected geographical direction (e.g. north), by a switch mounted on the antenna. Division by four is effected by discarding the lowest two bits when the counter output is converted into the two azimuth bytes that are subsequently fed to the computer.

4.3. Computer processing

The computer reads a data segment from the radar interface after each transmission pulse and first determines if any of the 112 bits conveyed in the 14 bytes from the shift register indicate the presence of a target. If a target is registered, a range is calculated from the relevant bit's position in the shift register, the sampling clock period and from the pre-set delay. The target azimuth bin is read directly from the 2 bytes containing the current angle counter value.

4.3.1. Noise reduction

Since the antenna rotation period is 3 s and the radar pulse repetition frequency is 1500 Hz, there are up to $1500 \times 3/600$ (= 7–8) transmitter pulses in each azimuth bin. The data segments resulting from these transmitter pulses are combined prior to recording and display in the following manner. A logical AND operator is applied to the 112 bit pattern of each segment and to the pattern of the previous one, so that a target is registered only if signals occur at the same range in two consecutive data segments. The resulting samples are then combined by a logical (inclusive) OR operator to produce a single (range) data set for each azimuth bin, which is then recorded and displayed on the monitor. This process reduces false alarm 'noise' on the radar display by ensuring that only above-threshold signal peaks that occur at the same delay after at least two consecutive transmissions are recognised as targets.

4.3.2. Target representation

The nominal pulse length of the radar is 10^{-7} s, so the width of the video signal peaks are of this order and sampling at 40 MHz means that, typically, each target will set 4 consecutive bits in the register. However, if a target is at short range and close to the beam axis, the amplitude of the video peak will be high, and its width at the threshold level may exceed 10^{-7} s and so set more than 4 consecutive bits. Conversely, low amplitude peaks will set fewer bits. A rather similar effect occurs in azimuth representation because as the 1.4° wide beam sweeps past a transponder, the video peaks will often be above threshold in more than one of the 0.6° azimuth bins. The number of bins thus occupied by a target will depend in part on its vertical offset from the beam axis—the greater the offset, the narrower the effective horizontal width of the beam and the smaller the number of occupied bins. The range and azimuth effects combine to produce a close cluster of r, θ fixes for each target for each revolution of the radar and these are individually plotted on the PPI screen. This cluster is centred on the target's azimuth, but the target range is given by the fix nearest to the screen centre because this represents the time elapsing between the start of the outgoing radar pulse and the arrival of the front of the (harmonic) echo. Targets above or below the beam axis, or at longer ranges, produce lower video peaks and occupy fewer bins in range and azimuth, and so produce fewer fixes per cluster.

4.3.3. Flight trajectory extraction

Selection of the fix in each cluster that best represents a target's position would seem at first sight to be a straightforward programming task. However, in practice, insects often fly above or below the horizontal plane defined by the rotating beam's axis and when this happens, the video peaks they generate may become weak and produce no fixes at all, or just single fixes. The first case produces gaps in a flight trajectory and the second mimics the random 'noise' fixes that occasionally occur in spite of the procedures outlined in Section 4.3.1 above. These effects are exacerbated if an insect lands or flies below radar cover for an extended period and its last known position is subsequently overflown by another tagged insect. In these cases, reliable selection of sequential position fixes can be quite a subtle process and for this reason we have not yet attempted to automate trajectory extraction. Instead, we use a cursor and mouse on frame-by-frame replays of the recorded fixes, and select and save those fixes that appear to best define the flight trajectory of the insect of interest. Each trajectory is then stored in a separate file.

5. The transponders

5.1. Properties required

The paramount requirement of a transponder to be fitted to an insect is that it be extremely small and light—ideally no more than a few percent of the insect body mass and for medium sized insects, e.g. bees, this sets a maximum weight of a few milligrams. The device must nevertheless be mechanically robust enough to survive both fitting to an insect in the field and the abrasion and bending that might be caused by grooming and foraging activities. Secondly, it must not obstruct wing beating action or impede landing and take-off. Thirdly, its aerodynamic drag at normal flying speed should be a small fraction of the parasitic drag on the insect's body and not cause any significant change in flight attitude. An additional and important operational requirement is that its antenna should provide omni-directional coverage in azimuth, so that signals are captured and returned with equal efficiency, whatever the insect's heading with respect to the radar position. Finally, the transponder is required to convert fundamental frequency power to radiated second harmonic power at sufficiently high conversion efficiency to achieve a useful working range.

