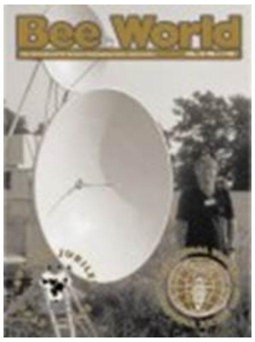

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Tracking bees with radar

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The flight patterns of bees have been studied for over 100 years, but due to their small size, bees can only be tracked by eye for a very short distance from the nest or hive. Scientists have employed various techniques, including mark-recapture[5], feeder experiments[26], homing experiments[23] and the interpretation of bee dances[25], to investigate bee foraging ranges. There is, however, still little detailed information about flight patterns between nest and forage sites, or about the behaviour involved in learning the features of the landscape. The adaptation of radar techniques for use in entomological research, has allowed insect flight paths to be accurately and continuously tracked over much greater distances. This article summarizes the progress made in applying radar to bee studies, and suggests some possibilities for the future.

Pioneer studies

In 1966, Ruttner & Ruttner, who had been studying the flight behaviour and congregation of honey bee drones in Germany[24], first suggested that radar would provide a useful tool for their work, but were unable to obtain suitably portable equipment. Loper *et al.*[11,12,13], working in Kansas and Arizona, USA, were later able to demonstrate the potential of conventional radar for bee studies, but also some of its limitations. They used a 3 cm (X-Band) modified marine radar, and found that they could successfully monitor drone activity at heights of between 15 m and 32 m above the ground. This enabled them to identify a number of 'drone congregation areas' and 'drone flyways'. They were also able to identify the paths of workers flying at high altitude.

They found however, that, despite the openness and generally flat nature of their site, flight in many areas and at low altitude was often obscured by 'clutter' from trees and undulations. In addition, they were unable to directly track virgin queens released into the drone congregation areas. Loper[10] suggested that a miniature radio transmitter mounted on a bee would enable this to be done. An infra-red emitting device, apparently mounted on a honey bee drone to illustrate its small size, and claimed to weigh 35 mg, had already been announced by a team at Oak Ridge National Laboratory, Tennessee, USA in 1988 (*New Scientist* 22/9/88), but no examples of its successful use have yet been published, and to date, no other 'active' transmitters small enough to be carried by a flying bee have been developed.

Recent developments with harmonic radar

Prof. Joe Riley and his colleagues from the University of Greenwich have, over a period of nearly 30 years, successfully used a number of different conventional radar

FIG. 1. The NRI radar unit: Alan Smith, Dr Don Reynolds, Prof. Joe Riley (*left to right*).

techniques to track insects, mainly tropical pests, flying at high altitude[18]. The specialized radar equipment was developed by the University's Natural Resources Institute (NRI), at their radar Entomology Unit, based at Malvern, UK (fig. 1). When the need to track tsetse flies arose, a novel approach was required. Tsetse flies are relatively small and fly at low altitude, so reflections from ground features (clutter) prevent them from being tracked using conventional radar. The NRI team therefore developed a harmonic radar for this task. In this technique, a non-linear conductor, such as a diode, is attached to a suitable antenna and is fixed to the target to be tracked. When this transponder is illuminated by a radar beam, currents at harmonic frequencies of the original signal are generated, and these currents re-radiate harmonics of the original signal. Suitably tuned, a radar receiver can detect this new signal even in the presence of vastly stronger clutter at the fundamental frequency. Because the energy for the transponder derives from the illuminating beam, the device does not need to contain a power supply, and so it can be extremely small. Harmonic transponders were first used successfully in an entomological context by Mascanzoni & Wallin[14], who used a 30-cm wavelength harmonic direction finder to follow walking carabid beetles, although only from a range of a few metres. By 1995, Prof. Riley's group had designed and constructed a 3-cm wavelength, azimuthially scanning, harmonic radar with a range of detection of 700 m, and had produced matching transponders only 16 mm in length and weighing just 12 mg.

Tracking bees

Bee research has been undertaken at IACR-Rothamsted since the early 1920s, and since the early 1940s, studies of pollination have formed an important part of the work[27].

FIG. 2. ***Bombus terrestris*** **fitted with transponder.**

FIG. 3. ***Apis mellifera*** **fitted with transponder.**

The pollination ecology group, currently led by Prof. Ingrid Williams has gradually moved from investigation of the pollination requirements of alternative arable crops to studies of pollen and gene flow in model crops such as field beans and white clover. Prof. Williams realized that the harmonic radar technique could be applied to studies of bee foraging behaviour, as it seemed likely that the miniature transponders could be mounted on a large and robust flying insect such as a bumble bee (fig. 2). Initial trials at IACR-Rothamsted in 1995, in collaboration with Prof. Riley's group, showed that both bumble bees and honey bees (fig. 3) could be tracked over distances of several hundred metres, without any apparent effect on their flight characteristics or foraging behaviour[2,15,20,29]. It was immediately apparent that the technique had great potential for use in bee flight and foraging studies, as well as in studies of other insect species.

Since 1995, Dr Juliet Osborne and colleagues at IACR-Rothamsted have been working on a project studying the foraging behaviour and ranges of bees in arable farmland. This work was prompted by the changes in land use which have occurred in the UK over the last 50 years[28], and which have severely reduced populations of wild bees[17], leading to possible problems of inadequate pollination of crops and wild plants[4]. Attempts to stabilize this decline by providing food plants[3] or nest sites[6], require knowledge of the foraging behaviour and foraging ranges of bees. Harmonic radar offered the unique prospect of looking in detail at foraging flights over longer distances.

