An Airborne Radar System for Desert Locust Control [and Discussion]

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An airborne radar system for Desert Locust control

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All elements for a complete and self-contained airborne radar system have now been developed and extensively flight tested, separately and together, in seven countries. The system is capable, in principle, of systematically seeking, locating and maintaining contact with most airborne locust populations; and, under recession conditions, of undertaking immediate control. Against widespread and heavy infestations, the same system would be capable of detection and quantitative assessment of targets, and of quantitative assessment of results of control.

The first element is an airborne Doppler radar navigation system, with precision wind-finding facility, able to seek, locate and explore in detail the semi-permanent zones of wind convergence, towards which incontrovertible evidence collected over 30 years has shown airborne locusts move, and in which they accumulate. The second element is the Cranfield airborne insect-detecting radar for quantitative assessment. Finally, the targets assessed as appropriate would be attacked forthwith, in flight by air-to-air spraying methods refined from those already quantitatively tested and employed in large-scale control operations during the 1950s and 1960s.

1. Introduction

The recent upsurge of the Desert Locust *Schistocerca gregaria* (Fôrsk.) appears to have established a case for radically new options both for monitoring and control. This paper is concerned with specific new options that have become available from research and development in recent decades with aircraft and radar in the context of 60 years of international cooperation in the study of this formidable migrant pest and its environment.

These recent findings have been provided by a series of coordinated programmes of field research, dating from what may have seemed at the time a far-fetched proposition tabled by the Desert Locust Control Organization for Eastern Africa (DLCO-EA) at a Food and Agriculture Organization (FAO) Working Group on Locust Control Methods at Rabat in 1963 (FAO 1963). This proposition envisaged that, by carrying appropriate wind-finding equipment, an aircraft would be able to seek and locate semi-permanent zones of wind-convergence, towards which airborne locusts necessarily move, travelling as they do, consistently downwind (Desert Locust Survey 1962*b*; Rainey 1963*c*), constrained, largely by temperature, to meteorologically low levels. Here they might be assessed by appropriate airborne radar, and attacked in flight by air-to-air spraying methods, which had already been developed, quantitatively tested and applied on a substantial scale during the 1950s and 1960s (Rainey 1958*a*, *b*; Desert Locust Survey 1962*a*). Those experiences provided evidence of greater effectiveness and less environmental contamination from such air-to-air spraying than from conventional methods. In 1963, however, appropriate potential airborne wind-finding equipment was only just becoming commercially available and no effective airborne insect-detecting radar system was yet in sight.

This paper outlines the evidence of progress in relation to the three elements of the proposed

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system, namely: reconnaissance using airborne wind-finding equipment, detection and assessment of flying insects by specially developed airborne radar, and air-to-air spraying of suitable concentrations of flying insects.

2. Airborne wind-finding for locating concentrations of flying insects

(*a*) *History*

Recognition of the consistently downwind displacement of swarms had an obvious value in seeking and following them. Already in 1952, special local early morning pilot-balloon observations were found particularly useful in determining the sector to be searched by aircraft for potential target swarms while they were still approaching (Rainey & Sayer 1953). Wind-finding directly from the searching aircraft was, however, found impracticable with the standard visual drift sight of those days, because of the degree of convective turbulence associated with the arid terrain and the flying heights (of the order of a hundred metres). Little was known of how gradual, or abrupt the wind transition might be in zones of wind convergence, and, indeed, doubt was expressed as to whether atmospheric discontinuities exist in the tropics, a view perhaps more relevant to 'oceanic' than continental conditions (Sawyer 1952). In 1953, however, H. J. Sayer had observed the zigzag tracks followed by swarms caught up in the ebb and flow of opposing winds over the Somali Horn, in the Inter-Tropical Convergence Zone (ITCZ) and the associated anabatic winds over the main escarpment. He was later able to show both the sharpness of this windshift, the opposing winds being shown by smoke generators dropped from aircraft at points less than 16 km apart, and the closeness of the association of this windshift with the position and the density of flying locust swarms, an association continuing, sometimes, for a month or more.

In the early 1960s Sayer drew attention to the commercial advent of the self-contained Doppler radar navigation with its facility of accurate wind-finding, and, in 1965, was able to arrange for a demonstration of this system in an Ambassador aircraft. This included an almost instantaneous response to yaw (provided by a touch to the rudder simulating a change in drift at a windshift), and the striking visual presentation of the decreasing windspeed during the final stages of landing and touch-down, manifested by decreasing groundspeed at steady airspeed.

Preliminary wind-finding trials of equipment fitted to a Pilatus Turbo-Porter were undertaken over East Anglia (Rainey 1972*b*), the aircraft being supplied by CIBA-Pilatus Ltd of Switzerland as part of the programme of work of the CIBA Agricultural Aviation Research Unit located at the Cranfield Institute of Technology. Doppler radar equipment of similar specifications had recently been tested in a Canberra aircraft of the Meteorological Research Flight (MRF), and in comparing results in a discussion at the Royal Meteorological Society in 1970, D. N. Axford (1970) of the MRF agreed that, at the much lower airspeeds of the Porter, (around 100 knots† compared with 400 knots of the Canberra), r.m.s vector errors as low as about 3 knots were a reasonable expectation for the Porter aircraft, wind being the vector difference between course-and-airspeed and track-and-groundspeed vectors. The accuracy of this wind-finding, together with the manoeuvrability of the aircraft, were, indeed, found to make it possible to locate and explore in a detail not hitherto possible, a variety of wind features of significance to airborne pests (Rainey & Joyce 1972).

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† 1 knot = 1.852 km h^{-1}.

(*b*) *Observations in East Africa*

The first field programme was undertaken in 1970 with the then East African Agricultural and Forestry Research Organization, where E. S. Brown's research on the African armyworm was begun, the larvae of this noctuid moth (*Spodoptera exempta* (Walker)) being responsible for devastating crop losses in 1960–61 throughout eastern Africa. Brown's work had shown a series of close analogies between armyworm outbreaks and locust migration (Brown *et al.* 1969) and these had led to weekly forecasts of the likelihood of armyworm outbreaks within districts in Kenya, Tanzania and Uganda. In mid-1970 this service was completing a successful first year (Betts *et al.* 1971; Betts 1976 and, with continuing support, has been maintained since (Odiyo 1979, and this symposium).

A long-standing problem of this species is the fact that in almost every year there is a period of several months when, in common with Desert Locust populations, all contact with the main population appears to be lost, commonly followed by a sudden re-appearance of moths in one or more of the light traps which Brown had established in a network covering much of eastern Africa.

A convergence zone that had already been found significant in relation to such armyworm moth concentrations (and, earlier, to important Desert Locust swarm movements (Rainey 1963*c*) occurs where westerly winds from the region of the Congo Basin meet the prevailing easterlies, and is known variously as the Congo or Zaire Air Boundary (ZAB), or the African Rift Convergence Zone. On at least two occasions, well established surges of the ZAB have been involved in the start of seasonal sequences of armyworm outbreaks from this area. One was in October 1971, when P. Odiyo (in Rainey 1979) noted that a marked incursion of westerly winds, observed at Lusaka in Zambia on 15 October, had already affected southwestern Tanzania at the time of the egg-laying inferred for the initial infestations of the 1971–72 armyworm season in eastern Africa. Quite independently, this same incursion of westerlies was selected to illustrate a typical surge for the ZAB (Bhalotra 1973). The second of these occasions was in December 1973. In this case, the synoptic analyses of the Malawi Meteorological Department for 21 and 22 December were later found (Rainey 1979) to have shown a temporary eastward surge of the ZAB, at the right time and in an appropriate area to have carried parent moths from known December infestations in Zambia into Mtwara district of southern Tanzania. Infestations there in January 1974 provided the putative progenitors of the sequence of infestations, from February to July, successively in Tanzania, Kenya, and particularly damaging in Ethiopia and Yemen (also in Nigeria at the same time). It would appear that the discovery and destruction of moth concentrations in zones of wind convergence on any of these occasions could have prevented the development of subsequent infestations.

In 1970, the Doppler wind-finding aircraft encountered the ZAB on 10 May as the sharply defined edge of a westerly incursion near Nakuru, Kenya, within 15 km of one of Brown's light traps and within a few hours of what was subsequently found to have been the peak armyworm moth catch of the season in that trap. This catch, moreover, proved to have sampled the parents of a further wave of armyworm attacks in the Nakuru district (Rainey 1972*a*; Haggis 1979).

(*c*) *Observations in Sudan*

The climate of the Sudan is dominated by the annual passage of the ITCZ, its movement northwards heralding the onset of the rains and its movement southward, the return of the dry season. In northern Sudan, between the latitudes of 14° and 19° N where the wind-finding work was conducted, the dry season is uninterrupted for seven months between November and June, and the advent of rains in July restores the opportunity for plant and animal life. The Inter-Tropical discontinuity (ITD), the boundary between the northerly trade and the southwesterly Monsoon winds, has long been recognized by meteorological services from Ethiopia westwards to the Atlantic as the major feature of surface synoptic analysis (World Meteorological Organization 1953; Clackson 1957; Tschirhart 1959, Walker 1958; Osman & Hastenrath 1969), and in northern Sudan its position is recorded on charts no less than eight times per day. These records show not only the seasonal progress and the regular daily movements of the ITD, but also irregular surges in which its position is displaced tens or hundreds of kilometres in a single 24-h period (Haggis 1982). The effect of these movements on the local climate is obvious, even without instrumentation, and insect activity is also clearly affected.