5.2. The antenna

The requirement for extremely low weight and drag dictated that the antenna for the transponder should be made of very fine wire, but the need for omni-directionality in azimuth meant that this wire also had to be maintained near to the vertical. This is because the directivity (gain) of such an antenna is isotropic in planes perpendicular to the wire axis, but not in the plane containing the axis (Hall, 1991). The wire therefore had to be stiff enough to remain upright when attached to an insect and springy enough to resist permanent deformation during handling and fitting in the field.

The primary function of the antenna is to capture the maximum amount of power from the radar transmissions and to deliver as much of it as possible to the diode. Longer antennas capture more power than shorter ones, but conversely, the requirement that the device be fitted to an insect meant, of course, that length had to be minimised. As a compromise, we opted for a centre-fed, half-wavelength resonant dipole, 16 mm long. This configuration gives a broad, single-lobe directivity pattern, with maximum gain perpendicular to the axis of the wire (Hall, 1991) and a resistive impedance at the centre terminals of 55–70 Ω at the wavelength transmitted by the radar (32 mm). Both of these factors were desirable for our application. Firstly, the broad lobe would minimise performance degradation caused by small departures of the antenna from the vertical (as would be produced by changes in insect pitch and roll angles). Secondly, the impedance was not dissimilar to that expected for the diodes we had selected as non-linear elements (see Section 5.3) and so should ensure efficient transfer of incoming power from antenna to diode.

The secondary function of the antenna is to collect from the diode as much power as possible at the second harmonic frequency and to radiate this predominantly in a horizontal direction and uniformly in azimuth. Ideally, one would use a separate antenna, optimised for these functions, but the severe constraints on size and weight in our application meant that the reception antenna had also to function for the harmonic transmissions. At the harmonic frequency, the reception antenna constitutes a full wavelength dipole and although this has a rather similar directivity pattern to a half-wave dipole, the impedance at the terminals is very high ($Z \sim 500 - j500\ \Omega$) (Hall, 1991). This meant that the antenna would reflect harmonic signals back into the diode, so outward transfer of harmonic power would tend to be inefficient. The conventional solution to this mismatch problem (use of a transmission line transformer) was impractical because of the size and weight constraints and so this source of inefficiency had to be accepted, at least in the short term. As it turned out, an overall conversion efficiency adequate for our requirements was achieved (see Section 5.5) without the use of matching elements.

5.3. Diode selection and impedance

A low barrier Schottky diode was selected as the non-linear element for the transponder because the intrinsically low junction capacitance reduces signal loss at high frequencies and the low barrier allows the diode to be turned on by very low induced voltages. Our transponder was intended to operate at 9.4 and 18.8 GHz (32 and 16 mm wavelength) so the diode had to function efficiently as these frequencies. The Hewlett-Packard type 5082–2774 detector diode appeared to meet this requirement and at zero bias had high voltage sensitivity (10 mV W^{-1}) at 10 GHz. We were able use the manufacturer's equivalent circuit to calculate the diode's input impedance for a given bias current, but in our application, the bias current depends on the power collected by the antenna which depends, in turn, on the distance of the transponder from the radar. As result, the calculation could be used only as a rough guide to the diode's impedance in a field situation, but this figure ($\sim 40\ \Omega$) nevertheless gave us some confidence that the device was a reasonable match to a half-wave dipole antenna at 9.4 GHz. On the other hand, use of the equivalent circuit indicated that at 18.8 GHz the diode impedance was $\sim 31\ \Omega$. To the extent that this figure was correct, the device would be badly matched to the antenna which would present the much higher impedance of a full-wave dipole at this frequency (see Section 5.2) and transfer of harmonic power to the antenna would be correspondingly inefficient. However, the diode model takes no account of the intrinsic non-linearity of the diode junction capacitance and resistance, so conclusions drawn from it about impedance are necessarily rather qualitative. We were discouraged from undertaking a more comprehensive non-linear analysis by the very limited success of an earlier attempt to model a diode attached to a dipole antenna (Kanda, 1980) and so concentrated instead on optimising the transponder performance empirically, by trimming the antenna lengths.