In 1996, collaborative experiments were carried out at IACR-Rothamsted using the NRI harmonic radar to track the foraging ranges of commercially reared *Bombus terrestris* workers[16]. Information on the speed, length, direction and straightness of flight was obtained from a total of approximately 100 tracks made by 21 individual bees. Although plots of attractive flowering crops

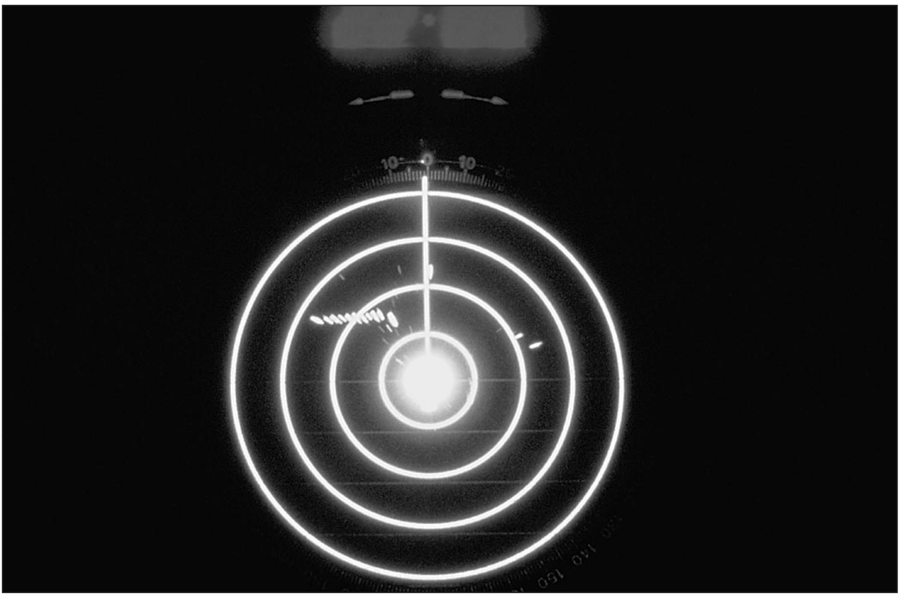

photo: **Joe Riley**

FIG. 4. Radar display showing track of moving bee.


photo: Norman Carreck

FIG. 5. Dr Beth Capaldi and Andrew Martin observing activity at the hive entrance.

were planted close to the two bumble bee colonies used, the radar showed that individuals often flew to more distant sources. Some bees were tracked up to 550 m from the nest, but may have flown further beyond the radar horizon. This demonstrates that bumble bees often forage further away from their nest than has hitherto been supposed, as suggested by Dramstad[5]. Analysis of pollen collected from the bees' bodies showed that they were constant to specific forage sources on successive trips. Combining the bee flight trajectories recorded by the radar, with data from a network of anemometers around the site, also provided information about bee flight speeds and how they compensate for wind drift[21].

For many years, Dr Gene Robinson and Dr Susan Fahrbach of the Department of Entomology at the University of Illinois, USA, have been studying links between brain function and bee behaviour, especially the physical changes which occur in the corpora pendunculata, or mushroom bodies, as newly emerged bees increase in age. They have concluded that the observed physical changes are involved in supporting the bees' transition from working within the hive to the more challenging task of foraging, and may represent storage and use of spatial information obtained during flight[7,8,9,30,31]. During her PhD studies with Dr Fred Dyer at the Michigan State University, USA, Dr Elizabeth Capaldi studied the ability of both naïve bees and older, experienced foragers to learn the features of their landscape during orientation flights following release at various distances from their original hive location[1]. The NRI harmonic radar again provided a unique opportunity to closely study these orientation flights and ultimately to relate flight behaviour to changes in the brain. During 1997, Dr Capaldi, now part of the team at the University of Illinois, came to IACR-Rothamsted to compare the flights of orientating and foraging honey bees (fig. 5). In her joint studies with IACR and NRI, she found that during orientation flights, which normally begin during the first week of adult life, bees were observed to leave the hive, turn to face it, hover backwards and forwards, whilst circling the hive, and then to make circling flights of varying distance for between 3–7 minutes before returning to the hive. The radar showed that the tracks of some bees were simple loops, whilst others were more complex. As the bees gained experience, tracks increased in length and became straighter until they resembled those of foragers[19]. Analysis of these data for publication is still proceeding.

In 1998, in another IACR–NRI joint study, Dr Osborne observed the orientation flights of naïve *B. terrestris* workers. Analysis of the tracks is not yet complete, but it appears that bumble bee orientation behaviour, although showing similarities to honey bee orientation flights, may also show some important differences.

Whilst at IACR-Rothamsted in 1996, the NRI harmonic radar equipment has also been used to study the flight of nocturnal moths responding to pheromone sources[22]. This work was part of a collaborative study between IACR, NRI and Dr Peter Valeur of the University of Lund, Sweden, and it was the first occasion on which nocturnal moth flight has been observed over any distance. The work was continued in 1998, where moth flight was studied in pheromone-treated areas. Also in 1998, the NRI team and Dr Glyn Vale of the Regional Tsetse and Trypanosomiasis Control Programme (Zimbabwe) carried out an experiment in which tsetse flies were finally successfully tracked using new ultra-light (< 1 mg) transponders.

There remain many potential applications of harmonic radar in the study of bee movement. In particular, simultaneous tracking of both drones and virgin queens would allow the study of honey bee mating behaviour, providing answers to questions, such as the role of drone congregation areas which have interested beekeepers and bee scientists for many years. The patrolling behaviour of male bumble bees, and the flights of queen bumble bees while searching for nest and overwintering sites could also be studied.

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