The Doppler equipped Porter located the ITD without difficulty at the first attempt and regularly afterwards, providing, between 29 September and 27 October 1970, a total of 31 traverses at latitudes between 19° and 14° N. Of these, 23 were made by day, between 06h00 and 11h00 (G.M.T. + 2), mainly at 150 m above ground, and 8 by night, between 02h00 and 06h00 at 300 m. No adverse flying conditions were encountered by day or by night, associated, no doubt, with the fact that the rains of the ITCZ occur well to the south of the ITD, commonly several hundreds of kilometres away. On 26 of the 31 traverses, the main windshift occurred between two successive observations. On 16 of these 26 occasions, the two successive observations were separated by only 3 km and by 7 km on the remaining 10. These main windshifts were between predominantly northeasterly and southwesterly directions, respectively drier and more humid.

Sampling of airborne insects by suction traps from ground level to 15 m above ground and by specially designed nets fitted to the Porter (Spillman 1980*b*) provided early Sudan evidence of increased numbers of small insects in the vicinity of the ITD (Bowden & Gibbs 1973; Russell-Smith in Joyce 1976; Rainey 1976*a*). Particularly important subsequent observations using ground-based radar (Schaefer 1976) showed the ITD as a very sharply defined discontinuity with a line-echo some 200 m wide (mainly from airborne moths) passing overhead within two minutes of a surface windshift, the windshift and line-echo being in close agreement in position, alignment and speed of displacement with corresponding inferences from the three-hourly synoptic analyses from the Khartoum Meteorological Office. The sharpness of the windshift was indicated by marked differences in the track directions on the plan position indicator of the insect echoes ahead of the line-echo and of those behind it. Aircraft wind-finding similarly showed close agreement in position and alignment between windshift and line-echo at the ITD (Rainey 1976*a*, figure 5.13).

By flying a box pattern extending some 25 km on either side of the ITD over the Sudan Gezira in September 1970 (Rainey 1976*a*, figures 5.9 and 5.10), it was possible to give a quantitative estimate of wind convergence and demonstrate a net inflow of air into the box on the horizontal plane at a rate of $1.6 \times 10^{-3}\ \mathrm{s}^{-1}$. On the simplest assumptions, this degree of convergence could be expected to increase the area density of airborne insects at a rate of $0.25\ \mathrm{h}^{-1}$ with a standard deviation of $0.11\ \mathrm{h}^{-1}$.

An association of winter displacements of Desert Locust swarms along both coasts of the Red Sea with alternating surges of northwesterly and southwesterly winds, marking surges of another semi-permanent zone of convergence, has long been recognized. This Red Sea Convergence Zone (RSCZ) was investigated briefly in 1970 and, as with the ITD, its location and exploration with the instrumented Porter presented no problem (Rainey 1976*a*). Observations over the Sudan coast near Tokar showed an air-mass boundary between cooler northerlies and warmer easterlies in close agreement with early inferences on the RSCZ made during a detailed investigation by Pedgley (1966) at DLCO-EA. The windshifts encountered during the two aerial traverses over the sea (figure 5.19 in Rainey (1976*a*)) were noticeable for brief spells of turbulence in otherwise smooth air, and the wind sequences found on the two occasions were sufficiently similar to justify two-dimensional treatment. This enabled convergence in the main transition zone, which was 3–5 km wide, to be estimated directly from the wind components perpendicular to the orientation of the zone. The convergence so found was at rates of 5 and 6 h^{-1}, at 09h05 and 07h13, respectively, on 17 November.

(*d*) *Observations in Burkina Faso*

Evidence was secured during limited wind-finding observations for the World Health Organization in Burkina Faso, of effects on airborne insects of more vigorous, but less persistent wind systems, particularly storm outflows and line-squalls. These provided support for an earlier suggestion (Marr 1971) that such systems could be of importance in the distribution of *Simulium damnosum* Theobald, the blackfly vector of onchocerciasis, and incidentally provided initial circumstantial evidence suggesting involvement of line-squalls in the damaging armyworm invasions of Sierra Leone and neighbouring countries as in 1979 (Rainey *et al.* 1976; Rainey 1989, figure 75).

(*e*) *Observations in Canada*

Field work in Canada, undertaken on behalf of the Maritimes Forestry Research Centre of the Canadian Department of the Environment, in connection with the control of the spruce budworm, *Choristoneura fumiferana* (Clem.), similarly directed attention to the contrast between the vigorous convergence at systems with a short lifetime, particularly thunderstorms (Dickison *et al.* 1983, 1986), and convergence of relatively limited intensity persisting for twelve hours or more. The latter displayed little associated weather (though still manifested by appropriately detailed synoptic analysis), and a corresponding absence of adverse flying conditions (Dickison, this symposium). They included sea-breeze fronts and related marine flows (Neumann 1980), the persistence of which was found to result, on occasion, in striking concentration of the spruce budworm moth (Rainey 1976*b*, 1989; Greenbank *et al.* 1980).

An outstanding case was that of 16–17 July 1974, when well-developed sea breezes moved into New Brunswick across both southern and southeastern coasts and temporarily dammed up a major inflow of moths from the west (Rainey 1989). A line-echo developed over the Chipman ground-based radar at 19h40 A.D.T. (G.M.T.-3), simultaneously with the arrival of the sea breeze front from the east, and stalled just west of the site for 4h. Moth densities were augmented after 22h00 by moths brought into the area on the Fundy sea breeze, which reached Fredericton at 22h15. There, 1.5 h later, an aircraft trap catch provided evidence of an exceptionally high density of moths, averaging 4×10^{-3} m^{-3} from aircraft take-off to the initial cruising height of 460 m. This estimate was in close agreement with moth densities recorded at the time above Chipman, 50 km away, both by radar and by a second trapping aircraft. Still higher moth densities were recorded at 23h00 at Renous airstrip in the central uplands of the Province, 90 km N.N.W. of Chipman, with radar observations of a westward-moving line-echo

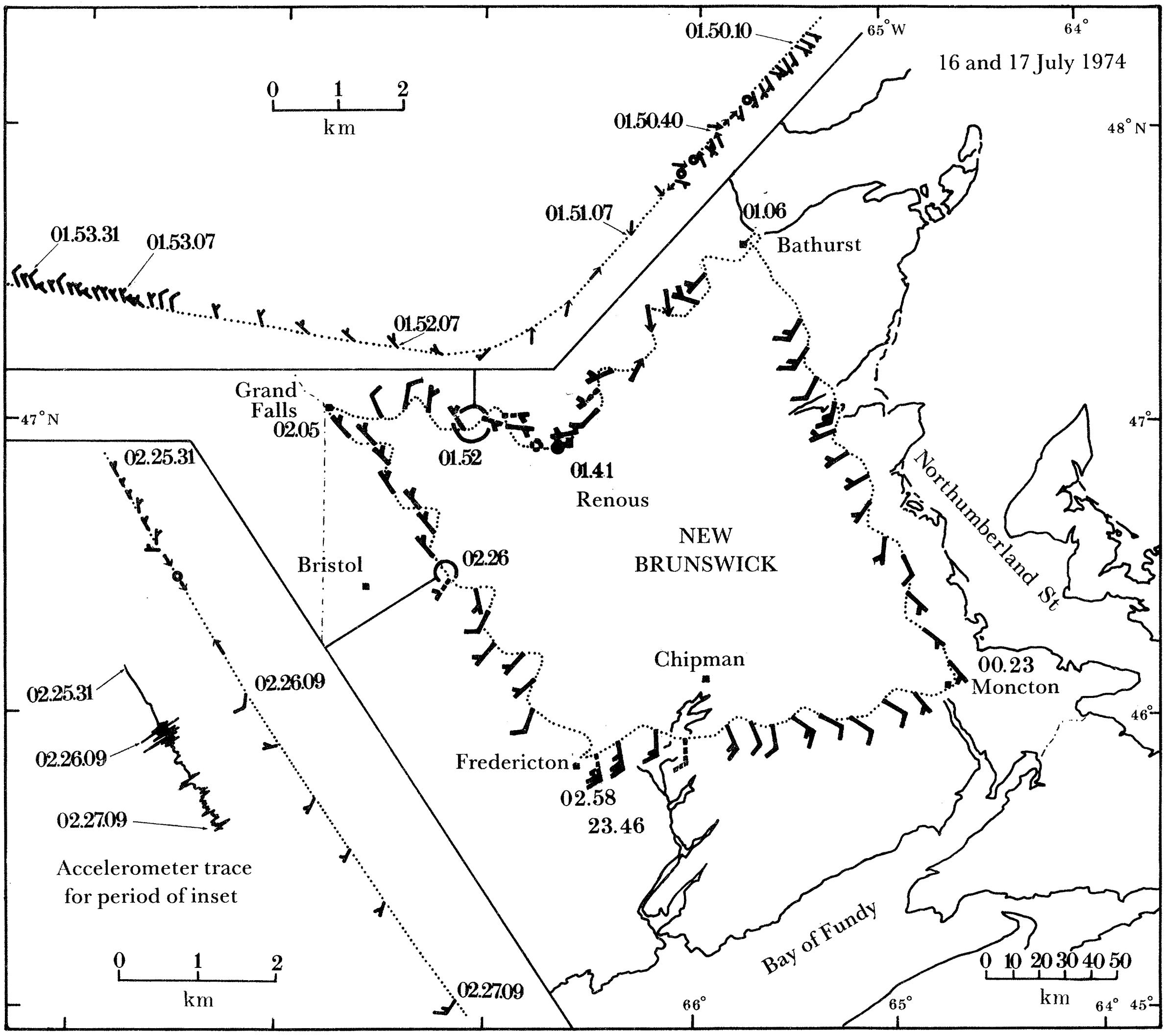

Figure 1. Winds measured by Doppler-equipped aircraft, New Brunswick, 16–17 July 1974, from Fredericton via Moncton to Bathurst at 460 m above sea level (a.s.l.) and thence via Grand Falls to Fredericton at 910 m a.s.l. Insets: details of winds measured along part of track indicated, and accelerometer trace for main area of turbulence. Main figure, wind direction: solid arrows measured by multiple drift; dashed arrows by single drift. Insets, only single-drift winds shown. Wind speed, 1 full barb = 10 knots; small circles denote clam. The 'dog tooth' flight track was designed to enable multiple-drift wind measurements; times of observation A.D.T (G.M.T-3) shown at main turning points on main figure, and in insets as h min s.