5.4. Fabrication methods

Our first model of transponder used diodes encapsulated in a robust plastic-on-ceramic package (Hewlett-Packard style C2) and fitted with gold-plated kovar leads. The initial step in fabrication was to solder an inductive loop (see Section 5.6) of 100 μm diameter copper wire, ≈ 2 mm in diameter, across these leads. Next, the dipole was formed by soldering onto the leads two straight 8 mm lengths of 110 μm diameter, copper-plated spring steel wire. This material, which is manufactured for missile control links, was ideal for our application because it was stiff enough to form a robust, free standing structure, springy enough to resist permanent deformation and of high electrical conductivity. The overall weight of the assembly was 10–11 mg and the device performed very well in field tests on large insects, such as bumble bees and even honeybees (Riley et al., 1996). Having proved the concept and produced a working transponder, our next objective was to investigate ways of reducing weight to a minimum, while retaining the mechanical robustness required for fieldwork.

The physical scale of our first model was at the lower limit of what could be tackled by hand soldering. So for our second, lighter models, we adopted the radically different procedure of building the transponder on a miniature glass tube 1 mm long, which acted as an electrically insulating central support. For the lighter transponders, the tubes had an internal diameter of 84 μm and an outside diameter of 250 μm. The corresponding diameters for the more robust models, using thicker wire, were 150 and 268 μm, respectively. The ends of a pre-formed loop of tungsten wire were fitted into the tube ends, then the two halves of the dipole were also inserted and a tiny spot of quick setting isocyanate glue (Loctite Super Glue) was applied at one end. Capillary action drew the glue fully into the tube, so the dipoles and loop became firmly fixed. To save weight, we used a diode without capsulation (Hewlett-Packard HSCH-5340) and, working under a binocular microscope, attached this 700×270 μm device to the outside surface of the tube, using UV-setting glue (Loctite Glass Bond). This adhesive allowed us to postpone setting until we were satisfied that the diode was in the centre of the tube and aligned with its longitudinal dimension parallel to the tube axis. The entire structure was then temporarily glued to a microscope slide with a 150 μm wide masking strip covering the central region of the diodes. Finally, electrical connections were made between the diode terminals, the dipole halves and the inductive loop, by vacuum deposition of a 0.5 μm gold layer on top of a 50 nm film of titanium. Up to 30 transponders could be gold-plated at a time using this method.

5.5. Laboratory measurement of transponder efficiency

The overall performance of the transponders was evaluated by standing them individually on an expanded polystyrene base, inside a microwave anechoic enclosure. The devices were then illuminated with highly attenuated 0.1 μs pulses conveyed from our 9.4 GHz transmitter through a 5 m length of waveguide 16 and launched through a small ($G = 16.4$ dB) calibrated rectangular horn. A second calibrated horn, orthogonal to the first, collected the harmonic signals radiated from the transponder and passed them directly into a calibrated 18.8 GHz receiver. Using equations similar to Eqs. (1)–(4) in Section 3 above, we were able to calculate the transponder's overall conversion efficiency, E_{dh}, defined as the ratio of the total harmonic power radiated by the device to the fundamental power which would have been absorbed by the dipole had it been centre-loaded with a matched resistive load.

We found, as expected, that E_{dh} varied with fundamental power density, but generally lay in the range from 0.3 to 0.9%. At the power density (30 Wm^{-2}) corresponding to the maximum range of detection we achieved, E_{dh} was $\approx 0.8\%$, confirming the value calculated from our field measurements of maximum range of detection.

5.6. The need for a DC path

Our first measurements of the efficiency of a transponder consisting of a simple dipole, centre-loaded with a Schottky diode were very disappointing, typically yielding values $< 1/100$th of those we had expected to achieve. One possible cause for such low efficiency was that the rectifying action of the diode was creating an electrostatic charge distribution between the two halves of the dipole, of sufficient magnitude to bias the diode into a non-conducting state. To test this possibility, we fitted a 4.7 nH miniature inductor across the diode terminals to provide a low resistance return path for any electrostatic charges, but which at the same time presented a relatively high impedance ($\sim 280\ \Omega$) to the 9.4 GHz signals. This produced a dramatic improvement in conversion efficiency and subsequent experiments showed that similar results could be achieved if we bridged the diode with a simple loop, 2 mm in diameter, of fine wire. Lightweight inductive loops were thus used in all our subsequent transponders. A secondary but important advantage of the DC path provided by the loop was that it protected the very sensitive diodes from accidental exposure to potentially damaging electrostatic voltages during handling in the field.

5.7. Attachment considerations

In order to allow insects to take off and land normally, the transponder had to be fitted so that it projected upwards from the dorsal side. The upper surface of the thorax seemed the most appropriate platform because in straight, level flight its attitude is relatively stable, so an antenna fixed to it would remain upright. Also, at least in the case of bees, it was well known that plastic marking discs (E.H. Thorne Ltd., Wragby, Lincs., UK) can be attached with adhesive to the thorax, without interfering with flight performance. When fitted with a vertical stub of miniature plastic tube, these discs became a natural choice for fitting radar transponders to both honey and bumble bees (Fig. 2). Laboratory measurements had shown that transponder conversion efficiency was re-

Fig. 2. A honeybee carrying a 3 mg transponder.

duced if the lower tip of the antenna was 2 mm above the thorax. Presumably, this was because the insect body distorted the electromagnetic fields and so reduced the antenna efficiency, but in any event, the problem was solved by using a slightly longer plastic tube to give a stand-off of 2 mm. For smaller insects, we dispensed with the discs and used a section of miniature plastic tube, with one end spread to form a fixing disc.

The transponder antenna was too tall to allow bees to move around within their nests or hives and so it had to be fitted as they left home and removed on return. To facilitate this process, we first glued standard numbered discs to the dorsal surface of the thoraxes of experimental bees, using the adhesive provided by the disc manufacturer (rather than the cyanoacrylate glues mentioned in some earlier papers). Bees so treated could move freely within their nests and on exit, the discs provided a convenient platform to which the matching transponder base could be quickly fixed using a pre-attached disc of double-sided sticky tape. Practical details of how the subject insects (bees and moths) were handled and the transponders fitted, are given elsewhere (Riley et al., 1998; Osborne et al., 1999; Capaldi et al., 2000).

6. Results and conclusions

The radar has been used in six field studies to date, two on bumble bees, two on moths and two on honey bees and has proved to be dramatically effective. Flight trajectories up to hundreds of metres long have been recorded, revealing hitherto unknown aspects of foraging behaviour, learning flights and compensation for wind drift (see Riley and Osborne, 2001 for a recent summary). Investigations are currently in progress that will provide new information on the way in which honey bees navigate and how they use information encoded in their dance language (Von Frisch, 1967) and many other experiments are envisaged.

Although the harmonic technique has proved extremely successful, it is important to emphasise some practical limitations. The first is that it requires a clear line of sight between the radar and target and this normally means that flight studies need to be conducted over flat terrain, preferably free from tall crops, trees and hedges. Secondly, the transponders all look alike to the radar, so if more than two or three tagged insects are in flight at the same time, their tracks can easily become confused. This has proved especially troublesome in our studies of moth flight, where the insects often land and then take off again hours (or even days) later. Thirdly, the radar indicates height of flight only to the extent that detected targets must be somewhere within the altitude range covered by the beam (from a few centimetres above the ground to 3–4 m, depending on range (Riley and Osborne, 2001)).