(suggested as the sea-breeze front from the east coast) with an exceptionally dense layer of moths 100–250 m above ground at a marked inversion of temperature. This concentration was confirmed by trapping from aircraft at a density of 10^{-2} m^{-3}. The wind-finding flight, passing over Renous at 01h45 at 910 m a.s.l., was measured very light southeasterly winds, which were abruptly replaced 35 km further west by 5–10 knots north to northwest winds (figure 1, top inset). The Fundy front from the south was last traversed at 02h26 local time, at 150 km from the coast, still moving inland, and marked by an abrupt onset of turbulence with an upward gust of 0.43 *g*, suggesting an up-current of 3 m s^{-1} (figure 1, lower inset), coinciding with a windshift from northwest to southwest 5–10 knots together with a 0.6° fall in temperature within a distance of 1.5 km, and a reappearance of moths at an altitude of 910 m at a temperature of only 12–14°. Very large numbers of moths were also reported on the ground at Bristol, only 30 km away.

This case shows the very considerable accumulation of airborne insects that can occur at a front which is relatively inactive in respect of weather (and, in meteorological terms, very limited in vertical extent), in circumstances of a continued and substantial supply of insects arriving from up-wind, comparable, in fact, to the arrival of locusts, in swarms or individually at the ITD from distant sources.

3. Airborne insect-detecting radar (ABR)

The second new component of the Rabat proposition was airborne insect-detecting radar, at the time no more than a concept for the future. Development and production was eventually commissioned in 1974 from G. W. Schaefer and his colleagues at the Cranfield Institute of Technology by the Canadian Forestry Service (CFS), for use in the Service's research programme on spruce budworm moth flight in New Brunswick. Here, as reported by Schaefer (1979), the prototype set was successfully flight tested in 1975 in a Cessna 185 of the CFS, and two production sets were in use in extensive flying programmes the following year, in an Aztec aircraft as well as in a DC-3 in which the Doppler wind-finding system had already been in use during the previous three seasons.

The radar equipment incorporated the same low-cost Decca RM 925 marine radar transmitter/receiver as already used in extensive observations of insect flight from the ground in the Sudan (Greenbank *et al.* 1980.) The airborne installation used an aerial system with a downwardly directed parabolic reflector of 0.91 m diameter fed by a rotating dipole, giving a conical beam of half-power width 2.4°. With a wavelength of 3.18 cm, a peak pulse power of 25 kW, a pulse-length of 0.1 μs, and a pulse repetition frequency of 1760 Hz, individual budworm moths (of body length about 1 cm and weight about 35 mg) could be detected down to the forest canopy from an aircraft height of 750 m, and moths at commonly recorded densities of 10^{-3} m^{-3} detected from a height of 1500 m. Correspondingly, Desert Locusts with a body length of 5 cm and weight 2.5 g could be detected by such a radar system at proportionately greater ranges.

The detected echoes were fed to a range-gating and processor system which sampled echo intensity at 32 levels below the aircraft, starting at 50 m down and ending at about ground level. On the aircraft, the density profile was displayed, pulse by pulse, on an A-scope; and the profile was integrated to display the area density of moths per hectare on a strip-chart. Complete intensity profiles were stored on tape at a rate of 128 s^{-1}. Each 32-level height distribution was recorded in 8 ms; 16 successive measurements were then averaged at each level, to produce smoothed profiles of airborne moth density (and of the predominant moth alignment) for 32 levels at a rate of eight profiles per second, i.e. for every 8 m of aircraft track.

The performance of the equipment was well demonstrated by a unique series of observations of the concentration of spruce budworm moths into a New Brunswick sea-breeze front (Schaefer 1979; Greenbank *et al.* 1980).

Again on 15 July 1976, detailed re-analysis of current local synoptic data directed attention at the pre-flight briefing to an inconspicuous feature over western New Brunswick in which budworm moths were observed by ABR in flight at increased densities (Dickison, this symposium). It was later suggested by C. Miller of the Maritimes Forestry Research Centre, Fredericton, that these moths had been involved in significant immigration of egg-laying moths into the Upsalquich area (Dickison, this symposium, figure 3).

Contrasting conditions were shown on the following night (16–17th), when the ABR equipment recorded moths in numbers 70 km downwind from budworm infestations of unprecedented severity in the Cape Breton area of Nova Scotia, among thunderstorms out to sea over the Cabot Strait and halfway to Newfoundland. These Cabot Strait observations helped to direct attention to the manner in which moth invasion from distances of hundreds of kilometres is likely to have been involved in the unprecedented severity of subsequent infestations in Newfoundland.

4. Air-to-air spraying as control technique of choice

The third element of the Rabat proposition was envisaged as direct attack from aircraft on flying locusts in the concentrations located and assessed by the airborne radar system, by using the special spraying techniques and materials which had been developed in the course of more than a decade of field and laboratory research and development (Kennedy *et al* 1948; Gunn *et al.* 1948; Rainey & Sayer 1953; Joyce 1962, Rainey 1963*a*), and applied on a substantial scale. These were found to provide rates of insect kill, in numbers of dead locusts per unit of insecticide applied, which have not been approached by any other pesticide application method. This conclusion may be shown by the fully assessed kill of 179 million locusts (about 350 tonnes), with a standard deviation of 24 million, which followed the application of 270 l of 85 % Diazinon (half the load of a Beaver aircraft), from a height of 30–60 m among moderately dense flying locusts in a large settling swarm near Hargeisa at 18h05 on 8 September 1957 (Rainey 1958*b*); visibly contaminated dead locusts were found up to 20 km from the sprayed site. This result would correspond to a complete kill of a swarm covering 4 km^2 at typical density of 50 million km^{-2}, namely a swarm larger than most recorded recession swarms.

The technique of air-to-air spraying of locust swarms was placed on a sound theoretical basis by the work of the Porton Laboratory in the 1940s and 1950s, and the mathematical model constructed by Sawyer (1950) allowed the performance of an individual spray-line, of known physical and insecticidal properties, applied within swarms of given density and orientation, to be calculated. This was based on the dispersal of droplets of the spray in accordance with their fall velocity, and the collection of droplets by individual locusts flying in the spray cloud. The resulting graphical treatment proved invaluable in the interpretation of the results of individual field operations against flying swarms (Rainey & Sayer 1953; Rainey 1958*b*), and in radically improving earlier spray tactics.

More recent studies in Cranfield, particularly by Spillman (1976), have emphasized the potential importance of very small droplets whose numbers in the droplet spectrum could not have been measured in the earlier work. Spillman pointed out that, while catch efficiency increases with droplet diameter and with increase in the speed of the insect relative to the air, it decreases with increase in the diameter of the part of the insect in the droplet's path. Taking the catch efficiency of a droplet of 50 μm diameter as 1.00, Spillman showed that the catch efficiency associated with the heads of flying insects only falls significantly when the droplet diameter is less than 40 μm, whereas for the smaller parts, such as the legs, antennae, and sensory hairs, the catch efficiencies drop by more than 10 % only when droplets have diameters smaller than 30 μm. However, the probability of a droplet being caught depends on the product of its numbers and lifetime in the vicinity of the targets, that is, within the swarm. Contact with the ground is the most probable fate of large droplets in a swarm of typical density of 0.01 m^{-3}, and this is to be avoided. In still air, the catch probability increases greatly with the increase in impaction parameter for the small droplets. In particular, a 10 μm droplet has a 7.5 times greater probability of being caught by a locust head than does one of 50 μm diameter. This ratio rises to 18.5:1 when considering the catch probability of the smaller parts of the insect.