Even with these constraints, harmonic radar represents a major step forward in our capacity to study insect flight. Commensurate biological results have already been achieved, and similar advances can be expected in the future.

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References

Barbie, S.M., 1978. Optimization of harmonic radar reflection from Schottky varactor diode tags. M.Sc. thesis, North Dakota State University, Fargo, North Dakota.

Boyd, L.E., 1979. Realization of a harmonic radar for insect tracking. M.Sc. thesis, North Dakota State University, Fargo, North Dakota.

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., Riley, J.R., 2000. Ontogeny of orientation flight in the honeybee revealed by harmonic radar. Nature 403, 537–540.

Chapman, J.W., Smith, A.D., Woiwod, I.P., Reynolds, D.R., Riley, J.R., 2002. Development of vertical-looking radar technology for monitoring insect migration. Comput. Electron. Agric. 35, 95–110.

Drake, V.A., Farrow, R.A., 1988. The influence of atmospheric structure and motions on insect migration. Ann. Rev. Entomol. 33, 183–210.

Drake, V.A., Harman, I.T., Wang, H.K., 2002a. Insect monitoring radar: stationary-beam operating mode. Comput. Electron. Agric. 35, 111–137.

Drake, V.A., Wang, H.K., Harman, I.T., 2002b. Insect monitoring radar: remote and network operation. Comput. Electron. Agric. 35, 77–94.

French, J., Priede, I.G., 1992. A microwave radar transponder for tracking studies. In: Priede, I.G., Swift, S.M. (Eds.), Wildlife Telemetry: Remote Monitoring and Tracking of Animals. Ellis Horwood, Chichester, UK, pp. 41–54.

Hall, G., 1991. The American Radio Relay League Antenna Book, sixteenth ed. American Radio Relay League, Newington, Connecticut, USA.

Hockmann, P., Schlomberg, P., Wallin, H., Weber, F., 1989. Bewegungsmuster und Orientierung des Laufkäfers *Carabus auronitens* in einem westfälischen Eichen-Hainbuchen-Wald (Radarbeobactungen und Rückfangexperimente). Abhandl. Westfälisc. Mus. Natur. 51 (1), 1–71.

Kanda, M., 1980. Analytical and numerical techniques for analyzing an electrically short dipole with a non-linear load. IEEE Transactions on Antennas and Propagation, AP–28, 71–78.

Kennedy, P.J., 1994. The distribution and movement of ground beetles in relation to set-aside arable land. In: Desender, K., Dufrêne, M., Loreau, M., Luff, M.L., Maelfait, J.-P. (Eds.), Carabid Beetles: Ecology and Evolution. Kluwer, Dordrecht, Netherlands, pp. 439–444.

Klempel, D.D., 1977. A harmonic radar for tracking individual insects. M.Sc. thesis, North Dakota State University, Fargo, North Dakota.

Loper, G.M., Wolf, W.W., 1986. Using the USDA-ARS insect radar unit to monitor honey bee drone activity. Am. Bee J. 126 (12), 832.

Mascanzoni, D., Wallin, H., 1986. The harmonic radar: a new method of tracing insects in the field. Ecol. Ent. 11, 387–390.

Osborne, J.L., Clark, S.J., Morris, R.J., Williams, I.H., Riley, J.R., Smith, A.D., Reynolds, D.R., Edwards, A.S., 1999. A landscape scale study of bumble bee foraging range and constancy, using harmonic radar. J. Appl. Ecol. 36, 519–533.

Reynolds, D.R., Riley, J.R., 1997. The flight behaviour and migration of insect pests: radar studies in developing countries. NRI Bulletin no. 71. Natural Resources Institute, Chatham, UK, 114 pp.

Reynolds, D.R., Riley, J.R., 2002. Remote-sensing, telemetric and computer-based technologies for investigating insect movement: a survey of existing and potential techniques. Comput. Electron. Agric. 35, 271–307.

Riley, J.R., 1974. Radar observations of individual desert locusts (*Schistocerca gregaria* (Forsk.) (Orthoptera: Locustidae). Bull. Ent. Res. 64, 19–32.

Riley, J.R., 1975. Collective orientation in night-flying insects. Nature 253, 113–114.

Riley, J.R., 1980. Radar as an aid to the study of insect flight. In: Amlaner, C.J., Macdonald, D.W. (Eds.), Handbook on Biotelemetry and Radio Tracking. Pergamon Press, Oxford, New York, pp. 131–140.

Riley, J.R., 1989. Remote sensing in entomology. Ann. Rev. Ent. 34, 247–271.

Riley, J.R., 1993. Flying insects in the field. In: Wratten, S.D. (Ed.), Video Techniques in Animal Ecology and Behaviour. Chapman and Hall, London, pp. 1–15.

Riley, J.R., Osborne, J.L., 2001. Flight trajectories of foraging insects: observations using harmonic radar. In: Woiwod, I.P., Reynolds, D.R., Thomas, C.D. (Eds.), Insect Movement: Mechanisms and Consequences. CAB International, Wallingford, UK, pp. 129–157.

Riley, J.R., Smith, A.D., Reynolds, D.R., Edwards, A.S., Osborne, J.L., Williams, I.H., Carreck, N.L., Poppy, G.M., 1996. Tracking bees with harmonic radar. Nature 379, 29–30.

Riley, J.R., Valeur, P., Smith, A.D., Reynolds, D.R., Poppy, G., Löfstedt, C., 1998. Harmonic radar as a means of tracking the pheromone-finding and pheromone-following flight of male moths. J. Insect Behav. 11, 287–296.

Roland, J., McKinnon, G., Backhouse, C., Taylor, P.D., 1996. Even smaller radar tags on insects. Nature 381, 120.

Schaefer, G.W., 1969. Radar studies of locust, moth and butterfly migration in the Sahara, Proc. Roy. Entomol. Soc. Lond. Ser. C 34, 33 and 39–40.

Schaefer, G.W., 1976. Radar observations of insect flight. In: Rainey, R.C. (Ed.), Insect Flight. Blackwell, Oxford, pp. 157–197 Symposia of the Royal Entomological Society No. 7.

Schaefer, G.W., 1979. An airborne radar technique for the investigation and control of migrating pest insects. Phil. Trans. Roy. Soc. B 287, 459–465.

Shefer, J., Klensch, R.J., Kaplan, G., Johnson, H.C., 1974. Clutter free radar for cars. Wireless World (May) 117–121 and (June) 199–202.

Shiao, J.A.-K., 1978. Solutions to problems associated with harmonic radar tracking of individual insects. M.Sc. thesis, North Dakota State University, Fargo, North Dakota.

Skolnik, M.I., 1990. Radar Handbook, second ed. McGraw-Hill, New York.

Smith, A.D., Riley, J.R., Gregory, R.D., 1993. A method for routine monitoring of the aerial migration of insects by using a vertical-looking radar. Phil. Trans. Roy. Soc. Lond. B 340, 393–404.

Smith, A.D., Reynolds, D.R., Riley, J.R., 2000. The use of vertical-looking radar to continuously monitor the insect fauna flying at altitude over southern England. Bull. Entomol. Res. 90, 265–277.

Tai, C.T., 1952. Electromagnetic back-scattering from cylindrical wires. J. Appl. Phys. 23, 909–916.

Von Frisch, K., 1967. The Dance Language and Orientation of Bees. Oxford University Press, London.

Vogler, J.G., Maguire, D.J., Steinhauer, A.E., 1967. DINADE—a new interrogation, navigation and detection system. Microwave J. 10 (4), 2–6.

Wallin, H., 1991. Movement patterns and foraging tactics of a caterpillar hunter inhabiting alfalfa fields. Func. Ecol. 5, 740–749.

Wallin, H., Ekbom, B.S., 1988. Movements of carabid beetles (Coleoptera: Carabidae) inhabiting cereal fields: a field tracing study. Oecologia 77, 39–43.