The Sawyer theory of air-to-air spraying, later elaborated by MacCuaig & Yeates (1972), visualized the release of a curtain of droplets above a swarm, the size being selected to ensure penetration through the depth of the swarm. Because of the low probability of direct hits on locusts by large droplets falling through a swarm, Sayer, in the 1960s, visualized suspending a cloud of small droplets within swarms and, since individuals comprising a swarm are in continual motion, both horizontally and vertically, and the life of the cloud was effectively commensurate with that of the swarm, all individuals would eventually pass through the cloud and collect a lethal dose. This concept receives vindication from the recent Cranfield studies. Moreover, there are strong statistical reasons for using small droplets (Spillman 1980*a*). Suppose that droplets, each containing one LD_{50} dose, are released in just a sufficient number that, on average, each target receives one contact. Then, assuming each droplet has an equal probability of contacting a target, it can be shown that about 37 % of the targets are likely to collect one droplet, 37 % none and 26 % more than one. If the diameter of the droplets is halved and the same volume of liquid applied, the number of droplets is increased eight times (but each only one eighth as lethal) so that the average number of droplets per target is increased to eight. Now, less than 1 % of the targets will be missed completely and nearly 70 % collect sufficient droplets to provide a dose between 0.75 and 1.25 of the LD_{50}, and less than 30 % are dosed to a greater level. The LD_{50} of 85 % Diazinon is about 1.5 μg g^{-1} of locust, and the object of spraying is to ensure that the vast majority of the individuals in a swarm collect at least two LD_{50} doses, and as few possible more than two. A single LD_{50} dose is contained in a droplet of approximately 240 μm diameter. Application of a spray curtain comprised exclusively of this droplet size, would, at best, result in a large fraction of the swarm collecting no insecticide. On the other hand, by reducing the droplet size to, say, 30 μm diameter, the number of droplets is increased 500-fold and, although 1000 hits are required for an individual to collect two LD_{50} doses, the probabilities are that nearly 100 % of the targets will collect between 0.75 and 1.25 of two LD_{50} doses and virtually none less or more. Unlike the 1960s, atomizers designed for aircraft are now available which will break down a spray liquid to give a narrow droplet spectrum in which the mode of droplet diameter is about 30 μm.

The model constructed by Sawyer took little account of turbulence, which was assumed to affect the locusts equally as it affected the droplets. However, the fall speed of the droplets now considered is so different from that of the locusts, that account must be taken of air turbulence and diffusion around the loci of their path within the swarm. Spillman (1980*a*) showed that small droplets used in conditions of low turbulence have a relatively high catch probability, particularly on the smaller parts of the insect.

It has long been recognized that the height to which locusts fly is limited by temperature, so that the topmost individuals in a swarm are at a level where the vertical upward velocity of the air has the velocity of the falling speed of a locust, about 1 m s^{-1}. If high flying 'cumuliform' swarms are to be attacked, great care must be exercised in choosing the height at which spray droplets are injected into the swarm. It is likely that this should be near to ground level, outside the swarm, so that droplets entrained in the same air that brings the locusts together impact on the flying insects as the entrained air rises within the swarm.

All air-to-air spraying involves problems of potential hazards of locust impact on the aircraft, for which appropriate airframe and engine modifications were incorporated from 1951 onwards to meet requirements of airworthiness authorities and aviation insurance (Rainey 1958*b*, 1963*a*). With these modifications, more than 3000 h of flying, involving varying degrees of physical contact with flying locusts, have been undertaken without accident attributable to locust impact.

5. Retrospective evidence for possible applications of the ABR system

(*a*) *In recession conditions*

The original Rabat proposals were tabled towards the end of a year of relatively trivial Desert Locust infestations, in striking contrast to the widespread and heavy attacks of the previous 14 years. The ABR was accordingly envisaged, in the first instance, for recession conditions (which, in fact, continued for five years). Moreover, this was the first period of locust recession to be centrally monitored with the aid of current daily synoptic weather charts and analyses by a Locust Forecasting Service, supported and itself monitored by all countries concerned. This made possible, in 1967, a systematic study, in unprecedented, though still not comprehensive detail, of the records of those five years of recession, by staff who had been responsible for the day-to-day monitoring, forecasting and warning service over this period. This study (Rainey & Betts 1979, figure 2) provided a new synthesis demonstrating a quite unexpected and significant degree of continuity of recorded locust populations, by reason of their mobility, and despite the inevitable spatial and temporal gaps in information. These results now make possible preliminary retrospective considerations of where and when the proposed airborne radar system might have been deployed during such a period, and how the operation of the system might have expected to have influenced subsequent locust developments.

In 1967, an important role in a developing upsurge was played by extensive populations of flying locusts produced in May on the Red Sea coast near the Egyptian–Sudan border and with which all contact had been lost during June–October 1967. To these missing populations can be attributed the important subsequent reported breeding in areas of the Atbara valley in the Sudan and the Mourdi depression at the same latitude in Chad, both of which would have come under the influence of the ITCZ during these months. In 1967 (as also in 1950), the ITCZ and its rains appeared to have extended further north than usual in Sudan and Chad. As in 1950, when breeding which took place in the normally arid areas of the extreme north Sudan (such as Wadi Howar) generated swarms which invaded Upper Egypt, the missing locusts of June–October 1967 likewise probably spent enough of these months in the vicinity of the ITD to have made this appropriate for search with a wind-finding aircraft in the same area and at the same time of the year as the first Porter ITD traverse 80 km north of Atbara on 29 September 1970.

From such a base as Dongola, in northern Sudan, a hypothetical 'search and strike' aircraft, with the same radar equipment and a performance comparable with that of a DC-3 (as used in Canada), could have maintained a daily patrol along perhaps 1000 km of the ITD, while also carrying sufficient insecticide (say, 500 l of 85% Diazinon) to deal in a single sortie with a whole swarm of a few km^2, the kind of size which appears to be characteristic of recession and early upsurge situations.

On the other side of Africa, early stages of the recent upsurge have suggested a closely analogous involvement of the ITD with missing locust populations and a further retrospective opportunity for the airborne radar system. After a whole year (1984) with no reports of Desert Locust swarms anywhere, the only slender clue to suggest that the species might still be present in numbers somewhere in west Africa was a report of four locusts showing the pinkish colouration which is manifest only by locusts from swarming populations, which were seen in April 1985 near Aioun-el-Atrouss in southeastern Mauritania. Further reports were lacking, and by June it was suggested that Desert Locust numbers might be at their lowest ebb since systematic collection of data started, some 60 years earlier. In late September, however, three ships reported scattered flying locusts at sea off the coasts of Mauritania and Sénégal, extending N.N.E.–S.S.W. over a distance of some 500 km. In early October many hundreds of square kilometers of advanced-instar hoppers (including hopper bands) and pink adults were discovered in southwestern Mauritania, necessitating control on a substantial scale. By the end of the month, there was the first report of a young swarm of the next generation. It was clear that there had been undiscovered breeding on a large scale, on the heavy rains which had been recorded at a number of points in the area in July and early August, and that the locusts seen at sea would have represented some of the last parent population.

Evidence of the close association between the ITD and the position and movements of a swarm in this area had been provided by the ground observations of G. B. Popov at Tamchakett in July, 1959. In view also of the evidence on the ITCZ for the summer of 1985 in west Africa provided by satellite and rainfall data (FAO Desert Locust Summaries 1985), there would appear to be little doubt that the ITD over Mauritania would have been an appropriate feature for ABR to search for the missing west African Desert Locusts in 1985 also.

Sea breeze systems have long been known to have significant effects on Desert Locust swarms. On the north coast of the Somali peninsula, for example, an afternoon sea breeze from a northerly quarter, reinforced by anabatic flow up the neighbouring escarpment, develops during the northern summer, and meets the opposing prevailing S.W. monsoon. During 1943–47, the additional meteorological observations of wartime helped to show that swarms landing on this coast in summer were probably mainly of local origin, swept out to sea by the powerful morning monsoon and subsequently brought in again by the sea breeze front (Brooks & Durst 1935; Rainey & Waloff 1948). Analogous effects of opposing monsoon and sea breeze have been recorded in the coastal areas of Gujarat in northwestern India, with swarms reported almost daily in the vicinity of the front between a regular southwesterly sea breeze and the north–northeasterlies above, clearly isolated from the main infested areas further inland for a two month period from mid-December 1954, and again for a three-week period of November–December 1962 (Rainey 1963*c*).

The significance of the RSCZ was again emphasized in 1985, when sufficient locusts to involve control operations had been found on the Ethiopian coast in August and in southwestern Arabia in September. Following sighting of Desert Locusts in numbers on a fishing trawler 40 km off Gizan on 10 November 1985, substantial infestations were discovered in Saudi Arabia from December onwards, initially in coastal areas. By early January, the total area infested between Lith and Qunfidhah was estimated to be 2500 km^2; 200 hopper bands had already been controlled since 10 December and a further 200 bands with fledglings and three swarmlets were controlled in mid-January. It may be that the missing locusts of the Red Sea area in October 1985 were in the vicinity of the RSCZ, where they might profitably have been sought.

During the 43 months of the 1964–67 study period, there were gaps of information, as in 1967, totalling 23 months, with each of these gaps similarly beginning with a disappearance of recorded locust populations and followed by a reappearance of such populations within areas and periods under the influence of the ITD or the RSCZ, accordingly suggesting, retrospectively, appropriate opportunities for ABR search for missing locust populations. In each of these individual cases, the evidence for this inferred continuity is admittedly circumstantial, but the cumulative significance of such an amount of independent circumstantial evidence must be near indisputable. Moreover, from 1935 to 1971, there was, in fact, no period of more than 4 months without swarms somewhere, and, on occasion, swarms were found to show adult life-times of more than 6 months (Rainey 1989). As evidence of the degree of continuity of recession populations began to accumulate in the early 1960s, attention was directed to the potentially cumulative effects of control against sequences of such populations. Possible evidence of such cumulative effects was indeed suggested by the west African sequence of September 1965–March 1966 and that in Pakistan and India of April 1964–September 1965 (Rainey & Betts 1979, figure 2).

With the increased effectiveness to be expected of both the 'search' and 'strike' elements of the proposed ABR system, a corresponding enhancement of the potentially cumulative effects of recession control could be expected.

6. ABR IN PERIODS OF UPSURGES AND HEAVY INFESTATIONS

No study comparable with that of 1963–68 is yet available for a recent period of heavy infestations, but loss of contact with significant locust populations is a problem not confined to periods of recession. In the course of the exceptional and heavy infestations of 1988, contact appears to have been lost for nearly a month with substantial populations of young swarms moving out of northwest Africa (and perhaps also the western Sahel) in late June, until they reappeared as an unexpectedly heavy invasion of Chad and western Sudan in late July, with corresponding difficulties in determining the full extent and distribution of the resulting oviposition and nymphal infestations. In this region and time of year, problems of repeated alternating northerly and southerly movements of locusts with the ITD, night flight and long-range displacement at low densities, may well all have been involved, so that effective reconnaissance would probably have been practicable only with the full facilities of the proposed ABR system.

The ABR system, moreover, provides an opportunity to study in quantitative terms the natural dynamics of locust populations which, at times, exceed 10^{11} individuals and probably rarely total as few as 10^{8} (Rainey *et al.* 1979). These individuals are also in almost continuous movement over a total area three times the size of Europe at speeds up to several thousand kilometres per month. If they were evenly distributed over the whole of the 30 million km^2 of the invasion area, they would constitute no economic problem. However, from time to time, a very large fraction of the total world population is concentrated in a very limited area. For example, the Northern Region of the Somali Republic was invaded between July and August 1960 by nearly 2000 km^2 of swarms bred in an area of over 500000 km^2 in Somalia, Ethiopia and southern Arabia during the previous months. Corpse counts after aerial spraying indicated that this invasion was of the order of 10^{10} individuals and represented the entire Desert Locust population of eastern Africa accumulated and confined by the wind systems already described within an area of some 5000 km^2 (Desert Locust Survey 1962*a*). Again, analysis of radar photographs made of swarms over New Delhi by the Cloud Physics Research Centre demonstrated the presence of flying locusts within 100 km of Delhi over a total of about 900 km^2 on 27 July and 1400 km^2 on 28 July 1962. Estimated volume densities gave an average value of between 0.07 and 0.13 m^{-3}, with numbers at heights up to 1500 m. These measurements provided an estimate of a total of 10^{11} locusts involved in this invasion. This, moreover, was at a time when swarms were present in a number of other places in India up to 600 km south of Delhi (Rainey *et al.* 1979).

10^{11} locusts, each weighing 2.5 g, represent 250000 tonnes of insects, each eating its own weight of food each day. It is concentrations such as these which create the unique catastrophe of locusts as crop pests. It is such concentrations that can overwhelm local control organizations, but their destruction could have profound effects on the future development of an upsurge. It is at such concentrations that control must be primarily directed and the ABR concept provides the necessary mobility to striking power.

7. Further considerations

In the 'search and strike' system envisaged against locusts, the role of the airborne insect-detecting radar would be the detection and assessment of locusts in flight, their densities being displayed as smoothed profiles recorded for 32 levels, and giving one such profile for about every 10 m of aircraft track. Downward visual observation from an aircraft above a flying swarm is difficult or impossible by reason of lack of contrast with the usually variegated background (Rainey 1963*b*). With the radar, satisfactory profiles could be expected throughout the vertical extent of the highest swarm likely to be encountered (say 2000 m), by reason of the relatively modest area densities even of high-flying swarms. The corresponding volume densities would be of particular value in target selection. Where necessary, target identification might be confirmed (as with the spruce budworm) by netting with the specially designed trap (Spillman 1980*b*). These facilities are of particular potential value in relation to a locust problem so far intractable, namely the assessment of the scale of escaping fledglings moving out of an area of hopper development, commonly at very low density, before assembling into swarms, at times at distances of a hundred kilometres or more. A complication in searching for airborne locusts in the vicinity of the ITD in its northern seasonal position on the fringe of the Sahara, is the marked reduction in flight activity by day to be expected by reason of high temperature, and the probably associated substantial flight activity by night instead. Successful search for locusts under these conditions would be readily possible for the ABR system.

While, with the ABR system in no more than two or three aircraft, no larger than a DC-3 or equivalent, very substantial improvement in overall coverage of Desert Locust infestations could be reasonably expected, this would still be far short of complete and continuous coverage of the entire area in which Desert Locusts may at times occur. The reports of the desert nomads, particularly of the Sahara, have long been recognized as a unique source of information on the desert rains (Dubief 1953). The special degree of intimacy of the desert nomads with the weather, the vegetation and the fauna of their continuously changing environment (Abdallahi 1979; Abdallahi *et al.* 1979) means that fuller use of their information would provide an essential complement to the data provided by the ABR and other remote sensing, of which the satellite infrared imagery described, for example, by Hielkema (this symposium) would be of especial value.

Moreover, in conclusion, perhaps the most important of all considerations on the ABR system would be the outstanding opportunities it could provide for nationals of the developing countries concerned, already with relevant professional training and expertise, for example, from national airlines, to participate and, in due course, accept responsibility for bringing to bear appropriate contemporary technology on what could prove to be a key element in a long-term solution of a major international problem.

REFERENCES

Abdallahi, O. M. S. 1979 Concluding discussion. *Phil. Trans. R. Soc. Lond.* B **287**, 475–476.

Abdallahi, O. M. S., Skaf, R., Castel, J. M. & Ndiaye, A. 1979 OCLALAV and its environment: a regional international organization for the control of migrant pests. *Phil. Trans. R. Soc. Lond.* B **287**, 269–276.

Axford, D. N. 1970 Divergence measurements from an aircraft. Discussion. *Q. Jl R. met. Soc.* **96**, 765.

Betts, E. 1976 Forecasting infestations of tropical migrant pests: the Desert Locust and the African Armyworm. *Symp. R. ent. Soc. Lond.* **7**, 113–134.

Bhalotra, Y. P. R. 1973 Disturbances of the summer season affecting Zambia. (16 pages.) Lusaka: Department of Meteorology.

Bowden, J. & Gibbs, D. G. 1973 Light-trap and suction-trap catches of insects in the northern Gezira, Sudan, in the season of southward movement of the Inter-Tropical Front. *Bull. ent. Res.* **62**, 571–596.

Brooks, C. E. P. & Durst, C. S. 1935 The circulation of air by day and night during the south-west monsoon near Berbera, Somaliland. *Q. Jl R. met. Soc.* **61**, 167–177.

Betts, E., Rainey, R. C., Brown, E. S., Mohamed, A. K. A. & Odiyo, P. 1971 Armyworm forecasting service. *Rec. Res. E. Afr. agric. For. Res. Org. 1970*, pp. 103–105.

Brown, E. S., Betts, E. & Rainey, R. C. 1969 Seasonal changes in distribution of the African armyworm *Spodoptera exempta* (Walk.) (Lep. Noctuidae), with special reference to eastern Africa. *Bull. ent. Res.* **58**, 661–728.

Clackson, J. R., 1957 *Tech. Notes, Br. W. Afr. Met. Serv. Lagos* no. 5.

Desert Locust Survey 1962*a* *Report of the Desert Locust Survey for June 1955 to May 1961*, Nairobi: East African Common Services Organization.

Desert Locust Survey 1962*b* *Final Report of the Desert Locust Survey 1961–1962*. Nairobi: East African Common Services Organization.

Dickison R. B. B., Haggis, M. J. & Rainey, R. C. 1983 Spruce budworm moth flight and storms: case study of a cold front system. *J. Clim. appl. Met.* **22**, 278–286.

Dickison, R. B. B., Haggis, M. J., Rainey, R. C. & Burns, L. M. D. 1986 Spruce budworm moth flight and storms: further studies using aircraft and radar. *J. Clim. appl. Met.* **25**, 1600–1608.

Dubief, J. 1953 *Essai sur l'hydrologie superficielle au Sahara.* (457 pages). Government of Algeria.

FAO 1963 Report on the 2nd symposium on Insecticidal Control of the Desert Locust: Aerial control, Rabat, Morocco. FAO-UNSF/DL/M/3. Rome: FAO.

Greenbank, D. O., Schaefer, G. W. & Rainey, R. C. 1980 Spruce budworm (Lepidoptera: Tortricidae) moth flight and dispersal: new understanding from canopy observations, radar and aircraft. *Mem. ent. Soc. Can.* **110**.

Gunn, D. L., Graham, J. F., Jaques, E. C., Perry, F. C., Seymour, W. G., Telford, T. M., Ward, J., Wright, E. N., & Yeo, D. 1948 Aircraft spraying against the Desert Locust in Kenya, 1945. *Anti-Locust Bull.* **4**.

Haggis, M. J. 1979 African armyworm *Spodoptera exempta* (Walker)(Lepidoptera: Noctuidae) and wind convergence in the Kenya Rift Valley, May, 1970. *E. Afr. agric. For. J.* **44**, 332–346.

Haggis, M. J. 1982 Distribution of *Heliothis armigera* eggs on cotton in the Sudan Gezira: spatial and temporal changes and their possible relation to weather. *Proceedings of the International Workshop on Heliothis management: 15–20 Nov. 1981*. India: ICRISAT, Patancheru, A. P.

Joyce, R. J. V. 1962 *Report of the Desert Locust Survey for June 1955 to May 1961*. Nairobi: East African Common Services Organization.

Joyce, R. J. V. 1976 Insect flight in relation to problems of pest control, *Symp. R. ent. Soc. Lond.* **7**, 135–155.

Kennedy, J. S., Ainsworth, M. & Toms, B. A. 1948 Laboratory studies on the spraying of locusts at rest and in flight. *Anti-Locust Bull* **2**.

MacCuaig, R. D. & Yeates, M. N. D. B. 1972 Theoretical studies on the efficiency of insecticidal sprays for the control of flying locust swarms. *Anti-Locust Bull.* **49**.

Marr, J. D. M. 1971 Observations on resting *Simulium damnosum* at a dam site in northern Ghana. *WHO/ONCHO*/71, 85.

Neumann, H. H. 1980 Prediction of New Brunswick sea breezes. *Am. met. Soc./Can. met. Ocean. Soc.* Second Conference. March 1980. Fredericton: Meteorology of Northern New England and the Maritimes.

Odiyo, P. O. 1979 Forecasting infestations of a migrant pest: the African armyworm *Spodoptera exempta* (Walk.). *Phil. Trans. R. Soc. Lond.* B **287**, 403–413.

Osman, O. E. and Hastenrath, S. L. 1969 On the synoptic climatology of summer rainfall over Central Sudan. *Arch. Met. Geophys. Bioklim.* B **17**, 297–324.

Pedgley, D. E. 1966 The Red Sea Convergence Zone. Part I: The horizontal pattern of winds. Part II: Vertical structure. *Weather, Lond.* **21**, 350–358, 394–406.

Rainey, R. C. 1958*a*. The comparative assessment of locust control methods. *Proc. Int. Congr. Ent., Montreal 1956* **10**, 263–268.

Rainey, R. C. 1958*b* The use of insecticides against the Desert Locust. *J. Sci. Fd. Agric. Lond.* **9**, 677–692.

Rainey, R. C. 1963*a* Tactics and strategy of the use of aircraft in locust control. *2nd Internat. Agric. Aviation Congress*, 219–227.

Rainey R. C. 1963*b* Aircraft reconnaissance and assessment of locust populations. *2nd Internat. Agric. Aviation Congress*, 228–233.

Rainey, R. C. 1963*c*. Meteorology and the migration of Desert Locusts: applications of synoptic meteorology in locust control. *Tech. Notes. Wld Met. Org.* **54**.

Rainey, R. C. 1972*a* Wind and the distribution of the Desert locust. *Proc. Int. Conf. Acridology, London 1970*, pp. 229–237.

Rainey, R. C. 1972*b* Flying insects as potential targets: initial feasibility studies with airborne Doppler equipment in East Africa. *Aeronaut. J.* **76**, 501–506.

Rainey, R. C. 1976*a* Flight behaviour and features of the atmospheric environment. *Symp. R. ent. Soc. Lond.*, **7**, 75–112.

Rainey, R. C. 1976*b* New prospects for the use of aircraft in the control of flying insects and in the development of semi-arid regions. *5th Internat. Agric. Aviation Congress*, pp. 229–233.

Rainey, R. C. 1979 Control of the armyworm *Spodoptera exempta* in eastern Africa and Southern Arabia: report of a mission to formulate an inter-regional project. AGPP: MISC/32. Rome: FAO.

Rainey, R. C. 1989 *Migration and Meteorology.* (308 pages.) *Oxford University Press.*

Rainey, R. C. & Betts, E. 1979 Continuity in major populations of migrant pests: the Desert Locust and the African armyworm. *Phil. Trans. R. Soc. Lond.* B **287**, 359–374.

Rainey, R. C., Betts, E. & Lumley, A. 1979 The decline of the Desert Locust plague in the 1960s: control operations or natural causes? *Phil Trans. R. Soc. Lond.* B **287**, 315–344.

Rainey, R. C., Haggis, M. J. & Coles, R. 1976 An exploration of the wind-systems of the main areas of reinvasion using aircraft. *WHO/OCP/SAP/76/WP6*.

Rainey, R. C. & Joyce, R. J. V. 1972 The use of airborne Doppler equipment in monitoring wind-fields for airborne insects: some recent results. *7th Internat. Aerospace Instrumentation Symp. Cranfield*, pp. 8.1–8.4.

Rainey, R. C. & Sayer, H. J. 1953 Some recent developments in the use of aircraft against flying locust swarms. *Nature, Lond.* **172**, 224–228.

Rainey, R. C. & Waloff, Z. 1948 Desert Locust migrations and synoptic meteorology in the Gulf of Aden area. *J. Anim. Ecol.* **17**, 101–112.

Sawyer, J. S. 1952 Memorandum on the Inter-Tropical Front. *Met. Rep. Lond.* **2**.

Sawyer, K. F. 1950 Aerial curtain spraying for locust control: a theoretical treatment of some of the factors involved. *Bull. ent. Res.* **41** 439–457.

Schaefer, G. W. 1976 Radar observation of insect flight. *Symp. R. ent. Soc. Lond.* **7**, 157–197.

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

Spillman, J. J. 1976 Optimum droplet sizes for spraying against flying targets. *Agric. Aviation.* **17**, 28–32.

Spillman, J. J. 1980*a* The efficiency of aerial spraying. *Aeronaut. J.* Feb. 1980, 60–69.

Spillman, J. J. 1980*b* The design of an aircraft-mounted net for catching airborne insects. Trends in airborne equipment for agriculture and other areas. *Proc. Seminar UN/ECE, Warsaw*, 169–180.

Tschirhart, G. 1959 *Monog. Mét. Nat., Paris.* no. **13**.

Walker, H. O. 1958 The Monsoon in West Africa. *Symposium on Monsoons of the World. New Delhi, 1958*, 35–42.

World Meteorological Organization 1953 The Inter-Tropical Convergence Zone. *Final report on the First Session of the Regional Association for Africa* (pp. 173–198). Antananarivo, Madagascar.

Discussion

M. J. Haggis (*ODNRI, Chatham, U.K.*). I should like to enlarge on the practicality of using an aircraft instrumented for wind-finding and with the various other equipment Professor Joyce has just described. The object of the exercises in which we engaged was, in Dr Rainey's words, 'to locate and explore zones of wind convergence likely to concentrate flying insects'. The most likely place to find such conditions is at a windshift, though more subtle situations occur (as explained by David Pedgley (this symposium)). Having located our potential target, we would measure the extent to which inflow of air exceeded outflow and the relative volume-densities of insects within and around the target area. Thus we hoped ultimately to identify and attack good air-to-air spray targets.

The fine detail included in published results (see, for example, Rainey 1976) was reached after applying numerous corrections to the readings. Such rigorous treatment is not necessary to gain a very fair picture of the windfield immediately, in-flight, even with the limited facilities of the small aeroplane from which so many of our observations were made.

First, how did we measure the wind from a moving aircraft? The wind is the vectorial difference between the direction and speed of movement of an airborne object relative to the air and its simultaneous movement relative to the ground beneath. By quantifying each of these, we could work out the wind by basic trigonometry.

The inertial navigation systems available in the late 1960s measured the aircraft's position relative to fixed beacons, possibly many thousands of kilometres away. For our purposes, using a small, low-flying and slow-moving aircraft, they did not provide a fine enough resolution, you can't draw an accurate triangle of velocities with one side 2 km long and the other two sides 2000 km, possibly even 12000 km long. We therefore used the Doppler system, which is self-contained within the aircraft, not dependent on far-distant beacons, and compact enough to be installed in a single-engined aircraft. In this system, three or four slightly divergent radar beams are simultaneously transmitted from beneath the aircraft, and the back-scatter of the return echo received from the ground is measured to compute the aircraft's displacement, registered as drift and groundspeed. Unlike current models, the version we used did not provide any read-out of windspeed or direction.

The Doppler display includes a roller map which moves under a pen to record the aircraft's position. The map, on which topography and other ground features are shown, is prepared in advance against a predetermined heading which, with map scale, is logged into the navigation computer. The equipment was guaranteed to an accuracy of 5 %; our experience confirmed this and, by manually annotating the trace in-flight, we could retrospectively isolate the major areas of error and identify to within 2 km the ground over which a computed wind observation had been made. In-flight corrections were made by re-setting the Doppler chart above a reference point such as the field base.

Standard aircraft instruments give compass heading, indicated airspeed (IAS) and pressure altitude. From IAS and pressure altitude we obtained true airspeed (TAS) by applying standard corrections, read off a Jeppesen CSG circular slide-rule. TAS and compass heading (with appropriate correction for magnetic variation) give aircraft movement relative to the air; groundspeed and track (true heading plus port drift or minus starboard drift), from the compass and Doppler meter, give aircraft movement relative to the ground. Initially, these vectors were drawn on the Jeppesen computer to obtain the wind vector, and indeed this method proved as quick and reliable as the programmable battery calculator that we also used in later field work.

In addition, we recorded height above ground from the radar altimeter, wet-bulb and dry-bulb temperatures, and the time of observation, a total of nine readings per set.

To minimize instrument errors, in particular the airspeed indicator (ASI), we regularly began field trials by flying, in fairly steady winds, a pattern that permitted multiple-drift wind-finding. The simplest such pattern is reciprocal headings on zero drift, but usually we flew a sexagonal track with each side just long enough to make 3–4 readings. The vectorial mean wind from all readings combined was almost always within 5 knots accuracy and often within 3 knots (Rainey 1972), and provided a reliable standard against which to compare the individual readings for systematic errors. If any were found, e.g. over- or under-reading of the ASI, we could then use a routine 'correction' to the single-drift wind computations.

For the flight trials in U.K. and all the African field work, we used a single-engined Pilatus Turbo-Porter aircraft, in which space was limited to the pilot and one observer in the cockpit, and a net operator with perhaps a second observer in the rear, behind the spray tank. An insect collecting net designed at the Cranfield Institute of Technology to soft-land the catch (Spillman 1980) was mounted under the port wing; the end-cap could be changed in-flight.

In the Porter all recording was done manually, usually at one-minute intervals, though for one observer (M.J.H.) half-minute readings were possible for limited periods of up to half an hour. As much of our flying was done at night, the recording sheets were attached to an aviation knee-pad fitted with a shielded lamp, so as not to interfere with the pilot's night vision, and careful use of a torch was needed for reading the Mk Vb strut psychrometer. This robust wartime instrument was chosen for measuring dry-bulb and wet-bulb temperatures, being suitable for the conditions we expected to encounter, as it was fully calibrated for dynamic heating and lag and the detailed corrections are published (Meteorological Office 1945). These corrections were only applied in retrospective analysis, whereas the others I have mentioned had always to be applied.

In Canada, we were provided with a DC-3 aircraft, which regularly carried a flight crew of two pilots, professional navigator and technician, and 1–4 scientists. All recording was automated: the instrument panel, comprising ASI, Doppler meter, compass, pressure altimeter, radar altimeter and clock was photographed usually at 2- or 12-second intervals, the frequency altered in-flight as required. Wet-bulb and dry-bulb temperatures were recorded as continuous traces from thermistor probes already calibrated for pressure correction. In addition, there was continuous trace output from the accelerometer, recording the fine detail of vertical turbulence and, after the first year, standard weather radar, recorded photographically. These facilities enabled in-flight draft mapping of winds. In 1976 the DC-3 also carried an insect detecting radar, which Mr Wolf operated. Like the Porter, the DC-3 was fitted with a Cranfield insect collecting net.

Coming now to how we used this equipment: it is important to emphasize that all flight plans were finalized and filed only after consultation with the forecasters at the local meteorological office and, in Canada, with additional guidance from Professor Dickison. This meant that we already knew the readily identified synoptic or subsynoptic windfield in which we were to fly and approximately where to be most alert to the details of its features.

For example, before our first interception of the Inter-Tropical Discontinuity (ITD) in Sudan on 29 September 1970 (figure 5.8 in Rainey (1976)) we were informed that the ITD was near Atbara; on arrival there we were told it had moved north about an hour earlier. We found it some 80 km to the north, perceived in-flight by the marked increase in port drift, decrease in groundspeed and change in humidity, and confirmed by working out the winds on the ground at the Station 10 desert airstrip before our return flight.

To quantify the rate of convergence across the ITD, we aimed to fly a 'box' pattern straddling the windshift, as mentioned by Professor Joyce. Although the pattern was planned in advance, its position could only be determined when and where we actually located the ITD: with in-flight wind computing by the second observer, our first 'box' pattern (Rainey 1976, figure 5.9) was begun 12 min after the initial interception of the windshift. A later refinement was to locate the ITD on the outbound flight so that on the return we could change insect nets before the anticipated traverses and again after completing the 'box', thus exposing nets entirely to the south of the ITD, across it, and entirely to the north (Rainey 1976, figure 5.11); a significantly higher insect density was found across the ITD than in either single airmass. On these and other occasions, the actual rate of convergence (e.g. Rainey 1976, figure 5.10) was computed retrospectively.

The next stage was to fly multiple closed patterns across a windshift line, a technique we developed in 1971 for the sea breeze front of southern England, which was being investigated by the Reading Department of Geophysics. Aided by their briefing on the advance of the front, we located it and began the zigzag pattern (Rainey 1976, figure 5.20) about 5 min later; by marking on the Doppler map the areas of turbulence encountered, we were able to reduce the size of zigzags on the return leg of the flight. The same technique was later used on the ITD in Sudan on an occasion of marked turbulence and very sharp windshift, particularly at the western edge of the pattern in figure 5.14 (Rainey 1976) where the groundspeed dropped by 6 knots in about 10 s, precluding any meaningful reading of instruments; however, although we tried to follow the line of turbulence marked on the Doppler map, the 'pattern' was spoiled by the abrupt northward displacement of the ITD by some more than 100 km in 3 h, as shown by subsequent synoptic analyses. This same technique was used in Canada to explore a minor but well-defined front (figure 13 in Rainey (1978)) at which significant convergence was measured (figure 14 in Greenbank *et al.* (1980)).

A further refinement to the closed pattern for measuring the rate of convergence across the ITD was at the same time to fly a very slow climb and descent, at a rate of about 60 m min^{-1} to obtain a vertical profile through it.

In conclusion, given an aircraft with the equipment described by Dr Rainey and Professor Joyce, and aided by no more than the standard information available at the meteorological office at the local civil airport, locating wind convergence zones, particularly the ITD, is fully practicable. The technology and techniques were available and flight tested 20 years ago, indeed our first flight trials were in December 1969. The techniques will be simpler with present day technology that includes read-out of ready computed winds. Searching for locust swarms might still be partly visual, but the day-to-day area of search could be narrowed down to a belt of, say, 300 km. Scattered locusts, flying even in low numbers, would be picked up on the airborne insect-detecting radar, their volume-density measured and variations in density with height, such as layers, identified. Having located and delimited a sprayable target, the aircraft could then fly a sampling run at the level of the highest insect density to check the identity of the insect echoes and measure the wind within them for optimum direction of spray run, before putting down a spray line. The exact location of each activity would be recorded on the Doppler map, eliminating the need for environmental contamination by repeated spraying over the same ground. The location of visual observations of insects or of other information like green areas (potential breeding areas), of relevance to both air and ground surveys, would also be precisely recorded on the Doppler map.

References

Greenbank, D. O., Schaefer, G. W. & Rainey, R. C. 1980 Spruce budworm (Lepidoptera: Tortricidae) moth flight and dispersal: new understanding from canopy observations, radar and aircraft. *Mem. ent. Soc. Can.* **110**.

Meteorological Office 1945 *Meteorological air observer's handbook.* (73 pages). London; HMSO.

Rainey, R. C. 1972 Flying insects as potential targets: initial feasibility studies with airborne doppler equipment in East Africa. *Aeronaut. J.* **76**, 501–506.

Rainey, R. C. 1976 Flight behaviour and features of the atmospheric environment. *Symp. R. ent. Soc.* **7**, 75–112.

Rainey, R. C. 1978 The evolution and ecology of flight: the 'oceanographic' approach. In *Evolution of insect migration and diapause* (ed. H. Dingle), pp. 34–48. New York: Springer–Verlag.

Spillman, J. J. 1980 The design of an aircraft-mounted net for catching airborne insects. In *Trends in airborne equipment for agriculture and other areas*, pp. 169–180. *Aero-Agro 1978. Proceedings: Seminar UN/ECE, Warsaw.* Oxford: Pergamon Press.

J. R. Riley (*ODNRI, Malvern, U.K.*). I suggest that the satellite-based Global Positioning System (GPS) should now provide a more accurate and much less expensive method of wind-finding from aircraft, than the Doppler systems described by Professor Joyce and Miss Haggis. I think also, that a forward looking, modified meteorological (precipitation) radar would be more effective in finding swarms than a downward-looking system, especially in the case of high-flying, cumuliform swarms. A downward-looking radar would be useful to make quantitative measurements of the density distribution within the swarms, once they had been found.

D. E. Pedgley (*ODNRI, Chatham, U.K.*). There is little doubt that an aircraft can be equipped to seek out windshift lines and sharply defined convergence zones, but Professor Joyce's strategy is based on the hypothesis, put forward by Dr Rainey in the 1940s, that flying locust swarms should tend to accumulate in convergence zones. How often does that happen? Examples can be quoted easily, but how typical are they? I ask because, as far as I am aware, convergence zones did not have a substantial role to play in slowing the movement of swarms that were examined for the WMO *Technical Note* (Rainey 1963) or for the 55 case studies prepared for the *Desert Locust forecasting manual* (Pedgley 1981). The majority of swarms are reported nowhere near convergence zones, either recognizable on synoptic weather maps or inferable from known mechanisms of formation. They are often highly mobile, and when they do slow down is it not usually from low temperatures or onset of breeding? I accept that convergence zones may go unrecognized, especially near coasts and mountains. It is in such limited parts of the Desert Locust area that the feasibility of a search-and-strike aircraft might best be tested for the control of swarms trapped in convergence zones. Two such areas are around the southern Red Sea and near the coast of northwest Africa, both of which are known for the accumulation of swarms at certain times of the years.

What are the chances of finding a worthwhile target in, say, 10 h flying time, and hence the costs in relation to the likely savings resulting from control?

References

Pedgley, D. E. (ed.) 1981 *Desert Locust forecasting manual.* vol. 1, (268 pages); vol. 2, (142 pages). London: Centre for Overseas Pest Research.

Rainey, R. C. 1963 Meteorology and the migration of desert locusts: applications of synoptic meteorology in locust control. *Tech. Notes Wld met. Org.* **54**.

R. J. V. Joyce. First, regarding persistent zones of wind convergence, I agree these exist only in a few special localities. A notable one occurs in the northern Region of the Somali Republic between July and September, occupying day after day some 5000 km². This zone acts as a temporary sink into which drain the Desert Locust swarms which have bred over some 500000 km² on the Short Rains in the Somali Republic, the adjacent parts of Ethiopia and in southern Arabia. There have been occasions, as in 1960, when a major fraction of the world population of Desert Locusts has accumulated in this zone, providing a unique opportunity for overall regulation of Desert Locust numbers. A similar persistent convergence zone appears to trap locusts in the Souss Valley of Morocco.

The convergence zone in the Northern Region of the Somali Republic has a diurnal movement; swarms settling in it in the early evening are disrupted when they take off the following morning in the strong southwesterly winds which, during the night, have replaced the convergence zone, and the swarms reform as the zone again moves south during the afternoon. The cohesion and density of the swarms is determined by the intensity of the convergence, opposing winds being separated by only a few kilometres.

Mr Pedgley states, that convergence is largely restricted to mountainous areas and it is here alone that 'Search and strike' would be useful, and that most swarms are in transit, not in zones of wind convergence, so that the contribution of the method to control is likely to be small. I find it difficult to accept this for the following reasons.

Dr Rainey has pointed out that, whilst the convergence hypothesis derived from largely circumstantial evidence based on studies on synoptic scales of 10^2 to 10^3 km^2, it is now supported by evidence on the structure of convergence on much smaller scales involving the flight of individual insects (and not always gregarious ones). These began with the radar studies of Professor Schaefer who observed not only locusts and grasshoppers concentrating in and moving with zones of wind convergence, but also moths of several species. Dr Riley, who continues these radar studies, observed individual armyworm moths moving from both sides into a front caused by the cold outflow from a rain-storm in Kenya at closing speeds of 25 km h^{-1} from points only one kilometre apart.

Again the rate of convergence of 0.25 h^{-1} across the ITD, measured by Rainey and Haggis, is of course the average over the whole 500 km^2 of the 'box' pattern; at the discontinuity itself the rate would be very much higher. The ITCZ, traversing Africa from east to west, is a particularly important regular seasonal system for accumulating swarms in transit during at least five months of the year, and search for locust concentrations along this discontinuity is, I believe the key to locust control. The ABR system makes such surveys possible and is, indeed, the only method which can provide quantitative information on the locusts in transit.

Mr Popov stresses the importance of source areas where breeding has taken place on a scale sufficient to produce swarming populations and the value of satellite imagery in providing a broad indication of areas of current rainfall or supporting vegetation where such breeding may be taking place. These areas can be vast, not less than 5000000 ha and frequently 10–100 times more, and must be searched in weeks rather than months. Many such areas are inaccessible to ground parties, either for security reasons or through terrain. They can be searched by airborne observers for gregarious hopper bands because, when basking, even first instars can be readily seen for at least one kilometer from the aircraft track. A properly calculated system of sequential sampling, requiring systematic random search, can be achieved only by aircraft fitted with accurate track-guidance. By this means, areas supporting an unacceptably high population could be identified, subjected to detailed search and, if necessary, control, and estimates could also be made of the numbers of locusts which could be expected to escape from those areas where the survey had indicated populations were within the acceptable range.

In this opening remarks, Dr Rainey drew attention to the two conflicting views on the origin of Desert Locust upsurges, but to me, the requirements of both point to the need to employ a specially instrumented aircraft, which we now connote the ABR system.

The actual cost of the Insect Detecting Radar is quoted by the Cranfield Institute of

Technology at U.S.$75000 and to this capital expenditure must be added the cost of suitable spray gear and a few other essential items for which a further U.S.$25000 is allowed. Installation of specialized equipment into the aircraft is estimated at U.S.$230000, giving a total capital expenditure of some U.S.$330000.

Operational costs include the wet charter of a suitable aircraft with an endurance of 6 h, interest on capital outlay and a provision of 15% of the capital for maintenance and up-dating of equipment. For a nine months charter and 600 h flying with a crew consisting of a pilot, two navigators and one operator of the specialized equipment, I estimate the cost at U.S.$900 per flying hour (table 1). Thus the annual recurring budget for the 'Search and strike' operation is estimated at U.S.$640000 in which estimate is a provision of U.S.$100000 for insecticide.

TABLE 1. SEARCH AND STRIKE FOR DESERT LOCUST CONTROL USING AIRBORNE RADAR SYSTEM

	U.S. $	
Capital costs		
airborne insect detecting radar system as specified by CIT including 4-channel strip chart recorder	50000	
data analysis		
microcomputer for data analysis & storage		
printer and plotter		
software for data collection		
consumables (paper, magnetic tapes etc)	25000	
Camp & domestic equipment	25000	
		100000
Preparation		
fitting of spray gear (Cranfield Venturi system)	50000	
navigation system	55000	
insect detecting radar	90000	
certification	35000	230000
total costs		330000
Operational costs		
interest on capital costs (at 8%)	26400	
maintenance & up-dating capital equipment	15000	
wet lease for 9 months (aircraft, crew, maintenance, insurance)	362000	
flying costs, say, 600 h at $219 h^{-1}	131400	
Total for 9 months operations		534800
Cost per flying hour	900	
Contingency costs		
subsistence: 4 crew at $40 per day	50000	
insecticide	50000	100000
Total recurrent budget provision (9 months)		634800
Total recurrent budget provision (in £ sterling)		400000

R. B. B. DICKISON (*Department of Forest Resources, University of New Brunswick, Canada*). Controlling eastern spruce budworm populations by spraying against migrating moths is obviously appealing to pest managers in Canada, but there are practical limitations. First, the feeding period of the insect (the larval period) is past, and the only accomplishment would be to limit the transport of viable eggs to new areas to establish or augment a larval feeding population in the following year. This is partly mitigated because 50% or more of the eggs are deposited before the female will emigrate. Secondly, environmental concerns have made it impossible, from a socio-political point of view, to spray under conditions where the ground surface impact area cannot be determined. Current regulations in New Brunswick prohibit spraying within one mile of human habitation, even for air-to-ground applications. It may be that the environmental impact is more perceived than real, but those who make political decisions are very reluctant to make such distinctions. This, of course, applies only to use of chemical insecticides, but, although pheromone control is under investigation, there is little encouraging evidence of an alternative to chemical insecticides against moths. Indeed, pheromones cannot be used against migrating spruce budworm moths, since mating takes place several days before emigration. Such environmental concerns are overwhelming for many perceived strategies of spraying airborne insect targets. Wherever human population densities are high, and environmental consciousness is keenly honed, I expect the strategy is impractical.

P. R. Jonas (*Institute of Science and Technology, University of Manchester, Manchester, U.K.*). In the paper, attention is drawn to the sizes of the droplets needed to optimise the effectiveness of spraying into an insect cloud. The results apply only to non-volatile sprays. If more environmentally friendly sprays are developed with an aqueous or other volatile base, then evaporation may significantly influence the effectiveness of spraying. Evaporation is particularly rapid for the smaller drops which, on the basis of the calculations, appear to be the most effective.

The calculations of spray effectiveness rely on the ratio of the mean time for droplets to be captured by insects to the residence time of the spray droplets in the cloud. Laboratory experiments on droplet capture by droplets suggest that moderate levels of turbulence in the droplet cloud may significantly increase the capture efficiency for droplets around 10 μm radius. It is possible therefore that your calculations of spray effectiveness may be rather pessimistic. It would be of interest to compare the results of the calculations with detailed observations of the capture by insects, possibly by spraying an inactive tracer.

In weather modification experiments, where the objective is to place material into particular regions within an orographically forced cloud, ground based aerosol generation is often used, with the air motion carrying the material into the cloud. Is the use of ground based sprayers feasible in this application, especially where pests are concentrated by stationary convergence induced by topographic features which might be predicted some time in advance?

R. J. V. Joyce. With regard to the formulation employed, we have always insisted that it must have a high degree of non-volatility, so the droplets which are produced at the nozzle remain that size until they are collected by the target. I don't think I need enlarge very much on capture efficiency, except to say that although it is greatest for droplets of diameter of about 50–60 μm, they will occupy the same air as the flying locusts for such a short time, that the decreased efficiency with which droplets of, say, 10 or 20 μm are captured is fully compensated by the fact that they are in the same air for so much longer.

As for injecting spray from the ground, I don't think that is at all practicable in the Sahel of Africa, either in terms of locating the convergence zone, or for that matter, in logistics.